



Validation of tidal turbine wake simulations using an open regional-scale 3D model against 1MW machine and site measurements

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ABSTRACT

Full-scale tidal turbines deployed in tidal channels are subjected to complex flow due to the effects of local bathymetry and coastline shape which modify the flow directionality, shear, twist and speed of the underlying tidally forced flow. In response to these effects, the wake of an operational tidal turbine will vary spatially and temporally. In order to predict wake form, which is a key step for scaling up tidal energy as developments move from single devices to arrays, we have developed and demonstrated an open source turbine-embedded regional three-dimensional (3D) hydrodynamic model for power and wake prediction. Simulation outputs have been validated against *in-situ* measurements acquired via ADCPs positioned downstream of and adjacent to the rotor-plane of an operating tidal turbine. Model predictive performance is parameterised by the relative difference between modelled and measured power-weighted rotor averaged velocity using speed binning and temporal-averaging. In the absence of the turbine representation, the difference between model and measurement for ebb and flood was found to be 0.81% and 1.04% respectively at the flow speed of 2.5 m/s. With the turbine represented as an actuator disc in the model, the averaged error of the velocity profiles in the wake is 4.4% and 5.2% at ADCP locations that are 3.7D and 6.2D downstream of the rotor plane during ebb. The model has been designed for use on moderately-priced workstations and the promising results, in terms of capturing key 3D flow features and predictions of wake velocity deficits, is a starting point for further development and may provide baseline data for alternative (e.g., higher fidelity, slower performance, or lower fidelity including 2D models with much faster performance).

1. Introduction

Tidal stream energy has a significant potential to produce renewable electricity to meet the ambitious targets of global energy transition and carbon emission reduction. In late 2021, the UK government announced the biggest investment into tidal power generation, with £20 million investment per year, kickstarting a brand new chapter for the tidal energy industry in the UK (GOV.UK, 2021). In 2022, four tidal energy projects in the UK were awarded Contracts for Difference (CfD) to commence operation between 2025 and 2027, with a total expected capacity of 40.82 MW (Jeffrey et al., 2023).

However, the majority of those tidal energy converters (TECs) are going to be deployed in channels or straits where the flow is subjected to the influence of local bathymetry, water depth, coastlines and headlands (Coles et al., 2021). Moreover, optimised and efficient deployments of the TECs in a tidal energy site are necessary for maximising energy yield in a limited area (Jordan et al., 2022).

Wakes generated from a TEC can influence the power generation and loading characteristics of downstream turbines, which leads to concerns regarding blade fatigue and reduced annual energy yield (Lam et al., 2023; Zhang et al., 2023). As such, studying the two-way interactions between a horizontal-axis TEC and the surrounding flow field become particularly important.

The conventional approach to modelling TECs and predicting turbine wakes generated is blade-resolved Computational Fluid Dynamics (CFD) (Jump et al., 2020). Although blade-resolved CFD models are capable of accurately predicting flow in the vicinity of the turbine blades, modelling TECs with both longer time and larger spatial scales are not practical due to their high computational cost (Zhang et al., 2020); modelling at larger scales requires simpler turbine representations such as actuator disc (Nguyen et al., 2016) or actuator line (Ouro and Nishino, 2021). While such CFD models and their simulation results can provide insights about wake characteristics from an individual

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TEC and wake interactions at array-scale, their inflow conditions are generally limited to steady flow without flow misalignment. This requires one to run multiple simulations with different modified inflow configurations to gain an understanding of the interactions between TECs and surrounding flow field at a site during a tidal cycle.

Regional hydrodynamic models such as Telemac3D (Hervouet, 2007), are an attractive option to simulate realistic three-dimensional (3D) flow across an extended domain with the considerations of the physical boundaries including islands, coastlines and bathymetry. Yet, there are limited studies related to TEC modelling in real environments with 3D regional models. Telemac2D, a 2D version of the Telemac3D, has an established method to implement and represent TECs based on drag forces similar to an actuator disc approach (Joly et al., 2015). However, this cannot take into account 3D flow structures and will likely misrepresent both the wake and the turbine response.

There are a few studies reported in the literature which represent TEC in regional hydrodynamic models to predict 3D turbine wake interactions (Ramos et al., 2019; Waldman et al., 2017; Michelet et al., 2020). Murphy et al. (2017) have implemented a drag parameterisation for a vertical-axis tidal turbine in Telemac3D by modifying the source code. Results were validated against physical model test data which shows promise in capturing far-stream turbine wake velocity distributions. Thiébot et al. (2020) investigated turbine-wake interactions at the farm-level by implementing horizontal-axis TECs in Telemac3D with an actuator disc approach. While the wake field study with realistic flow conditions was conducted at a regional scale and the actuator disc formulation was validated at laboratory scale, the authors acknowledged that there are uncertainties related to the wake characteristics predicted by their model since the required data measured downstream of a full-scale turbine were not available for calibration and validation.

To the best of our knowledge, there are currently no studies that verify or validate TEC-embedded regional models against in-situ wake data measured downstream of a full-scale turbine by seabed-mounted instruments. The majority of numerical models presented in the literature were validated against lab-scale experimental wake data measured by various techniques, such as Acoustic Doppler Velocimetry (ADV) (Stallard et al., 2015), Laser Doppler Velocimetry (LDV) (Morandi et al., 2016) and Particle Image Velocimetry (PIV) (Lust et al., 2018), while the representation of TEC ranges from porous disc to scaled turbine (Harrison et al., 2010; Lust et al., 2020). Although lab-scale measurements can provide insights into turbine behaviour and turbine-wake interactions at lower cost and risk, scaling of the turbine characteristics can be difficult, not to mention the challenge of creating realistic and complex inflow conditions that a full-scale turbine is subjected to. In fact, the differences between the wakes generated by a full-scale and lab-scale turbine are yet to be explored due to the lack of field data. This draws scepticism as to whether laboratory experiments can accurately represent realistic flow conditions and wake fields.

Considering the research gaps and problems identified from the literature, this article addresses these aspects by demonstrating and validating a full-scale TEC model embedded in Telemac3D against in-situ wake data measured by ADCPs at the European Marine Energy Centre (EMEC) tidal energy test site during the Reliable Data Acquisition Platform for Tidal energy (ReDAPT) project (Sellar et al., 2018). This project centred on the design, installation and operation of a 1 MW horizontal-axis TEC, the DeepGen-IV. In this article, the Telemac3D model is validated against measured ambient flow velocities and directions, wake predictions from the TEC-embedded model are compared with in-situ wake measurements, and the performance of the TEC-embedded model is discussed.

2. Methodology

2.1. Governing equations in Telemac3D

Telemac3D solves the free-surface incompressible unsteady Reynolds-Averaged Navier–Stokes (RANS) equations using finite element approximation with or without the hydrostatic pressure assumption (TELEMAC-3D, 2021a). The continuity and momentum equations being solved are:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \quad (1)$$

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \Delta(U) + F_x \quad (2)$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \Delta(V) + F_y \quad (3)$$

$$\frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} + V \frac{\partial W}{\partial y} + W \frac{\partial W}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + \nu \Delta(W) + F_z \quad (4)$$

where U , V , and W are the 3D components of velocity in the horizontal (x and y) and vertical (z) directions respectively. ν is the kinematic viscosity and tracer diffusion coefficient, t is the time step, p is the pressure and ρ is the water density ($\rho = 1025 \text{ kg/m}^3$). F_x , F_y and F_z are source terms denoting the wind, the Coriolis force and the bottom friction or any other physical processes being modelled.

The pressure is split up into hydrostatic pressure and dynamic pressure terms:

$$p = p_{atm} + \rho_0 g(Z_s - z) + \rho_0 g \int_z^{Z_s} \frac{\Delta \rho}{\rho_0} dz + p_d \quad (5)$$

where p_{atm} is the atmospheric pressure, g is the acceleration due to gravity ($g = 9.81 \text{ m/s}^2$), Z_s is the free surface elevation, ρ_0 is the reference water density, $\Delta \rho$ is the variation of density around the reference density and p_d dynamic pressure.

The Telemac3D basic algorithm is based on three computational steps on a 3D unstructured mesh, which is made of prisms that are automatically constructed by Telemac3D (TELEMAC-3D, 2021a). The first step solves the advection terms only in the momentum equations to find the advected velocity components. The second step computes the new velocity components taking into account the diffusion terms and the source terms in the momentum equations. The last step computes the water depth from the vertical integration of the continuity equation and the momentum equations only including the pressure-continuity terms. The resulting 2D equations are written as:

$$\frac{\partial h}{\partial t} + \frac{\partial(uh)}{\partial x} + \frac{\partial(vh)}{\partial y} = 0 \quad (6)$$

$$\frac{\partial u}{\partial t} = -g \frac{\partial Z_s}{\partial x} \quad (7)$$

$$\frac{\partial v}{\partial t} = -g \frac{\partial Z_s}{\partial y} \quad (8)$$

where u and v here refer to the 2D variables of the vertically integrated velocity and h is the water depth. Eqs. (6) to (8) are then solved to obtain the vertically averaged velocity and the water depth. With the water depth, elevations of various mesh points and then those of the free surface can be recomputed. Finally, U and V can be computed through a combination of the equations linking the velocities while W is computed from the continuity equation.

Further details on the theoretical basis of Telemac3D, including basic algorithm and model verification details, can be found in TELEMAC-3D (2021a) and Moulinec et al. (2011), while the full derivation of Eqs. (1) to (5) is described further in Hervouet (2007).

