Overview of resource and turbine modelling in the Tidal Stream Industry Energiser Project: TIGER

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Abstract—**Tidal energy projects require numerical modelling for the assessment of tidal site conditions and turbine/array performance. The Interreg TIGER project has offered a unique opportunity to implement a wide range of numerical models. This paper provides an overview and comparison of the different numerical models developed by academic partners in the TIGER project. The models cover a variety of spatial and temporal scales. The largest scale models provide long-term climatic studies covering the entire English Channel region, at relatively low resolution, whilst the highest-resolution models provide detailed information about short-term and small-scale turbulent flow and its interaction with tidal turbines. The models are used for various purposes. At one end of the scale, the models have been used to inform the large-scale techno-economic assessment of tidal energy and its impact on the energy mix in the UK and France. At the other end of the scale, the numerical models provide information that feeds into detailed engineering design of tidal turbines at particular sites, and assessment of the energy yield. The models showcase the range of computational tools available to aid the development of the tidal energy industry. This paper will be useful for investors, technology developers and project stakeholders to help identify suitable numerical models to support and develop ongoing and future tidal stream projects.**

Index Terms—**Resource Assessment; Turbulence; Wave-Current interaction; Loads modelling; Wake modelling**

I. Introduction

The Tidal Stream Industry Energiser Project (TIGER) is the largest project ever funded by the European Union Interreg program, with a value of €45.4 million. The objective is to demonstrate that tidal stream energy is a maturing industry, capable of achieving an accelerated cost reduction pathway. The project aims to drive the growth of tidal stream energy by installing up to 8 MW of new tidal capacity at six sites in and around the English Channel region, illustrated in Fig. 1. Further details on the TIGER project can be found at https://interregtiger.com. To support the development of the projects at these sites, academic partners in the project have implemented a range of numerical models for estimation of tidal site conditions and tidal turbine/array performance and loading.

Development of tidal energy projects requires modelling at various scales. At the largest spatial scales, sites for potential deployments must be identified and compared. Once sites are identified, the spatial and temporal variation of flow conditions across the site must be considered, with regard to currents, turbulence and waves. At the smallest scale, the interactions between the local flow and turbines need to be calculated to estimate the power production and structural loading. The impact of the turbines on the flow also must be calculated, to assess potential changes to large-scale flow conditions, understand wake recovery mechanisms and device loading, and optimise array layouts. Within this paper, the various models are classified as either regional-scale, site-scale, or turbine-scale models, although there is some overlap in the scales considered by some models. The models provide information about flow conditions and interaction between flow and turbines at different levels of fidelity and corresponding computational cost.

The purpose of this paper is to provide a high-level overview of the numerical modelling conducted as part of TIGER and how this information has been used. Due to the wide range of models used within the TIGER project and the large number of simulations conducted, it is not possible to describe all the details of the model implementations and results here. Instead, the focus of this paper is on the unique contributions and novel results from each model, and their wider implications for the tidal industry. Further details can be found in [1] and references therein. The paper is organised as follows. Regional-scale models are discussed in Section II, and site-scale and turbine-scale models are discussed in Sections III and IV respectively. Finally, a discussion and conclusions are presented in Section V.

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II. Regional-scale models

The regional-scale models considered here solve the Reynolds-averaged Navier-Stokes (RANS) equations for incompressible flow, and related equations derived under various assumptions (see e.g. [2]). When the horizontal length scales of the flow are much greater than the vertical length scales, it can be shown from the momentum equation that vertical pressure gradients are nearly hydrostatic. The additional assumption

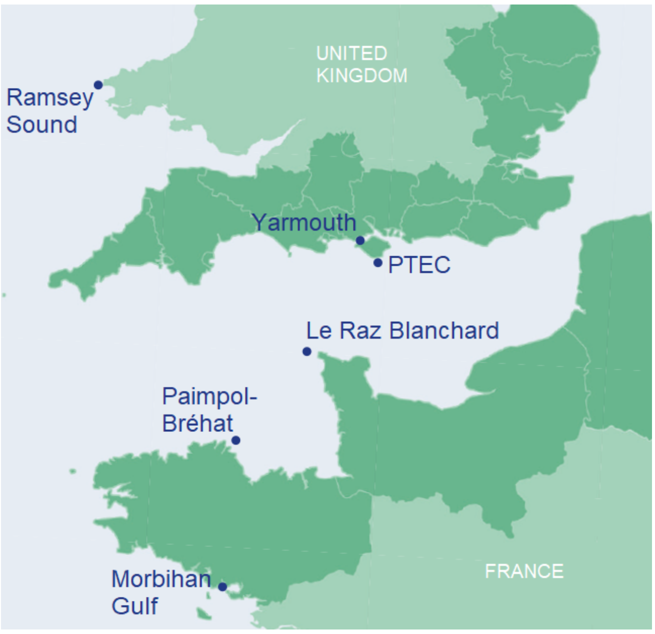


Fig. 1. Demonstration sites considered within the TIGER project.

of hydrostatic pressure leads to the 3D shallow water equations (SWE). Depth-averaging these equations leads to the 2D SWE. Within the TIGER project, Delft Flow, Thetis and MIKE21 have all been run using the 2D SWE, whilst Telemac has been run using both 2D and 3D SWE and 3D non-hydrostatic equations.