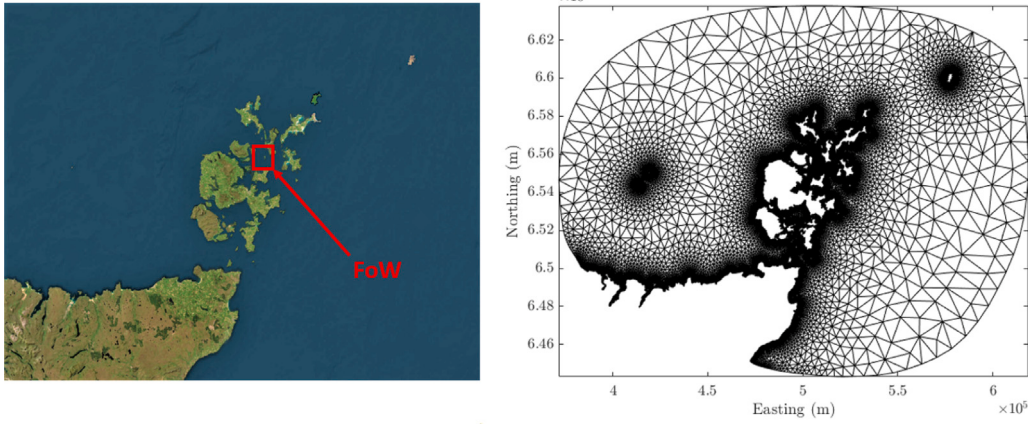


Fig. 1. Left: Satellite image. Right: 2D mesh showing the hydrodynamic model domain which includes the Orkney islands, northwest region of the Scottish mainland, coastal isles and outer isles. Red rectangle shows the location of the EMEC tidal energy test site, Fall of Warness (FoW). Coordinate reference system is WGS84/UTM30N (EPSG:32630).

2.2. Model setup and configurations

The hydrodynamic model domain covers the Orkney islands, the northwest region of the Scottish mainland, coastal isles and outer isles, as shown in Fig. 1. Although the area of interest for this study is the EMEC tidal energy test site at the Fall of Warness (FoW), the model domain was extended sufficiently far away from coastal areas to allow a good representation of the tidal forcing from the tidal atlas data.

The 2D mesh of the whole model domain was constructed using two sub-meshes with decreasing cell sizes. Fig. 2 illustrates a zoom-in view of the 2D mesh at FoW and shows the area in the vicinity of the DeepGen-IV and ADCP deployments. To capture the transient flow effect around the turbine and instruments, the second sub-mesh covers approximately $20D \times 10D \text{ m}^2$ ($D = 18 \text{ m}$) around the turbine and was refined to 3 m resolution. From our preliminary studies it was noted that a strong shear layer was formed on the northeastern side of the channel, and thus, would affect the flow structures on both flood (flow from the west) and ebb (flow from the east) tides. To resolve the shear layers and capture the vortex shedding from the island in between the channel, the 2D vorticity field was generated from depth-averaged velocity to identify the core regions of maximum vorticity. They were then represented as a set of hardlines with 30 m resolution for the mesh to grow from. Before embedding the turbine in the regional model, preliminary model simulations in a rectangular channel with hydrodynamic conditions that are representative of the FoW were conducted to determine the optimal cell size in the regional model. The resulting developed 2D mesh without the TEC implementation contains 101 105 nodes and was discretised vertically into 10 sigma layers which are evenly distributed and movable between the free surface and the bottom seabed. The resulting 3D mesh contains 1 011 050 nodes.

To improve the models representation of the strong shear flow on the northeastern side of the FoW formed by the island headlands, high-resolution bathymetry data were used to ensure that flow interactions at the boundaries could be reflected appropriately. Fig. 3 shows the bathymetry across the model domain which was interpolated onto the horizontal mesh. Bathymetric data at the FoW were obtained from the Seabed Mapping Data Service from the UK Hydrographic Office (UK Hydrographic Office, 2020) with a spatial resolution of 3 m , while EMODnet (European Marine Observation and Data Network (EMODnet), 2020a) digital bathymetry with a spatial resolution of 115 m was used for the wider domain.

A slip condition was used on the bottom and the lateral walls. Bottom friction in the model was defined using EMODnet Seabed Habitats type data (European Marine Observation and Data Network (EMODnet), 2021b). Substrate class names were provided in the form of a shapefile, which could be mapped to a set of C_{100} drag coefficients. The

drag coefficients were then mapped onto the horizontal model mesh nodes allowing spatially varying bottom roughness values to be calculated, which is shown in Fig. 4. The corresponding friction coefficient was computed in Telemac3D using the Nikuradse formulation.

Initial tidal conditions at the open sea boundary including the velocities and elevation were obtained from the global TPXO database (OSU TPXO Tide Models, 2021), from which 15 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, MM, Mf, M4, MN4, MS4, 2N2, and S1) were used. Wind-induced stress on the free surface and wave-current interactions were not considered since the effects of wind and wave were not integrated into our model. A 0.25 s time step was adopted in the simulation to satisfy the Courant-Friedrichs-Lewy (CFL) condition for the 3 m cell size around the locations of the instruments. To reduce the demand for data storage spaces, the output of the simulation was written every 30 s and therefore results in 2881 samples for a day of simulation. 44 parallel processors were used in the computation which led to a simulation time similar to real time.

There are various turbulence closure schemes provided by Telemac3D. Instead of using the default $k - \epsilon$ model, Smagorinski and mixing length model were adopted for the horizontal and vertical directions respectively to obtain the eddy viscosity. Use of the Smagorinski formulation better captures the sub-scale turbulence in highly non-linear flow, whereas the mixing length model is found to be more optimal in the vertical. Further information on the turbulence model formulations can be found in TELEMAC-3D (2021b). The non-hydrostatic assumption was used to better capture the surface response and the Coriolis force was calculated using a constant Coriolis coefficient of 1.25×10^{-4} based on the latitude at the centre of the model domain.

2.3. Full-scale turbine description

The DeepGen-IV 1 MW horizontal-axis tidal energy converter (TEC) was deployed during the Reliable Data Acquisition Platform for Tidal (ReDAPT) project conducted between 2012 and 2014, as shown in Fig. 5. The full-scale TEC has three blades, variable pitch control and a diameter (D) of 18 m , which results in a blockage ratio of less than 1% as the channel occupied by the TEC is approximately 2 km across from Eday to Muckle Green Holm (McNaughton, 2014). Moreover, the TEC is bottom-mounted on a piled tripod and the rotor hub is 18 m above seabed. The turbine nacelle is manually rotated around the vertical axis of the support structure during slack tides so that the rotor plane is facing into and perpendicular to the principle flow direction during flood and ebb when the inflow speed reaches the cut-in of 1 m/s . The rated speed is 2.7 m/s and the cut-out speed is 3.4 m/s to protect the blades and generator from the impact of strong flow.

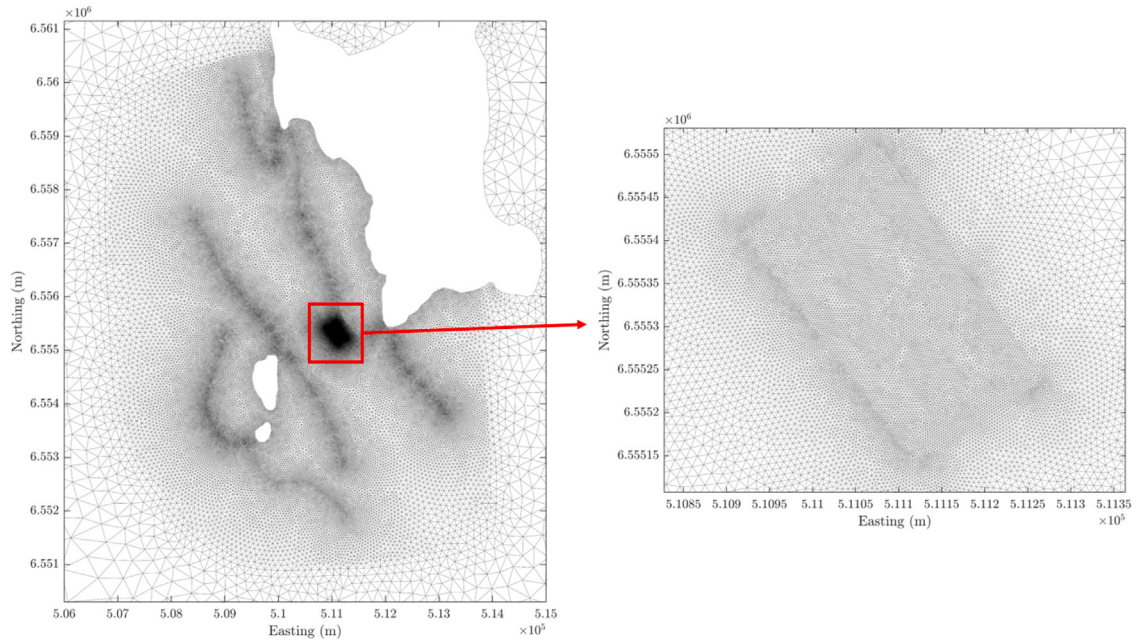


Fig. 2. Left: A zoom-in view of the sub-mesh at Fall of Warness (FoW) - red rectangle illustrates the area of interest in the vicinity of the DeepGen-IV and ADCP deployments. Right: A $20D \times 10D$ m² ($D = 18$ m) sub-mesh with 3 m cell size covering the turbine and instrument locations. Coordinate reference system is WGS84/UTM30N (EPSG:32630).

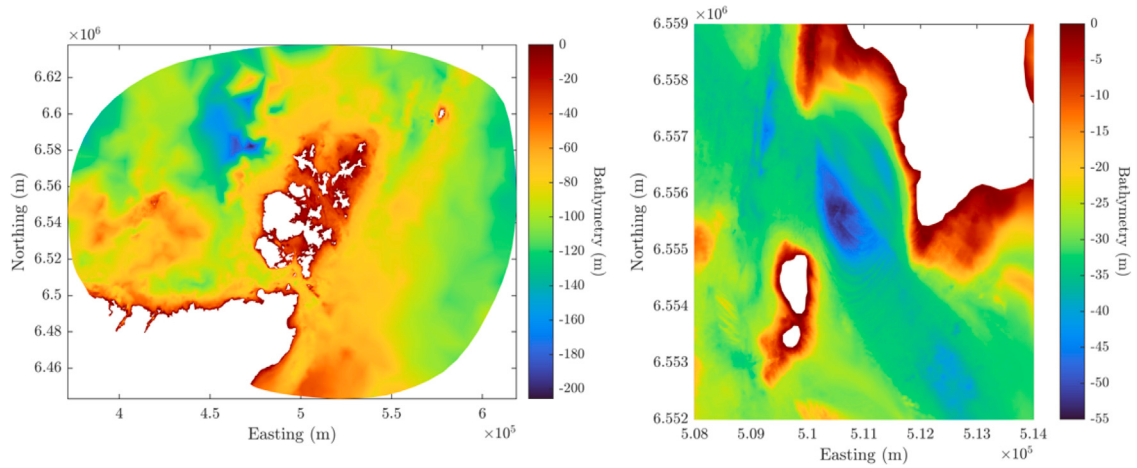


Fig. 3. Left: Interpolated bathymetry of the model domain. Right: Its zoom-in view at Fall of Warness (FoW). Coordinate reference system is WGS84/UTM30N (EPSG:32630).

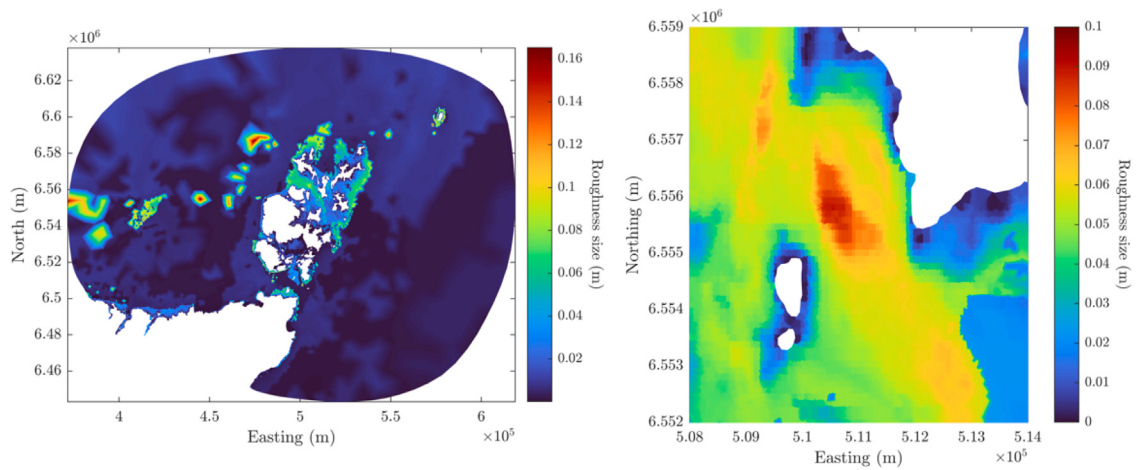


Fig. 4. Left: Interpolated roughness value of the model domain. Right: Its zoom-in view at Fall of Warness (FoW). Coordinate reference system is WGS84/UTM30N (EPSG:32630).



Fig. 5. The DeepGen-IV 1 MW tidal turbine being deployed from Hatson Quay, Kirkwall, Orkney.

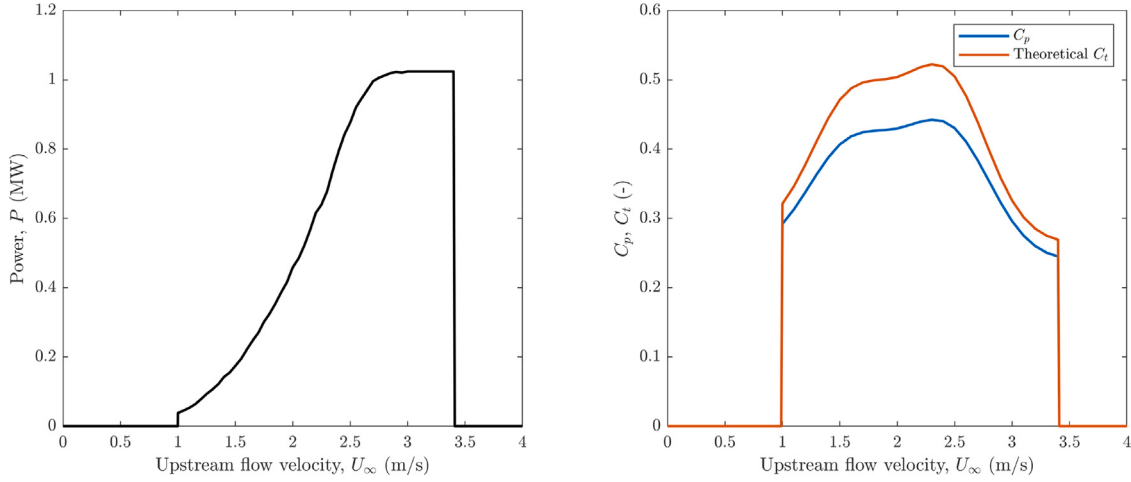


Fig. 6. Left: Power curve of the DeepGen-IV turbine. Right: Power coefficient and theoretical thrust coefficient against freestream flow velocity.

2.4. Turbine representation and implementation

The full-scale turbine in our Telemac3D model is represented by an actuator disc where the thrust force of the turbine is distributed across the swept area of the turbine blades. The expression of thrust force, F_t , is shown in Eq. (9),

$$F_t = \frac{1}{2} \rho C_t A U_\infty^2 \quad (9)$$

where C_t is the thrust coefficient, A is the rotor swept area and U_∞ is the upstream flow velocity.

Since the thrust coefficient is dependent on the upstream flow velocity, turbine geometry and operating characteristics, the power coefficient as a function of upstream flow velocity was evaluated using the DeepGen-IV turbine power curve as shown in Fig. 6 (McNaughton, 2014). Hence, the axial induction factor, α , could be obtained with Eq. (10) using the momentum theory (Schaffarczyk, 2014), which can then be substituted into Eq. (11) for calculating C_t .

$$C_p = 4\alpha(1 - \alpha)^2 \quad (10)$$

$$C_t = 4\alpha(1 - \alpha) \quad (11)$$

To reflect the effect of thrust exerted by the disc on the surrounding flow, an additional source term, S_i , which is also the volumetric force, is added to the RANS momentum equations. S_i is derived by thrust divided by the disc volume. Therefore, this can be further simplified to Eq. (12), where Δx is the thickness of the disc.

$$S_i = \frac{\frac{1}{2} \rho C_t A U_\infty^2}{\Delta x} \quad (12)$$

Meanwhile, power output from the modelled turbine as a function of upstream flow velocity and C_p can be obtained with Eq. (13).

$$P = \frac{1}{2} \rho C_p A U_\infty^3 \quad (13)$$

Using the sigma transformation in Telemac3D to construct the 3D mesh results in evenly distributed movable layers between the free surface and the bottom seabed; this is undesirable when representing the bottom mounted DeepGen-IV turbine using the TEC embedded model. Therefore, it is important to fix the altitude of the layers in the model which represents the turbine rotor. The number of layers in the TEC embedded model was increased from 10 to 14 for capturing the flow interactions between the rotor bottom tip and the seabed. 5 layers from a total of 14 were used to represent the turbine rotor from

Table 1

ID, deployment duration and coordinates of the ADCPs involved in the model validation. Distance from rotor plane in turbine diameters for respective ADCPs during the ebb tide are shown. Coordinate reference system is WGS84/UTM30N (EPSG:32630).

ID	Campaign ID	Deployed	Recovered	Days	Easting (m)	Northing (m)	Distance from rotorplane in D (m)
ADCP01	ADCP01_NW_Dep5	2014-06-22	2014-08-05	41	511 072	6 555 354	3.7D
ADCP02	ADCP02_NW_Dep5	2014-07-07	2014-08-16	40	511 052	6 555 394	6.2D
ADCP03	ADCP03_SE_Dep5	2014-07-07	2014-08-17	41	511 142	6 555 260	2.8D
ADCPTD7	ADCPTD7_02_Dep6	2014-09-17	2014-11-27	71	511 078	6 555 286	2.3D

its bottom to upper tip extent. It is worth noting that the disc cross-section is not exactly circular because the disc volume is formed by prisms. Although increasing the mesh density of the turbine enclosure would improve the represented turbine geometry, i.e. more circular, it has been shown in Rahman et al. (2018) and Thiébot et al. (2016) that the effect of node spacing within the actuator disc on wake prediction is insignificant once a reasonable resolution is obtained.

While the actuator disc method is widely used in representing wind and tidal turbines for wake predictions, blade rotation and turbine support structures such as the piled tripod and nacelle are not modelled. This in turn would lead to an under-prediction of turbulence and drag in the near wake region. Preliminary model runs showed a large under-prediction of wake form when compared to field measurements. A scaling factor of 4.5 was applied to the modelled thrust coefficient to generate modelled wake forms which agreed with wake measurements.

More details related to the turbine implementation in Telemac3D can be found in the fortran file from our GitHub repository (GitHub, 2023).

2.5. ADCP measurements

An extensive amount of in situ ADCP measurements and operational data from the DeepGen-IV turbine were obtained during the ReDAPT project. Full information regarding the series of ADCP and TEC deployments over the measurement campaign period at the FoW tidal test site can be found in Evans et al. (2023a,b), while the methods for data filtering and quality control can be found in Sellar et al. (2018). The details of the ADCP deployments involved in this study are summarised in Table 1, with their corresponding locations relative to the TEC shown in Fig. 7. All the ADCPs considered in this study have a vertical bin size of 1 m. The sample rate of ADCP01 and ADCP02 is 1 Hz, while that of ADCPTD7 is 0.5 Hz. The depth of the locations where the instruments and the TEC were deployed, is between 43 and 46 m. ADCP01 and ADCP02 were located 3.7D and 6.2D downstream of the TEC rotor plane respectively during ebb tide, while ADCP03 was 2.81D upstream of the rotor plane. ADCP01 and ADCP02 were able to capture the wake characteristics of the TEC during the ebb tides of the deployment period. However, the location of ADCP03 was not covered by the wake structures for the majority of the validation period during flood tides. Data measured at the ADCP01/02 and ADCPTD7 locations are available at <https://doi.org/10.7488/ds/3448> and <https://doi.org/10.7488/ds/3449>.

2.6. Validation of model predictions without TEC

The validation of model predictions under ambient flow conditions covers seven days from 2014-10-09 00:00 to 2014-10-16 00:00. The model was spun up over a 24 h period prior to the validation simulating period using the initial conditions generated from the global TPXO database. The validation period was chosen considering that the free-surface effects from wind and waves were insignificant, where the mean significant wave height during this validation period was less than 0.8 m.