Some of the models considered also include parameterisations of tidal turbines. In the 2D models which include turbines, these are represented with an enhanced bottom friction term over the area of the array, whereas in Telemac 3D (non-hydrostatic), turbines are represented by actuator disks. In some of the applications discussed below, the models have been run at higher resolution over particular sites. However, in the present work, the classification of regional-scale and site-scale models is made based on the governing equations, with the regional-scale models using the RANS equations, and the site-scale models discussed in Section III, using a Large Eddy Simulation (LES) approach.

A. *Delft suite*

Wave-current interactions were assessed with a fully coupled flow-wave model developed using Delft3D Flexible Mesh (DFlow FM) and SWAN. DFlow FM is the hydrodynamic flow solver which forms the core of the Delft3D Flexible Mesh suite of models and solves the shallow water equations, described above. SWAN is a third-generation spectral wave model used predict the wave spectrum in the coastal and shallow water zones. SWAN, like other spectral wave models determines the evolution of the action density in space and time. Wave breaking, white-capping, triad interaction and quadruplet interaction all affect the energy propagation of the sea state. The model accounts for these by employing various numerical schemes. A full description of the model is available in the SWAN technical documentation [3].

The models have been used to generate a 33-year hindcast (1st January 1990 – 31st December 2022) dataset of flow and wave conditions throughout the English Channel with a focus on two sites: the PTEC site off the Isle of Wight and Le Raz Blanchard. The flow model was run on an unstructured mesh of the entire channel region with resolution ranging from 2km-20m, whereas the wave model was run on three levels of nested rectangular grids. An outer wave grid with 2km resolution covered the whole channel with higher resolution nested grids shown in figure 2. The models were used for: resource quantification, extreme value modelling, input to techno-economic modelling, inputs for the dynamic analysis of tidal turbines, and model inter-comparisons. The models were used in [4] to explore the impact of including wave effects in tidal resource assessment modelling. It was found that the effects are significant with instantaneous differences in tidal stream power of up to 9.6% between coupled models and flow only models.

The coupled models were also used to investigate joint extremes of waves and currents at tidal sites. A novel method for estimating environmental contours was developed [5] and used to construct 3D environmental contours of flow speed, wave height and relative direction between waves and currents [6]. The results showed that in sites of strong tidal flows, the most extreme wave conditions tended to occur when the wave and currents are propagating in opposite directions, due to the wave-current interactions. Fig. 3 shows an example of the joint density of the component of significant wave height in line with the current direction against current speed, for a location in Le Raz Blanchard. The increase in wave heights in opposing currents is clearly visible.

In Le Raz Blanchard the data were used in a model comparison study focusing on unsteady load predictions for tidal stream turbines. The full study is reported in Annex A of [1]. Within the TIGER project the model output was supplied to developers and used in their technical and economic site assessments. At time of writing, research is ongoing looking at spatial variability of the flow and wave conditions. The study is using the model outputs to identify whether there are advantages to selecting locations with slightly lover peak flow speeds to benefit from less severe wave conditions.

B. *Telemac*

Telemac is an open source model for free surface flows. It solves the shallow water equations (Telemac2D) or the 3D Reynolds-Averaged Navier-Stokes (RANS) equations (Telemac3D) using the finite element method. Within the TIGER project, Telemac has been applied at three sites: Le Raz Blanchard, Paimpol-Bréhat and Morbihan Gulf. The bathymetry data were provided by the SHOM (French Navy), as well as the sediment maps that permitted to estimate the bed roughness. The TPXO database was used to predict sea level and current velocity at the domain boundary. Meteorological and wave effects were not

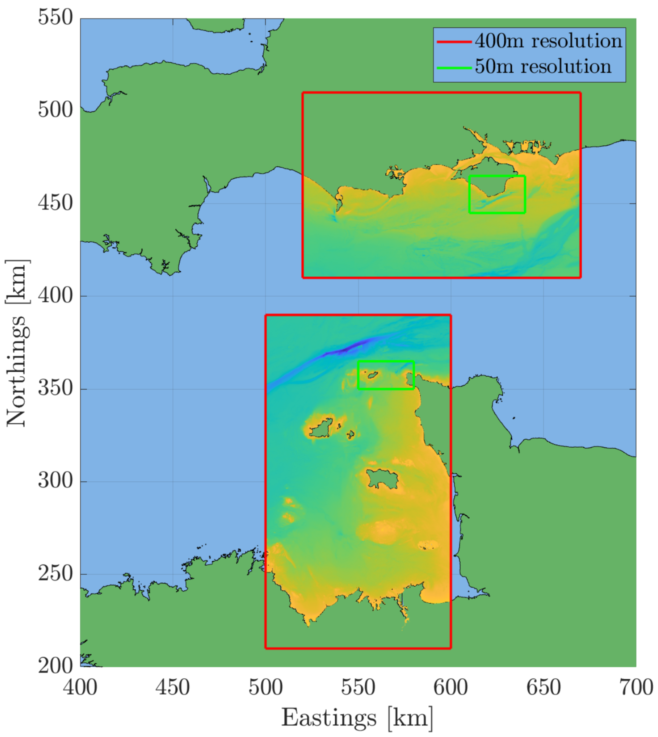


Fig. 2. Nested wave domains for the SWAN wave model, showing seabed bathymetry in the focal areas.