Validation of model predictions is based on (i) time-series of the hub-height current velocity magnitude and direction; and (ii) speed-binned velocity profiles at ADCPTD7. The error metrics used to evaluate the time-series model predictions are the correlation coefficient (R), the

coefficient of determination (R^2), the root mean square error ($RMSE$) and the mean absolute error (MAE), defined by Eqs. (14) to (17). y_i and x_i are the modelled and the measured values at time step i respectively. $\bar{y}_i$ and $\bar{x}_i$ are the corresponding time-mean values, calculated using Eqs. (18) and (19).

$$R = \frac{\sum_{i=1}^N (y_i - \bar{y}_i)(x_i - \bar{x}_i)}{\sqrt{\sum_{i=1}^N (y_i - \bar{y}_i)^2} \sqrt{\sum_{i=1}^N (x_i - \bar{x}_i)^2}} \quad (14)$$

$$R^2 = \left(\frac{\sum_{i=1}^N (y_i - \bar{y}_i)(x_i - \bar{x}_i)}{\sqrt{\sum_{i=1}^N (y_i - \bar{y}_i)^2} \sqrt{\sum_{i=1}^N (x_i - \bar{x}_i)^2}} \right)^2 \quad (15)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - x_i)^2} \quad (16)$$

$$MAE = \frac{1}{N} \sum_{i=1}^N |y_i - x_i| \quad (17)$$

$$\bar{y}_i = \frac{1}{N} \sum_{i=1}^N y_i \quad (18)$$

$$\bar{x}_i = \frac{1}{N} \sum_{i=1}^N x_i \quad (19)$$

Modelled velocity profiles were also compared to the measured and errors of the modelled profiles are represented as relative difference in power-weighted rotor averaged velocity ($U_{PWR A}$). Measured power-weighted rotor averaged velocity ($U_{PWR A_{mea}}$) can be obtained by averaging the velocity measurements from the 18 vertical bins within the rotor range. Greater weighting was applied to the bins closer to the rotor hub plane. Hence, the expression of $U_{PWR A}$ is shown in Eq. (20),

$$U_{PWR A} = \left(\frac{1}{A} \sum_{i=1}^{18} A_i U_i^3 \right)^{\frac{1}{3}} \quad (20)$$

where A is the rotor swept area of the turbine, A_i is the vertical bin area over the rotor swept area, U_i is the velocity magnitude for each vertical bin. Modelled power-weighted rotor averaged velocity ($U_{PWR A_{mod}}$) can also be calculated by Eq. (20) after interpolating the modelled velocity profiles. Thus, bias in $U_{PWR A}$ can be expressed as Eq. (21).

$$\Delta U_{PWR A} = U_{PWR A_{mod}} - U_{PWR A_{mea}} \quad (21)$$

2.7. Validation of model predictions with TEC

To evaluate model performance on wake prediction, a validation period between 2014-07-16 at 00:00 and 2014-07-20 at 00:00 was selected. Modelled velocity profiles sampled at the coordinates of ADCP01 and ADCP02 were filtered and compared against field measurements from ADCP01 and ADCP02 during ebb tides. Fig. 8 illustrates the measured power and rotor-averaged reference velocity during the ADCP deployment and validation period, from which the ebb and flood tides were distinguished with blue and red colours respectively. The validation period covers four days and was selected because of the availability of measured wake data due to turbine operation. Moreover, ebb tides were selected for validation while flood tides were not because the location of ADCP03 was not in the wake of the TEC. Hence, velocity measurements from ADCP03 were used as reference inflow velocity for ebb tides. Furthermore, the validation was limited to the wake data with its corresponding inflow velocity between cut-in and rated, i.e. 1.0 m/s and 2.7 m/s. This is because the blades of the full-scale TEC are pitched when the inflow velocity is above rated in order

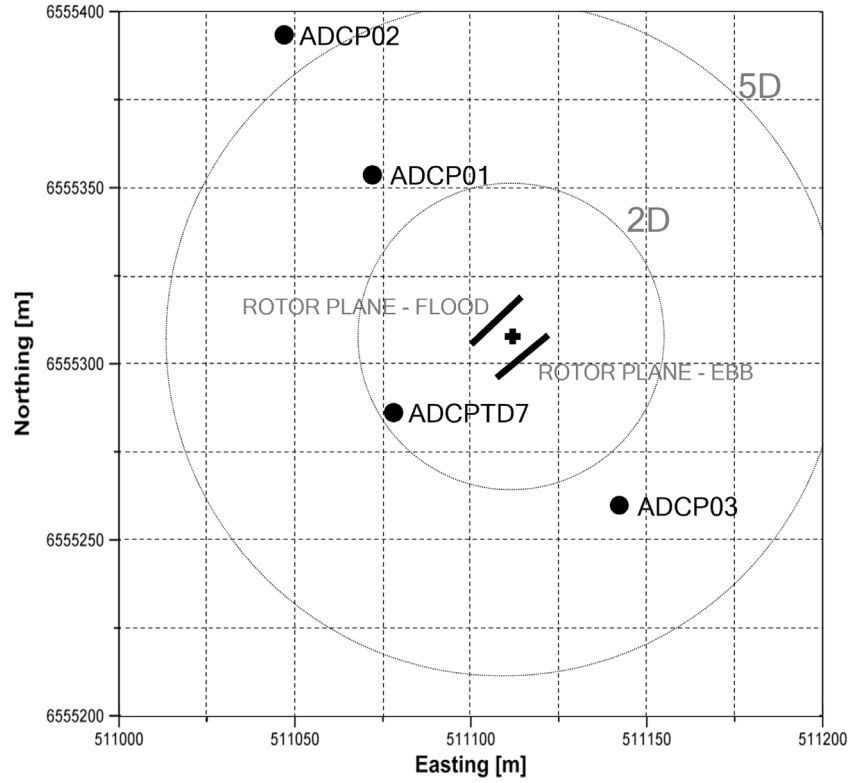


Fig. 7. ADCP locations relative to the DeepGen-IV turbine and the rotor plane at the FoW tidal test site. Coordinate reference system is WGS84/UTM30N (EPSG:32630).

to maintain rated power generation at a desirable tip-speed ratio. Yet, blade pitching would affect the resulting rotor thrust, thus, it is unfair to validate the modelled wake with inflow velocity above rated since the effect of pitch control on thrust is not reflected in the theoretical C_t curve.

On the other hand, it is expected that both the wake predicted from the model and that in reality vary temporally and spatially during the evolution throughout the selected ebb tides. Therefore, additional filtering on the predicted wake data was performed to select useful wake profile samples when the wake centreline overlaps the locations of ADCP01 and ADCP02. As such, the relative difference in angle between the centreline of the wake and instruments to the TEC were obtained, while a threshold of plus or minus 3 degrees was adopted. As a result, the samples of the wake profiles selected are the representations of the instantaneous moments where the wake core is covering the locations of ADCP01 and ADCP02.

After that, the filtered wake profiles at those two ADCP locations were binned according to the reference inflow velocity virtually probed at the ADCP03 such that the mean and standard deviation of the wake profiles for each speed bin can be obtained, which could then be further compared against in-situ measurements. Six speed bins of 1.5, 1.7, 1.9, 2.1, 2.3 and 2.5 m/s were chosen for this validation study and a speed delta of plus or minus 0.05 m/s was adopted. This results in a total of 719 (1/30 Hz sample rate) and 64,200 (1 Hz sample rate) useful samples of modelled and measured vertical velocity profiles respectively in the wake throughout the validation period. Moreover, the rotor plane in the model was shifted approximately 6 m along the rotor rotational axis from the TEC centre in order to represent the actual position of the rotor plane during ebb and flood tides. The TEC orientation in the model was fixed to 319.8 deg from the north during ebb tides and 136.7 deg from the north during flood tides, which are the median modelled inflow angles covered throughout the four days of the validation period.

3. Results

3.1. Model predictions without TEC

To evaluate model predictions of current velocity and direction, and water elevation, time series of modelled quantities are compared against ADCP measurements as shown in Fig. 9. These data suggest that the velocity magnitude at hub height (U_{hub}) demonstrates good agreement between modelled results and measurements on both flood and ebb tides, although there is a slight overestimation of peak U_{hub} during the ebb. This over-estimation does not affect the validation of wake modelling performance as only inflow velocities between the cut-in and the rated speeds, i.e. 1.0 m/s and 2.7 m/s, were considered. Nevertheless, there is an overall good agreement between the modelled and measured current direction at the hub height (θ_{flow}) within the validation period except during the slack tides. Table 2 illustrates the error metrics for the three time-series variables during flood, ebb and combined. There is a good match between model predictions and measurements in general. Correlation coefficient (R) for the variables during the overall period is ranged between 0.957 to 0.997 while coefficient of determination (R^2) is ranged between 0.941 to 0.993. The mean absolute error (MAE) is 0.196 m/s for U_{hub} , 8.073 deg for θ_{flow} and 0.0512 m for water elevation. Poor correlation between modelled and measured current direction at hub height is observed when the overall period is separated into flood and ebb. This can be explained by the slight phase difference in current direction. Nevertheless, this would not affect the evaluation of model performance on wake predictions as the velocity profiles in the wake are grouped by speed bins and filtered by wake positions.

Figs. 10(a) and 10(b) highlight the good model performance in predicting velocity profiles during both ebb and flood tides. Velocity magnitude profiles at ADCP07 were grouped into speed bins from 1.0 to 3.0 m/s with an interval of 0.5 m/s. Distance from seabed (Z)

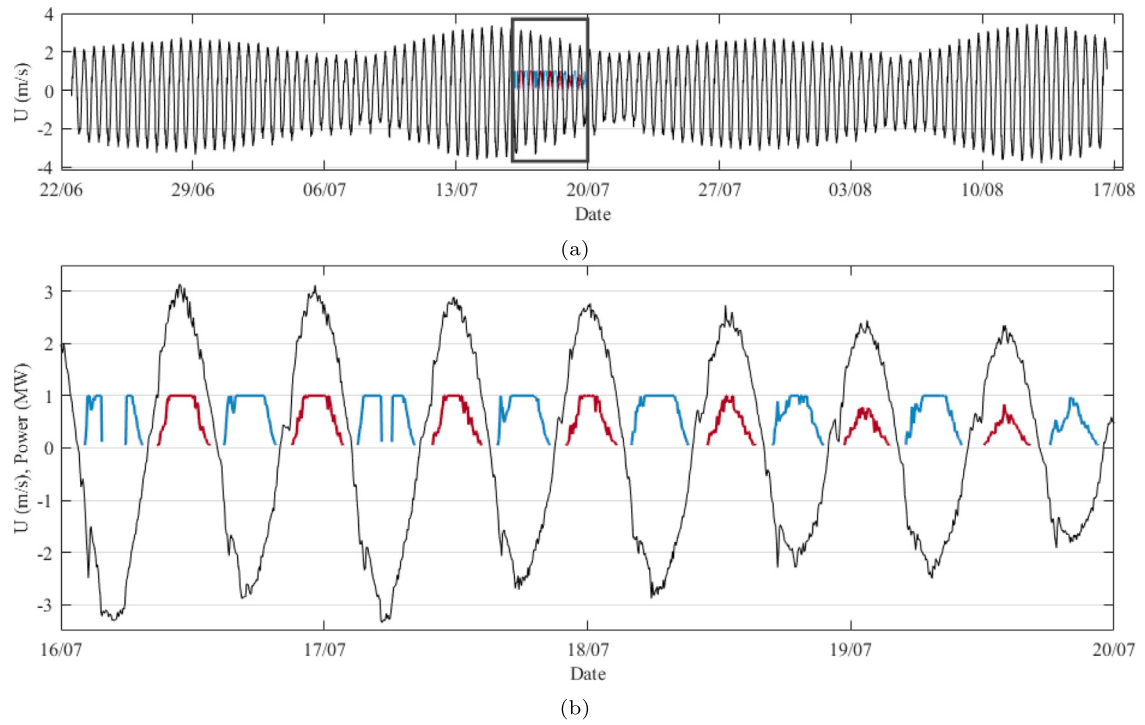


Fig. 8. (a) Rotor-averaged reference velocity over the deployment period of the ADCPs considered in this study. Black rectangle encloses the validation period selected for assessing the model predictions on wake. (b) Measured power and rotor-averaged reference velocity during the validation period of the TEC-embedded model. Ebb and flood tides are distinguished with blue and red colours respectively.

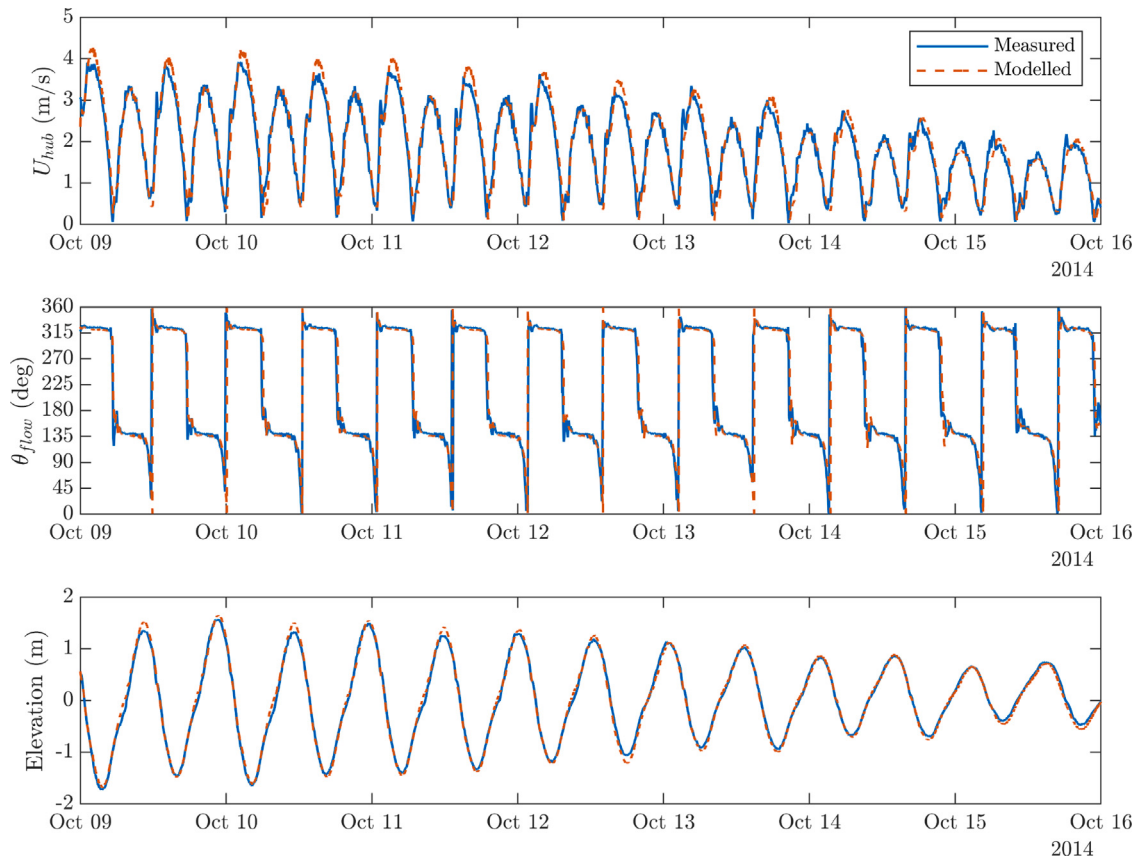


Fig. 9. Time-series velocity magnitude at hub height, current direction at hub height and water elevation during the validation period at the location of ADCPTD7.

Table 2

Error metrics for the time-series velocity magnitude at hub height, current direction at hub height and water elevation during flood, ebb and both. Units for $RMSE$ and MAE are m/s, deg and m for the three variables respectively.

Variables	R			R^2			$RMSE$			MAE		
	Flood	Ebb	Overall	Flood	Ebb	Overall	Flood	Ebb	Overall	Flood	Ebb	Overall
U_{hub}	0.982	0.963	0.971	0.963	0.920	0.941	0.172	0.305	0.249	0.013	0.262	0.196
θ_{flow}	0.895	0.71	0.957	0.539	0.367	0.952	3.872	3.330	19.34	3.206	2.658	8.073
Elevation	0.993	0.997	0.997	0.983	0.993	0.993	0.075	0.055	0.0656	0.058	0.044	0.051

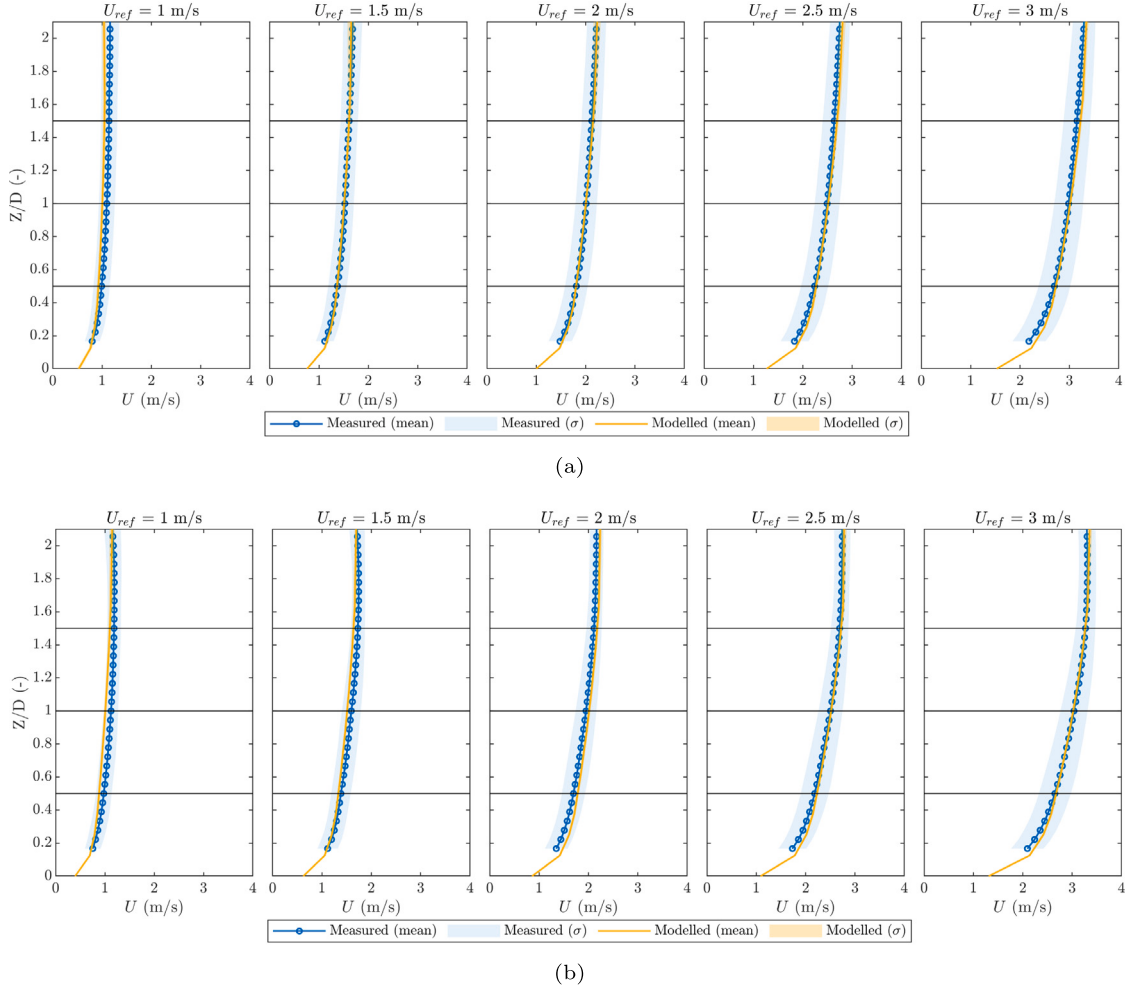


Fig. 10. (a) Velocity magnitude profiles at the location of ADCPTD7 during the flood tides of the validation period. Black lines represent the distance of hub height and rotor tips from seabed. Highlighted regions indicate the standard deviation of the velocity profiles. (b) as (a) but during the ebb tides.

in both figures was normalised by the diameter of the turbine. Whilst measurements were acquired within the top 15% of the water column, they were not shown in both figures because acoustic side-lobes can cause interference for the data in this region. The mean of the modelled velocity profiles for both ebb and flood tide at different speed bins show excellent agreement with measurements. Meanwhile, it can be noted that the standard deviations (σ) of the modelled velocity profiles for both ebb and flood are negligible compared to that of the measured. This is further discussed in Section 4.2. Table 3 further supports the good model performance by illustrating the relative difference between modelled and measured U_{PWRRA} at different speed bins for ebb and flood. Considering the four speed bins between 1.5 m/s and 3.0 m/s, the absolute difference in U_{PWRRA} ranges between 0.1% and 5.3%. It is increased to 9.8% and 8.1% at the speed bin of 1.0 m/s for ebb and flood respectively. This relatively large error can be explained by the difference in eddies formed in the model and the field during the slack tides which affects the flow field when current flow is accelerating.