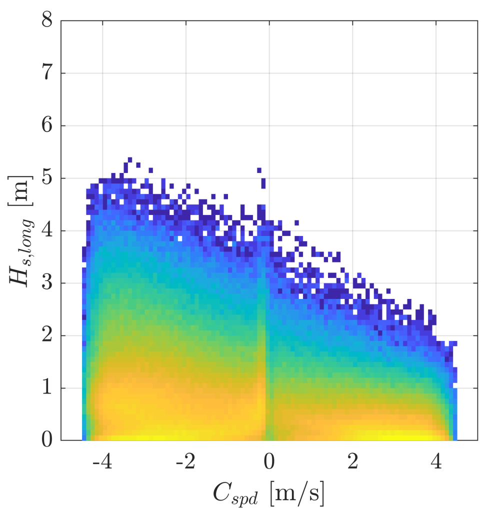


Fig. 3. Joint density of current speed and component of significant wave height in line with current direction, for a location in Le Raz Blanchard, from coupled wave-current Delft model. Negative current speed indicates opposing wave and current directions.

included. The turbulence closure scheme was the k-ε model. Cell sizes varied according to the targeted applications. They ranged between 10 km and 15m for the simulations without turbines and were refined up to 1 m for simulations with actuator disks. For resource assessments without turbines, models configurations were validated with measurements of water elevation and current speeds (e.g. six ADCP time-series in Le Raz Blanchard, two in Paimpol-Bréhat and four in Morbihan Gulf). For wake-field studies relying on actuator disks, model predictions of turbulence and velocity deficit in wake have been validated from lab experiments [7].

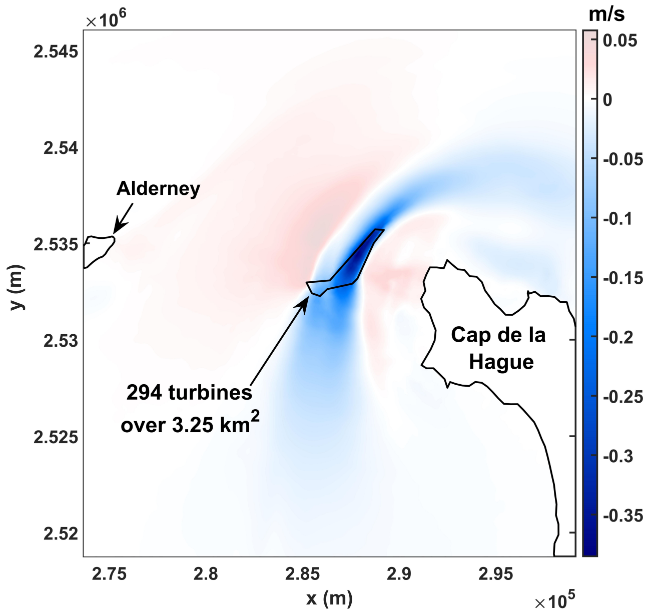


Fig. 4. Time-averaged flow perturbation induced by 294 turbines deployed in Le Raz Blanchard. Results have been obtained form a Telemac2d simulation in which turbines are represented with an enhanced friction term. Coordinates system (in m): EPSG 2192

In 2D, Telemac has firstly been used to characterize the resource of the three aforementioned sites (simulations without turbines). Secondly, for Le Raz Blanchard, different tidal arrays have been represented with an enhanced friction term [8] to analyse the effect of energy extraction on the resource considering several scenarios (different array locations and turbine densities). An example of the time-averaged influence of 294 turbines on the current magnitude is shown in Fig. 4. The feedback between the tidal arrays and the resource itself fed into a techno-economic analysis of the site conducted by ORE Catapult. Thirdly, for the Morbihan Gulf, simulations with turbines were used to analyse the effect of tidal current exploitation on the hydrodynamics of the site. These simulations were used to assess the extent and the magnitude of the flow perturbation.

In 3D, Telemac has been used to characterize the hydrodynamics of Le Raz Blanchard and Paimpol-Bréhat. Model outputs of Le Raz Blanchard were used in a cross-comparison of different models and to aid the deployment and recovery of an ADCP. A model configuration of Telemac3D with actuator disks was also used to assess the performance of different array layouts and to analyse the influence of blockage ([9], [10]).

C. Thetis

Thetis is an open source, unstructured grid coastal ocean model built using the Firedrake finite element framework. Wind and wave effects are not included in the model. The model is run in depth-averaged mode in order to achieve acceptable computational efficiency to run simulations for the range of purposes set out in Table 1. This prevents the models from being able to resolve the boundary layer flow in the vertical plane, which has been deemed acceptable given the accuracy of the model in two dimensions, and the additional computational efficiency this provides [11]. Within the TIGER project, a Thetis model of the Ramsey Sound, initially presented in [11], has been used by the University of Plymouth (UoP), and developed for several studies. In addition, UoP has developed new hydrodynamic models of Le Raz Blanchard.

Fig. 5 shows the domain and computational mesh from the Ramsey Sound model, which covers a large section of the Irish Sea, as well as incorporating parts of the Celtic Sea and Northern Channel. The spatial resolution of the mesh is 8 km at its outer extremities, and refined to around 250 m around coastlines to capture intertidal processes, and to 25 m within the Ramsey Sound to resolve complex flow features around bathymetric features such as Horse Rock and the Bitches. In some of the model runs, tidal arrays have been included in the model, represented using an enhanced drag coefficient, C_a, defined as

$$\lambda = \frac{A_t n}{A_a}, \tag{1}$$

$$C_a = \frac{1}{2}\lambda C_d, \tag{2}$$

where λ is the array density, defined as the ratio of the total swept area of the array to the plan area of the array. A_t is the swept area of a turbine rotor, n is the number of turbines in the array, and A_a is the plan area of the array. C_a is the turbine array drag coefficient and C_d is the drag coefficient of a single turbine. This approach is often referred to as the continuous array drag approach, which is different to the discrete turbine drag approach where each individual turbine is assigned its own drag term. The continuous drag approach cannot simulate local blockage effects caused by the wakes/bypass flow of upstream turbines impinging on downstream turbines, for example. These impacts were minimised in the Thetis modelling by upholding a relatively low array density, to maintain high spacing between turbines, as recommended in [12].