Table 3

Relative percentage difference between modelled and measured U_{PWRRA} at various speed bins for ebb and flood tides. U_{ref} here represents the reference velocity virtually probed at the location of ADCPTD7.

U_{ref}		1.0 m/s	1.5 m/s	2.0 m/s	2.5 m/s	3.0 m/s
$\frac{\Delta U_{PWRRA}}{U_{PWRRA_{meas}}} \times 100\%$	Ebb	-9.81%	-5.34%	3.38%	0.81%	-0.40%
	Flood	-8.14%	-0.76%	-0.12%	1.04%	1.21%

3.2. Comparison of modelled and measured power

Other than wake prediction, undisturbed upstream flow velocity predicted by the model can be used to calculate the power generated by the 1 MW DeepGen-IV turbine. Fig. 11 illustrates the comparison of modelled and measured power of the turbine during the validation period. It is noticeable that the full-scale turbine did not operate for a short period during the first ebb tide on 2014-07-16 and 2014-07-17. This is because the flow velocity has reached above the cut-off

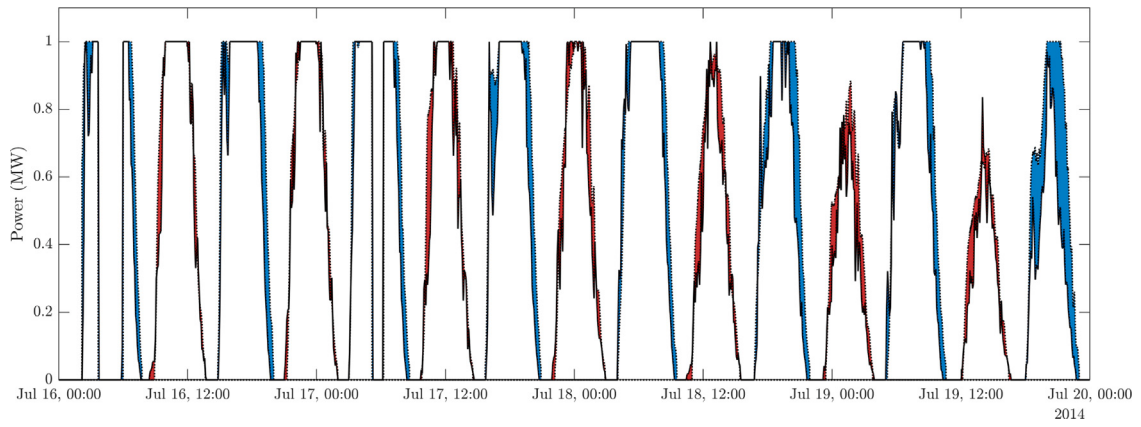


Fig. 11. Comparison of modelled and measured power of the TEC during the validation period. Blue and red colours represent the difference between measured and modelled power during ebb and flood respectively.

Table 4
Error metrics for assessing model performance in predicting power generation.

Variable	R			R^2			$RMSE$ (MW)			Energy yield % difference (%)		
	Flood	Ebb	Overall	Flood	Ebb	Overall	Flood	Ebb	Overall	Flood	Ebb	Overall
Power	0.982	0.961	0.950	0.965	0.924	0.903	0.070	0.129	0.147	11.187	16.714	14.469

speed of the turbine, i.e. 3.4 m/s. Meanwhile, blue and red colours represent the difference between measured and modelled power during ebb and flood respectively. It is observable that the majority of the difference is concentrated on the deceleration phase of the ebb tides. This can be attributed to the overestimation of flow velocity at the upstream location during the deceleration phase of the ebb tides. Table 4 shows the error metrics for assessing model performance in predicting power generation during ebb, flood and the overall validation period. Good correlation was found between the model predictions and measurements. It is noticeable that the modelled power agrees better with measurements in flood when compared to ebb, as the percentage difference in energy yield for flood is 11.2% while that for ebb is 16.7%. Nevertheless, this indicates that further calibration of the model velocity predictions is required and can improve the model performance in predicting power generation.

3.3. Temporal and spatial wake evolution

The 1 MW DeepGen-IV full-scale turbine was operated in a highly unsteady environment and expected to generate unsteady wakes downstream. Our model predictions provide evidence to support this hypothesis. Fig. 12 illustrates the temporal and spatial wake evolution at hub height during a selected ebb tide on 2014-07-18. Velocity magnitude distribution during the same period without TEC being embedded was used as the baseline to demonstrate wake generation and evolution for the TEC-embedded model. Snapshots of the velocity magnitude deficit distribution were captured at the reference inflow velocity (U_{ref}) of 1.1, 1.5, 1.9, 2.3 and 2.7 m/s for both acceleration and deceleration phase of the tide. Relative locations of ADCP01 and ADCP02 to the TEC rotor plane were also shown in the figure. When U_{ref} is 1.1 m/s, it is evident that the predicted wake does not cover the ADCP locations in the beginning as the wake is on the east side of the instrument locations. Yet, the wake structure gradually shifts and covers the locations of ADCP01 and ADCP02 when U_{ref} is increasing from 1.1 to 2.7 m/s. After the flow velocity reaches its peak and then decreases, as demonstrated in the bottom row of the figure where U_{ref} decreases from 2.7 to 1.1 m/s, the location of ADCP01 is situated in the central region of the wake while that of ADCP02 is in the edge of the wake structure.

Furthermore, it can be seen in Appendix A Supplementary Video 1 that the predicted wake starts to meander once U_{ref} increases above 2.7 m/s. This phenomenon continues in the deceleration phase of the

ebb tide as the wake is meandering over the locations of ADCP01 and ADCP02. This is attributed to the large-scale eddies and shear generated when the current is flowing past the headland on the northeastern side of the channel. It demonstrates that it was appropriate and necessary to introduce mesh refinement at the region with high vorticity as discussed in Section 2.2 since the vortex shedding and shear layer can be resolved. On the other hand, it is observable that there are gains and deficit of velocity magnitude at the other regions that are not affected by the modelled TEC and its associated wake generation. Taking the snapshot at $U_{ref} = 1.9$ m/s during the deceleration phase as an example, there are velocity gains at the region around (−3D, 6D) and velocity deficit at (6D, 18D). This occurs as a result of the slightly out-of-phase eddies between that generated from the model run with and without TEC embedded.

As for the predicted wake from the TEC during the flood tide, it does not cover the location of ADCP03 for the majority of the time as shown in Fig. 13. Thus, it is reasonable to not validate the wake model using results from flood tides, as this would likely lead to inaccurate interpretation and conclusion. Appendix A Supplementary Video 2 also demonstrates the wake meandering effect during the flood tide. Similar to that observed in the ebb, the wake meandering is predominant on the deceleration phase of the tide. This can also be attributed to the shear layer developed when current is flowing past the headland in the north of the instrument locations.

3.4. Velocity profiles in the wake

Since the predicted wake during the ebb tide was meandering over the locations of ADCP01 and ADCP02, it further supports the need to filter vertical velocity profiles based on the relative locations of the wake and instruments such that samples are selected when the wake is overlapping the instrument locations. Figs. 14 and 15 shows the comparison between modelled and measured vertical velocity profiles in the wake of the validation period at the ADCP01 and ADCP02 location respectively. The filtered velocity profiles were grouped into various speed bins as mentioned in Section 2.7, while the velocity magnitude (U) was normalised by U_{ref} which is the reference inflow velocity virtually probed at the ADCP03 location from the model. It is apparent that there is more velocity deficit at both modelled and measured wake profiles for the location of ADCP01 as compared to that of ADCP02. This is because ADCP02 is 6.2D downstream of the TEC

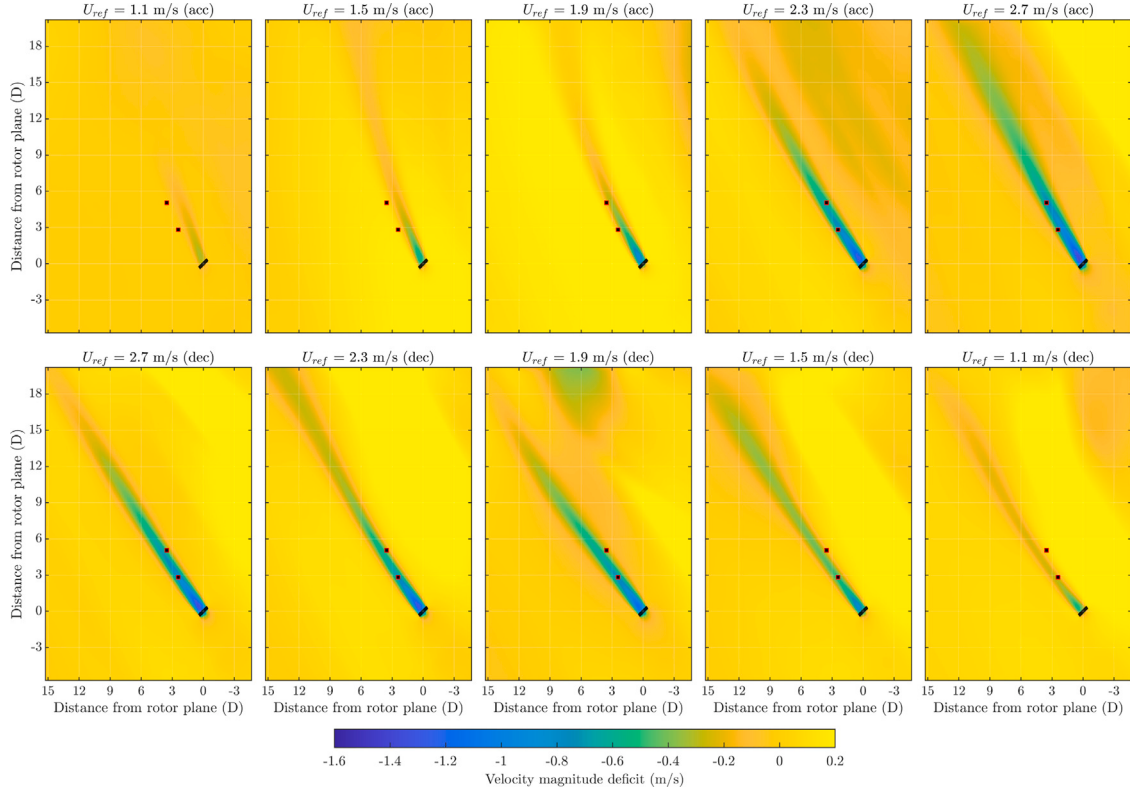


Fig. 12. Temporal and spatial wake evolution during an ebb tide on 2014-07-18. ‘acc’ and ‘dec’ indicate the acceleration and deceleration phase of the ebb tide respectively. Distribution of velocity magnitude deficit is shown in the horizontal plane at hub height. Rotor plane is represented as a black rectangle while the locations of ADCP01 and ADCP02 are shown with squared markers. U_{ref} here represents the reference inflow velocity virtually probed at the location of ADCP03.

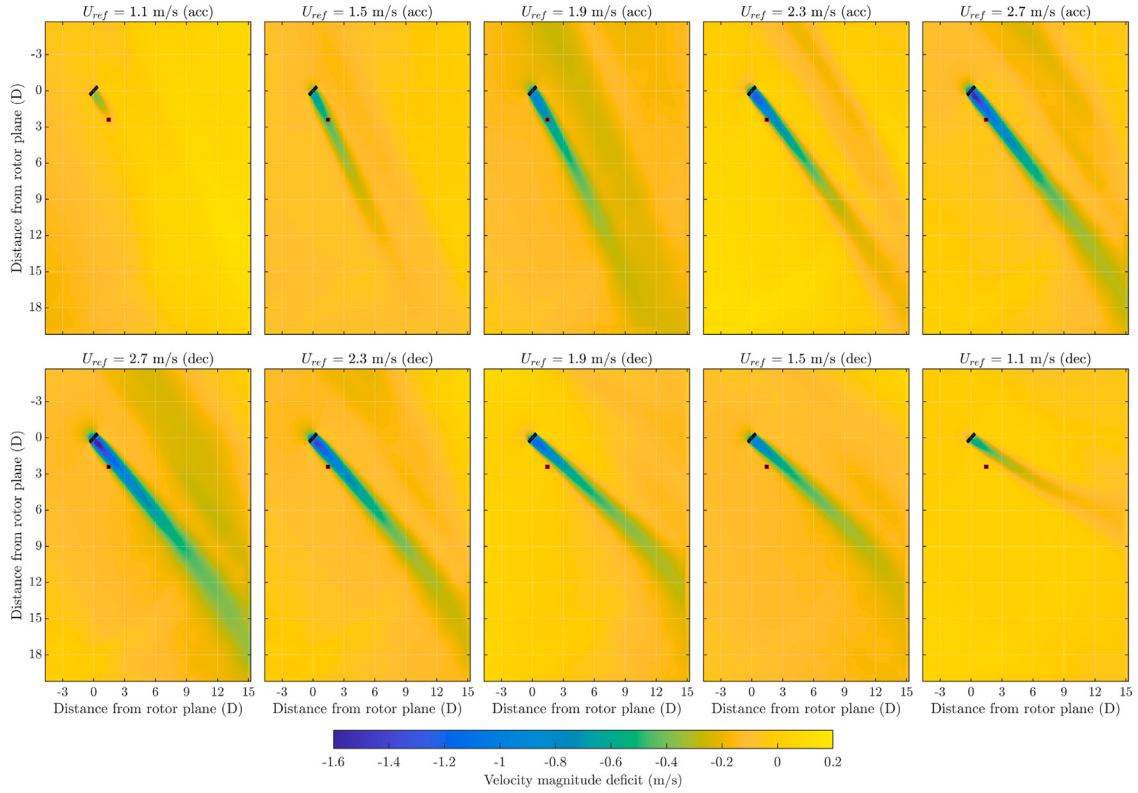


Fig. 13. Temporal and spatial wake evolution during a flood tide on 2014-07-17. ‘acc’ and ‘dec’ indicate the acceleration and deceleration phase of the flood tide respectively. Distribution of velocity magnitude deficit is shown in the horizontal plane at hub height. Rotor plane is represented as a black rectangle while the location of ADCP03 is shown with a squared marker. U_{ref} here represents the reference inflow velocity virtually probed at the location of ADCP02.

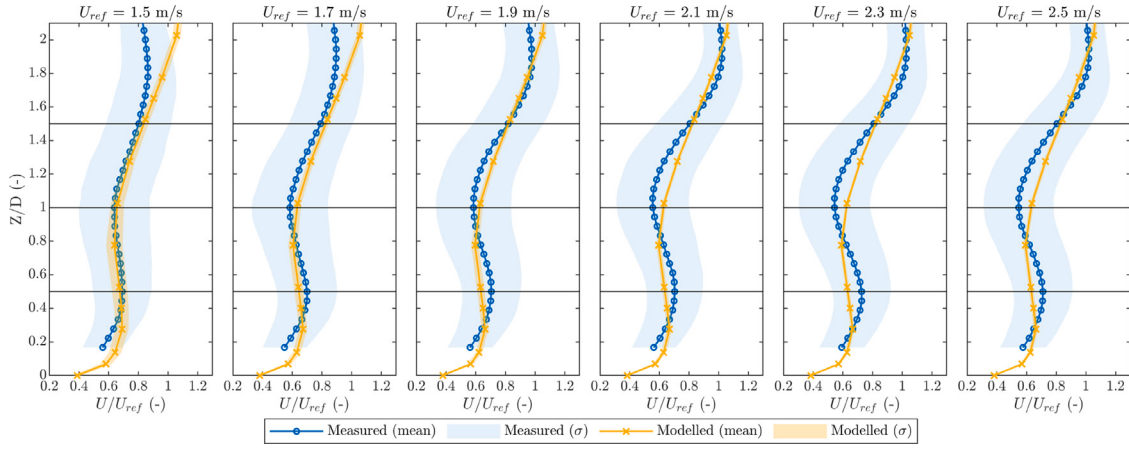


Fig. 14. Vertical velocity magnitude profiles at the location of ADCP01 in the wake of ebb tides during the validation period. Black lines represent the distance of hub height and rotor tips from seabed. Highlighted regions indicate the standard deviation of the velocity profiles.

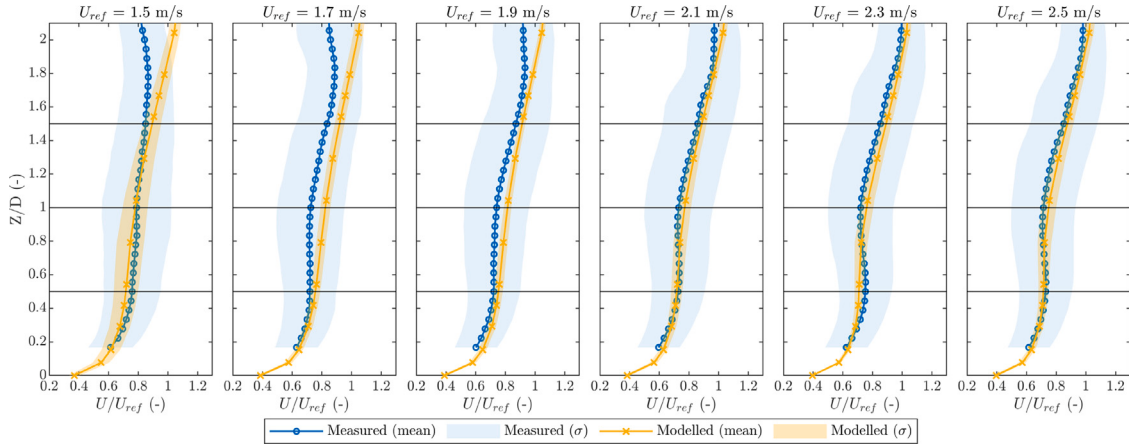


Fig. 15. Vertical velocity magnitude profiles at the location of ADCP02 in the wake of ebb tides during the validation period. Black lines represent the distance of hub height and rotor tips from seabed. Highlighted regions indicate the standard deviation of the velocity profiles.

rotor plane while ADCP01 is only 3.7D. Meanwhile, the velocity deficit at hub height is increased as U_{ref} increases since U/U_{ref} was reduced from 0.63 to 0.54 for ADCP01 and 0.79 to 0.71 for ADCP02 across the speed bins. It is also observable that the standard deviation (σ) for the measured wake profiles at each vertical bin is larger than that for the modelled. This will be further discussed in Section 4.2. Furthermore, it is noticeable that there is an overall tendency of disagreement between the measured and modelled velocity at the top of the water column. This is because the model assumes no wind and wave-driven surface effects which would affect the velocity profiles especially from mid-depth to the surface. Other than that, diverging-beam ADCPs also tend to have higher uncertainties in measuring current near the free surface due to the assumption of flow homogeneity within the beam spread during the transformation of the velocity components from beam direction to the instrument coordinate system (Sellar et al., 2015).