The Thetis model of the Ramsey Sound was used to quantify the performance of various tidal arrays, using 0.5 MW, 15 m rotor diameter turbines. The array plan area was derived based on a range of practical constraints that determine the viability of turbine positioning. These constraints included depth (LAT), bathymetric gradient, flow speeds, shipping lanes, and conservation areas. Simulations were run to quantify the performance of the array when 20 – 80 turbines are distributed evenly over the array plan area. Table II-C summarises the estimated annual energy yield and capacity factor of the arrays. Results show that whilst the annual energy yield of the array increases by 200% as the number of turbines is increased from 20 to 80, there is a 25% reduction in the array capacity factor. Given that operational projects are requiring capacity factors of 0.4 to achieve financial close [13], these results indicate that Ramsey Sound is highly unlikely to be able to facilitate large scale array development, until capital and operational costs reduce.

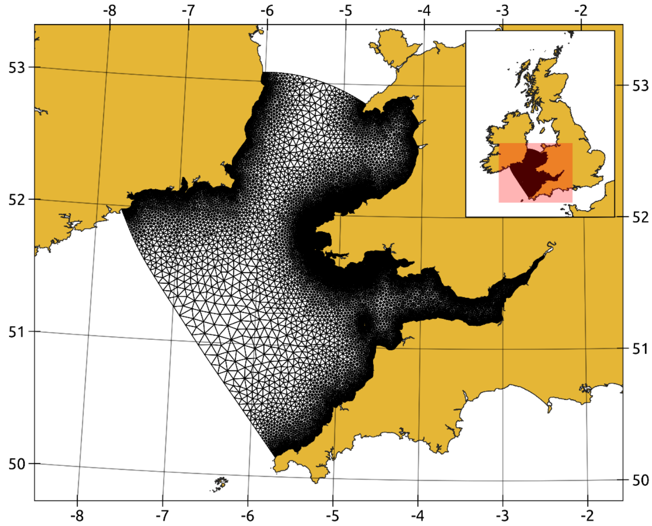


Fig. 5. Domain and computational mesh for Thetis model of Ramsey Sound and surrounding seas.

TABLE I
ANNUAL ENERGY YIELD ESTIMATES FOR ARRAYS IN THE RAMSEY SOUND

No. Turbines	Array Capacity	Annual Energy Yield	Capacity Factor
20	10 MW	34.8 GWh	0.40
40	20 MW	63.3 GWh	0.36
60	30 MW	87.4 GWh	0.33
80	40 MW	103.6 GWh	0.30

D. MIKE21

To investigate tidal stream energy potential at the Gulf of Morbihan site, the MIKE 21 Flow Model was used to simulate the tidal hydrodynamics in the area of interest, using a 2D SWE approach. The area consists of many islands, channels and river outflows. The computational domain was setup using an unstructured mesh with cell sizes ranging from 10 km to 10 m. The bathymetric data was based on the Litto-3D dataset from SHOM, with a resolution of 10 X 10 m, and a higher-resolution 1 X 1 m dataset gather by UBS for the entrance of the Gulf of Morbihan. The model was run for a period of 1 month, from December 2014 to January 2015, coinciding with the deployment of two ADCPs, one in the channel between Île Longue and Pointe du Monténo, and the other in the channel between Île Berder and Île de la Jument (see Fig. 6). ADCP measurements showed peak flow speeds around 3.5 m/s. The mean flow speed from the model output at the Île Longue site was found to be 1.8 m/s and the corresponding mean power density was found to be 3.1 kW/m^2.

III. SITE-SCALE MODELS

The purpose of the site-scale models implemented in TIGER is to provide detailed information about turbulent flows across the sites. Both the models described here use an LES method to model turbulence. The first one relies on an in-house version of Telemac3D. The

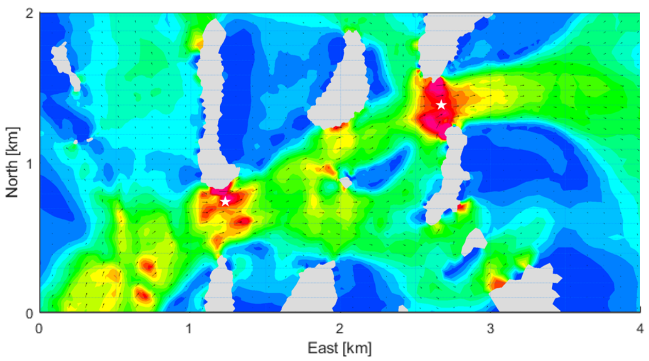


Fig. 6. Example map of current velocities from MIKE21 model of Gulf of Morbihan for 24/12/2014 at 00:20. White stars indicate locations of ADCPs.

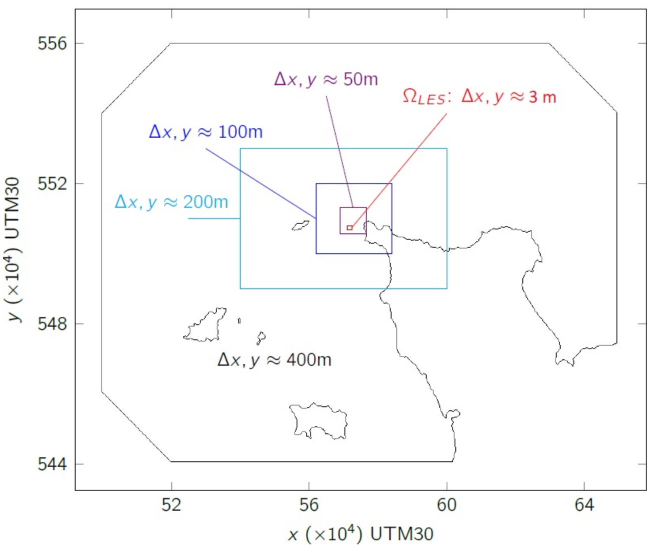


Fig. 7. Horizontal cell sizes of the RANS - LES model of the Raz Blanchard.

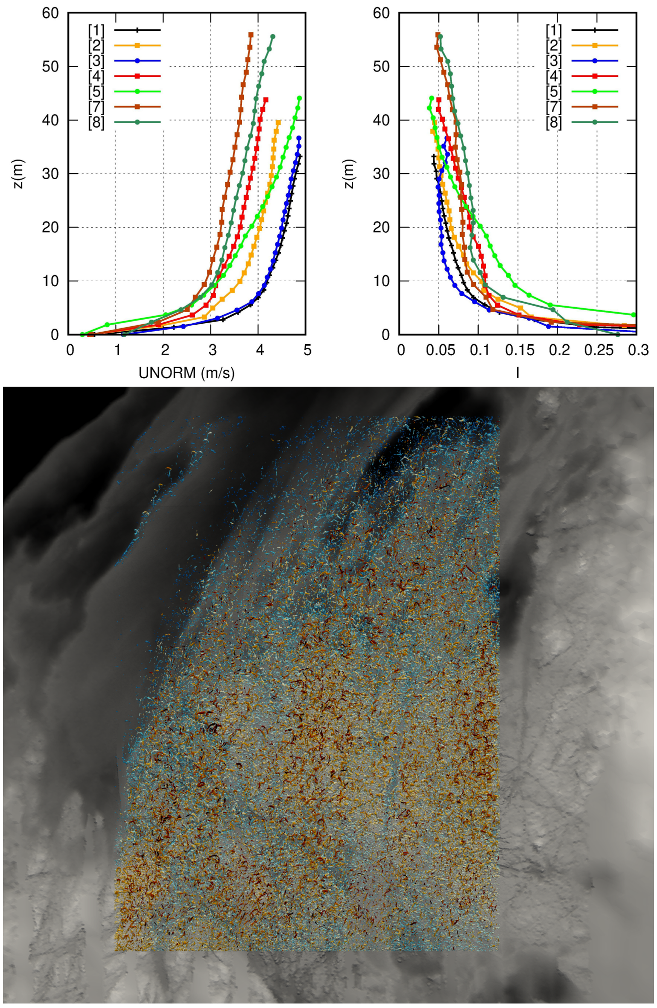


Fig. 8. Vertical profiles of velocity magnitude and turbulence intensity at several locations within the LES area (top) and Turbulent structures identified with the λ_2 criterion coloured by the elevation (bottom) on the 10/07/2017 at 7 am (Flood peak).

second one uses the Lattice Boltzmann Method (LBM) and relies on the Palabos library.

A. Telemac 3D-LES

Telemac 3D-LES was initially developed during the THYMOTE project [14] and was applied to the Raz Blanchard (France) [15]. The model was further developed within the TIGER project [16]. The model is able to simulate turbulent flows over an area of several km^2 at high accuracy and high resolution, for a duration of around one day of real time. The Telemac 3D-LES model is based on the open-source code Telemac [2]. The original (RANS) code was modified to allow LES [14]. For the present purpose, the LES domain was embedded in a larger domain where tidal dynamics were simulated with a RANS approach and the boundary conditions were given by the TXPO atlas of tidal constituents (Fig. 7). In the LES domain (Ω_{LES}), the Anisotropic Minimum Dissipation model (AMD) was used [17] whereas in the RANS domain (Ω_{RANS}), the one-equation closure model of Spalart and Allmaras [18] was used. The coupling between LES and RANS formulations was presented in [19]. In the application presented here, the horizontal cell sizes were refined up to 1m in the LES zone (the dimensions of the LES zone is 1.8 km × 2.5 km). In the RANS domain, which covered a 150 km × 120 km surface area, the cell size increased up to 500 m at the open boundary. The bathymetric data were provided by the French Navy SHOM. The time step was set to 0.375 s.

In addition to water elevation and current velocities, Telemac3D-LES provides the six components of the Reynolds tensor. Examples of results are illustrated in Figure 8 where vertical profiles of current magnitude and turbulence intensity were plotted (on the top) to highlight the spatial variability of current characteristics within the site of interest. Figure 8 also shows that the model enables the mapping of large eddies that are generated and transported within the race. Here, eddies were identified with the λ_2 criterion.