By comparing the modelled and measured wake velocity profiles at the locations of ADCP01 and ADCP02, it is observable that the modelled wake profiles at the ADCP02 shows a better agreement to the measured counterpart when compared to that at the ADCP01. This is further supported by the evidence in Fig. 16 and Table 5, from which the differences between modelled and measured wake velocity profiles were quantified as errors in relative percentage difference between modelled and measured power-weighted rotor averaged velocity. The average error for all the speed bins at ADCP01 is 4.4% while that for ADCP02 is 5.2%. The modelled wake velocity profiles are over-predicted for all the cases across the speed bins and the two locations except for the one

in which $U_{ref} = 1.5$ m/s at ADCP02. Also, an increasing trend of errors for ADCP01 as U_{ref} increases can be observed. However, this is not the same for the errors observed at ADCP02, most likely due to the larger variations of modelled wake velocity profiles.

4. Discussion

4.1. Implications of temporal and spatial variation of wake on the comparison of downstream velocity profiles

Full-scale tidal turbines are subjected to unsteady flow and generate unsteady wakes in reality. Figs. 12 and 13 from Section 3.3 support this by demonstrating the evolution of the modelled wake during flood and ebb tides. The modelled wake varies spatially and temporally as the current flow increases and then decreases. At $U_{ref} = 1.9$ m/s from Fig. 13, it is obvious that the wake structure covers the location of ADCP03 while the current flow is accelerating. However, this is not the same when the flow is decelerating since the modelled wake drifts away from the ADCP03 location. It implies that the comparison of modelled and measured wake profiles by only grouping them into different inflow velocity bins is not effective because modelled data probed at the measurement location might contain flow characteristics that are not directly related to the wake. As a result, the mean of the modelled wake profiles which are only grouped by velocity bins would most likely underestimate the velocity deficit when compared to the mean of the measured wake profiles. Therefore, it is important to filter modelled

Table 5

Relative percentage difference between modelled and measured $U_{PW,RA}$ of the wake profiles at various speed bins during ebb tides of the validation period. U_{ref} here represents the reference velocity virtually probed at the location of ADCP03.

U_{ref}		1.5 m/s	1.7 m/s	1.9 m/s	2.1 m/s	2.3 m/s	2.5 m/s
$\frac{\Delta U_{PW,RA}}{U_{PW,RA_{mea}}} \times 100\%$	ADCP01	1.49%	3.88%	2.78%	5.70%	5.61%	6.84%
	ADCP02	−0.99%	11.57%	8.12%	3.45%	3.28%	3.49%

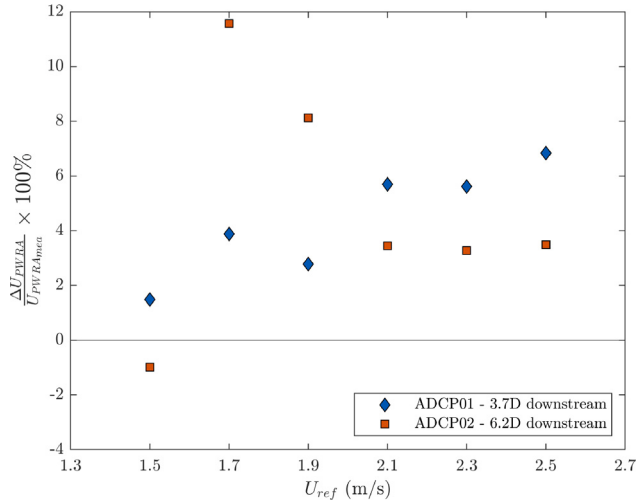


Fig. 16. Relative percentage difference between modelled and measured $U_{PW,RA}$ of the wake profiles at various speed bins during ebb tides of the validation period.

wake data based on the relative difference in positions between the instrument and the wake centreline, which is what was done in this study.

4.2. Evaluation of the TEC-embedded regional 3D hydrodynamic model

The attractiveness of using regional hydrodynamic models to predict current flow and turbine wake was briefly introduced in Section 1. Results from Section 3.3 together with Supplementary Video 1 and Video 2 in Appendix A further strengthen the claim of using regional hydrodynamic models to predict full-scale turbine wakes. Wake meandering is observed in both flood and ebb tides which can be explained by the large-scale eddies and shear generated when current is flowing past the headland at both sides of the channel. This shows the suitability and applicability of using this TEC-embedded 3D model to predict wake from the 1 MW full-scale turbine, since the model has demonstrated (in Section 3.1) its robustness in simulating realistic 3D ambient flow at the site with the consideration of physical boundaries including islands, coastlines and local bathymetry.

The model also demonstrates its capability in predicting power generated by the 1 MW full-scale turbine, as shown in Fig. 11. Although the percentage difference in energy yield for flood and ebb is 11.2% and 16.7% respectively, the average absolute percentage difference in $U_{PW,RA}$ of the speed-binned velocity profiles in ambient flow between 1.5 and 3.0 m/s are 2.5% and 0.8% for ebb and flood respectively. This indicates that there is a spatial variation of agreement level between the predicted and measured flow velocity which is caused by the difference in flow features presented in the site and the model such as shear layer and eddies. Further calibration of the velocity field is required to improve the agreement between the predicted and measured energy yield. The calibrated model can then be applied to array modelling and planning by introducing multiple turbines in the regional domain. Wake-to-wake interactions between turbines and energy yield of the tidal array can then be investigated.

It can also be noted from Fig. 10(a), 10(b), 14 and 15 that the standard deviations of the modelled velocity profiles are negligible

compared to that of the measured. The reason for this is that the model adopts unsteady RANS approach to simulate hydrodynamics. This implies that the model cannot resolve the small-scale eddies in the turbulent flow. In spite of this, the mean of the modelled velocity profiles is in good agreement with the site measurements throughout the water column and Figs. 12 and 13 show the necessity for conducting data filtering prior to the comparisons.

However, the TEC-embedded model also has several limitations and potential improvements that should be noted. Firstly, free-surface effects due to wind and wave activities were not considered in the model. Even though wave activities for the validation period selected in this study is minimal, applying this model to predict turbine wake and power in other days when the wind and sea conditions are energetic would require the consideration of wind and wave effects. Secondly, the predicted wake from the TEC-embedded model should be characterised in the future and physics-based correction factor for the actuator disc should be further studied to include the effects of support structures and tip loss such that accuracy of the modelled wake can be improved by means such as non-uniform distribution of thrust. Power-weighted rotor-averaged velocity in the upstream can also be used to represent the non-uniform inflow for calculating rotor thrust. Meanwhile, we also noticed that there are significant differences between the theoretical thrust coefficients of the DeepGen-IV and the thrust coefficients used in other studies (Ramos et al., 2019; Waldman et al., 2017; Thiébot et al., 2020; Rahman et al., 2018), from which the thrust coefficients are approximately twice as large as our derived values from the published power curve. The requirement in our work for such an unexpectedly large scaling factor remains under investigation. Thirdly, a sophisticated field measurement campaign should be conducted specifically for wake measurement in the future. More instruments should be deployed to measure flow field downstream of the operating TEC such that the spatial resolution of the measured wake can be increased. Finally, further calibration on the ambient flow field of this regional hydrodynamic model is beneficial to improve the agreement between the predicted and measured energy yield.

5. Conclusion

In-situ wake measurements of full-scale tidal turbines are rare in the tidal stream energy sector. The majority of numerical models for wake prediction were previously validated against model-scale experimental data. Although tank-scale turbine measurements can provide insights into turbine behaviour and wake characteristics, it is difficult to recreate the realistic and complex inflow conditions that a full-scale turbine is subjected to. Therefore, it leads to uncertainties in the model validity for turbine wake prediction.

This study focuses on the demonstration and validation of an open regional-scale, TEC-embedded 3D hydrodynamic model for turbine power and wake prediction. In-situ measurements from seabed-mounted ADCPs downstream and at the side of the 1 MW DeepGen-IV tidal turbine were used to validate model predictions. The comparison of the measured and modelled velocity profiles under ambient flow conditions at the ADCPTD7 location shows excellent agreement at both ebb and flood tides, since the absolute difference between modelled and measured power-weighted rotor averaged velocity is ranged between 0.1% and 5.3% for the four speed bins between 1.5 and 3.0 m/s.

TEC-embedded model results demonstrate that the predicted wake varies temporally and spatially throughout both ebb and flood tides. This necessitates modelled wake data filtering to ensure equitable

comparisons. A data filtering method was implemented based on the relative difference between the instrument locations and the wake centreline, such that the samples of the wake profiles selected are the representations of the instants when the wake structure overlaps the ADCP locations. The modelled wake profiles after filtering were then grouped into six speed bins ranging from 1.5 to 2.5 m/s, which correspond to the reference inflow velocity probed at the upstream ADCP location. The mean of the modelled wake profiles at various speed bins agrees well with the measurements, since the averaged absolute difference in power-weighted rotor averaged velocity is 4.4% and 5.2% for ADCP01 and ADCP02 respectively, which are 3.7D and 6.2D downstream of the turbine rotor plane during ebb tides. The TEC-embedded model also demonstrates its capability in predicting power generation. Yet, further calibration of the model velocity predictions is required to improve the model performance in predicting power, as the percentage difference in energy yield for flood and ebb are 11.2% and 16.7% respectively.

Wake meandering can also be observed in the time-series velocity deficit distribution. This is caused by eddies and shear generated at the northeastern side of the channel during both flood and ebb. It illustrates the complexity of the unsteady flow field that a full-scale turbine is subjected to and the benefits of using a regional-scale hydrodynamic model for wake modelling. Future work to the TEC-embedded model includes support structure modelling for improving the model performance in predicting near-wake. Further calibration of the model parameters for predicting flow velocities is also beneficial to yield prediction. Nevertheless, the performance of the TEC-embedded model demonstrates potential in extending this work to array-level modelling and farm layout planning by introducing multiple turbines in the domain, from which wake-to-wake interactions and farm-level energy yield can be investigated.

CRedit authorship contribution statement

Mohammed A. Almoghayer: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Raymond Lam:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Brian Sellar:** Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Chris Old:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization. **David K. Woolf:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

References for data/code have been cited in the manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.oceaneng.2024.117402>. Video S1 and S2 show the temporal and spatial modelled wake evolution during an ebb tide and flood tide respectively.

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