B. Palabos

Palabos is an open source C++ library that implements the lattice Boltzmann method (LBM) for the numerical simulation of unsteady flows [20]. The model is suited for the simulation of turbulence. For tidal flow simulations, it takes account of the seabed roughness at a fine scale ($\simeq$ 0.3 m). However, its high needs in computational resources limit its spatial ($\simeq$ 0.5 km^2)

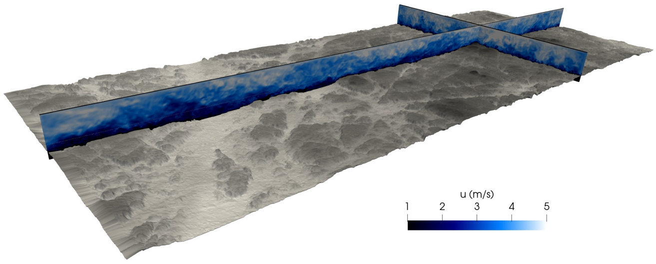


Fig. 9. Flow velocity in the Raz Blanchard: LBM-LES simulation.

and temporal ($\simeq$ 30 min) coverage.

In the frame of the TIGER project, it has been used to simulate tidal flows at the Raz Blanchard, shown in Fig. 9, and Paimpol-Bréhat sites. For both sites the simulations were validated in terms of 10-min averaged velocity against ADCP measurements. At the Raz Blanchard site, they were also validated in terms of Reynolds tensor profiles. The simulations bring to light the generation of large-scale turbulent flow structures [21] and the role played by specific seabed macro-roughness. The generation of turbulence has a significant impact on the spatial variations of the flow characteristics at a very local scale [22], which calls for a particular attention to this matter for the turbine positioning. Also, an asymmetry in these spatial variations can be observed between flood and ebb [23]. The model has also been used to assess the limitations of ADCP measurements [24]. Indeed, the seabed roughness invalidates the homogeneity assumption required for the estimate of turbulence intensity in the vicinity of the seabed.

IV. Turbine-scale models

Turbine-scale models focus on interaction between the flow and turbines, as opposed to the site-scale models which focus on the interaction between the flow and local bathymetric features. As such, flow conditions (water levels, currents, turbulence and waves) are input from larger scale models. Turbine-scale models are run for shorter time periods of order 5-30 minutes, over which the flow conditions are approximately stationary.

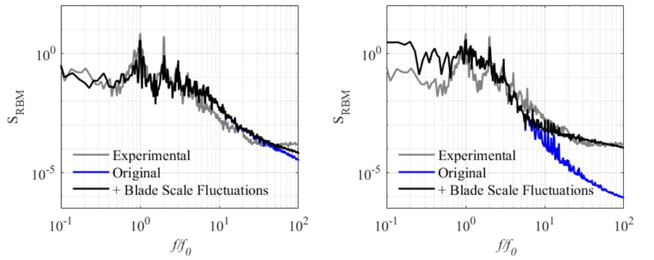
In the models implemented in TIGER, the fluid loads on the turbine blades are calculated in the same way, using look-up tables of lift and drag coefficients for blade sections, as a function of the in-flow velocity and angle of attack, sampled at a number of points along the blades. In the unsteady BEM model, the effect of the turbine on the flow is not modelled, and the spatial and temporal evolution of the flow field is calculated before run time. In contrast, the DOFAS, DOROTHY and Palabos models explicitly calculate the evolution of the flow and the influence of the turbine on the flow, so that the models can be used for the characterisation of turbine wakes.

A. Unsteady BEM

The Unsteady BEM codes used in the TIGER project have been developed in-house to provide an efficient method to predict the power output and cyclic loading on tidal turbine components. The code requires an input flow field which can be generated using pre-run turbulent CFD simulations or synthetic turbulence models. This flow field can also contain features such as vertical and transverse shear and waves. Within the project this code has been applied to investigate a range of site conditions, at both the EMEC test site in the UK [25] and at Raz Blanchard in France. Unlike resource models the spatial grid is not site specific within this code. The spatial grid here is used to define the onset flow conditions. As the method is not computationally expensive code, a high-resolution grid can be used. The grid spacing typically employed for defining the time-varying onset flow-field is of the order of 0.25 m to 1 m for turbines of diameter 20 m. Smaller spacing, e.g. 0.01 m can be employed for finer turbulence length scales and for differing sizes of turbine under consideration. As with the spatial grid, the temporal settings are not restricted due to the computational cost. However, for validation with experiments and to consider quasi-steady intervals of tidal resource specific time periods used range from 60 to 600 seconds. The output variables are sampled at high frequency, typically corresponding to the experimental dataset, or to resolve relevant frequencies of unsteady onset flow. For simulations focused on wave-induced kinematics O(10) time steps per wave-cycle are typically employed. For simulations with turbulent onset conditions, a higher frequency range is modelled, and this can vary with the turbulence model employed to synthesis the onset flow.

Within the TIGER project, several tidal devices have been modelled, including a laboratory scale turbine for which load data is available from prior publications [26], a publicly-available geometry for the TGL 'full-scale' turbine [27], [28] and the Orbital Marine Power (OMP) device [29]. The tidal device modelled consists of two rotors each with two blades, following the design of a full-scale floating device by OMP. In addition, a blind modelling study has been conducted between University of Le Havre Normandie and the University of Manchester to assess the level of fidelity required in the inflow to device scale models and the uncertainty in the loading and power production from the different methods.

Blade element models are typically dependent on input of lift and drag coefficient polar curves. The in-house unsteady BEM code used at University of Manchester has been extended to include the contribution from higher frequency blade-scale fluctuations of the lift and drag forces due to the turbulent relative velocity to the blade [30]. This has been shown in provide better predictions in the fatigue loading when highly coherent structures are present in the onset flow, such as observed in field measurements and when modelled using a synthetic eddy method, shown in Figure 10. This work is informing analysis of control strategies for mitigating load variation, both for single turbines subject to unsteady onset flow, and for turbines in arrays subject to upstream turbine wakes.



(a) von Kármán (b) Synthetic Eddy Method

Fig. 10. Influence of blade-scale fluctuations on the load spectra of root bending moment, for (a) the von Kármán method and (b) the synthetic eddy method, used to generate turbulent inflow to the in-house unsteady BEM model.

B. DOFAS

The Digital Offshore FArms Simulator (DOFAS) is an in-house large-eddy simulation (LES) code that adopts the spatially-filtered Navier-Stokes equations to explicitly resolve the turbulent scales larger than the grid size, whilst modelling the smaller ones using a sub-grid scale model, commonly adopting the Smagorinsky or WALE models. The computational grid is discretised into a rectangular Cartesian grid with staggered storage of velocities, with a fully-explicit fractional-step method to advance the simulation in time and an algebraic multigrid to resolve the Poisson pressure equation. DOFAS can represent tidal stream turbines with an Actuator Line Method (ALM) to resolve the turbine (both horizontal and vertical axis) rotor's blades with a Prandtl correction to account for tip losses, or with an Actuator Disc Method (ADM). The use of ALM or ADM allows to have relatively coarse grid resolutions without the need for explicitly resolving the rotor geometry, which alleviates the inherent computational cost of performing LES [31]. Ouro et al. [32] validated the accuracy of the LES-ALM method in DOFAS in terms of hydrodynamic coefficients and turbulent flow statistics in the wake of small-scale tidal turbine arrays. DOFAS is capable of modelling dozens of turbines. Ouro and Nishino [33] performed the LES of several arrays to show that staggered configurations are more insensitive to turbine spacing than aligned layouts, with the former yielding larger energy output due to the bypass flow generated between upstream turbines.

In the representation of real project conditions, DOFAS can represent irregular bathymetry or singular bed features with a direct-forcing immersed boundary method [34] in a computationally efficient way. Hydrodynamically smooth and rough wall functions are available to enable the use of relatively large grid cells near the walls and thus reduce the computational requirement. Ocean waves can be explicitly simulated in DOFAS with a level-set method adopting linear or second-order Stokes theories an absorption layer at the outlet in order to avoid wave reflections [35].

Examples of the work conducted during the TIGER project with DOFAS are shown in Figs. 11 and 12. Two-rotor devices have been simulated to investigate wake dynamics and influence of hub-to-hub spacing. Periodic loading induced from ocean waves and their impact in wake recovery has been investigated for various wavelengths ranging from deep to shallow wave conditions.

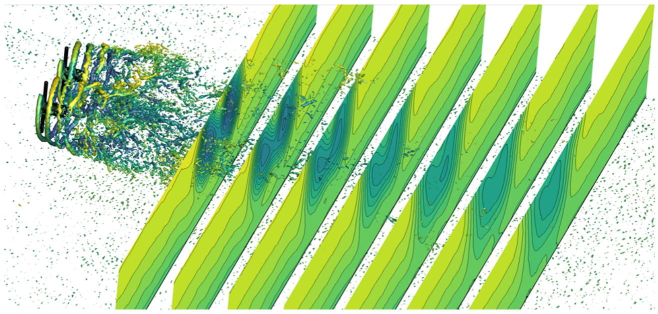


Fig. 11. Wake structures induced by two tidal turbine rotors represented with Q-criterion isosurfaces, and cross-sections with mean streamwise velocity distribution at various downstream stations, modelled using DOFAS.

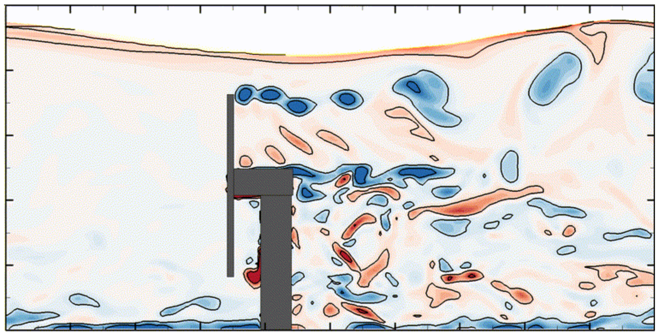


Fig. 12. Contours of spanwise vorticity around a tidal stream turbine operating under the action of ocean waves, modelled using DOFAS.

C. DOROTHY

DOROTHY is code based on the Lagrangian Vortex Particle Method developed by ULHN [36], [37]. The Vortex Particle Method uses a Lagrangian resolution of the fluid domain, discretised into fluid particles representing the vortex perturbation of the flow. The particles are advected using Runge-Kutta time stepping schemes. Re-distributions of the fluid particles on a regular Cartesian grid are carried out every few iterations to maintain a homogeneous distribution of the particles over the flow domain. The flow evolution is governed by the incompressible Navier-Stokes equations. The present implementation also includes an LES-type diffusion model, implemented via a Particle Strength Exchange (PSE) model. DOROTHY also includes a possibility for the representation of ambient turbulence [38]–[40], using either Jarrin's Synthetic Eddy Method (SEM) or Poletto's Divergence-Free SEM. These methods have been integrated into the Lagrangian code as an added term applied to the upstream velocity throughout the entirety of the chosen study space. They allow for the artificial reproduction of any turbulence intensity, Reynolds stress tensor, and integral length scale of turbulent behaviour in the flow.

In earlier versions, DOROTHY used a panel method for a simplified zero-thickness representation of the turbine blades [36]. However the computation of blade loads with this method proved difficult. During the

TIGER project, a new representation of the turbine blades has been implemented using the lifting line method [41]. The resulting model is referred to as the Lifting Line Vortex Particle Method (LL-VPM).

Compared to blade element momentum theory, the advantages of the LL-VPM method is to compute the wake, to have inherently 3D effects in this wake and possible load fluctuations. But this is also with a higher computational cost. Compared to blade resolved CFD, the advantage of LL-VPM is having much less meshing issues (VPM is Meshless) and naturally dealing with interactions between turbines or future fluid-structure interactions. With respect to the computational cost, a dedicated study is currently being performed. Nevertheless, the pressure distribution is, for instance, not available from the LL-VPM model.

Various outputs are available from the model, including:

- Position and vorticity weight of all the emitted fluid particles
- For each blade section:
  - Bound, trailing and spanwise circulations
  - Local velocity, Reynolds number and angle of attack
  - Local lift and drag coefficients
  - Normal and tangential to blade forces
- Integrated values:
  - Global angle of rotation the turbine
  - Global loads: thrust, torque and associated coefficients

Post-processing the output particle data allows to generate a map of the vorticity and velocity in the wake. With all these outputs the interaction between several turbines can be assessed. The evolution of loads along the blade over the time can also be studied.

An array of four turbines was considered as a demonstration case, based on the former Alstom devices with an open geometry, projected to be installed in the Raz Blanchard at the location and with the set-up of the NEPTHYD project, with three upstream turbines and one downstream turbine and a flat sea bed [42]. Fig. 13 shows wake characteristics of the 4-turbine array. A more recent study [43] reproduced the same computations with an earlier version of the LL-VPM model to assess load fluctuation due to wake interactions. This has been computed for a turbulence intensity of 10 % at different yawed flows showing the influence of the central upstream turbine on the downstream one. As the angle increases, a greater interaction can be observed. At an inclination angle of 10°, a weak interaction is observed. For the 15° and 20° cases, clear interactions can be observed, where a greater portion of the downstream turbine is in the wake of the upstream turbine.

D. Palabos

The open-source library Palabos was also used to model the flow around tidal turbines in turbulent flows [44]. Palabos solves the LBM on a multi-level Cartesian grid for which a suitable approach for modeling turbines is the Actuator Line Model [45]. The

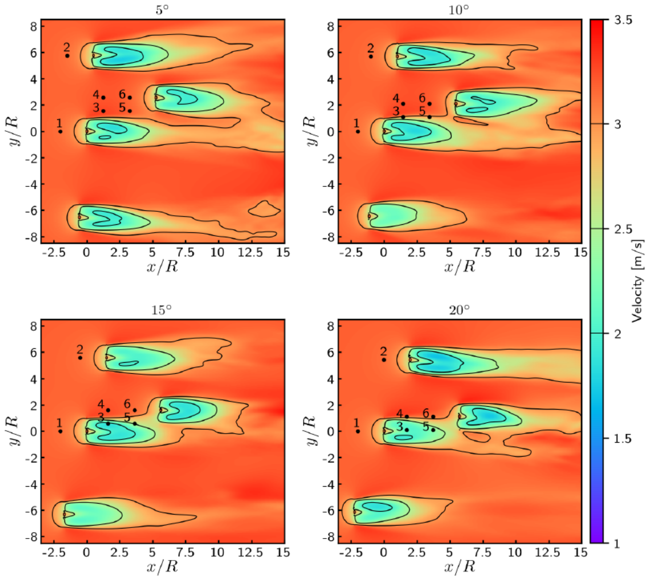


Fig. 13. Wake characteristics of 4 tidal turbines projected to be installed in the Raz Blanchard, modelled with the Lifting Line Vortex Particle Method. This has been computed for a turbulence intensity of 10 % at different yawed flows showing the influence of the central upstream turbine on the downstream one. Figure reproduced from [42].

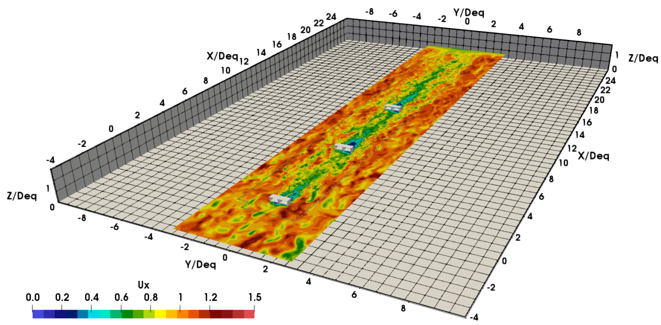


Fig. 14. Instantaneous axial velocity in m.s^{-1} around three Hydroquest© turbines, each 150 m apart. Palabos ALM-LBM-LES simulation.

LBM is coupled with the Smagorinsky Large Eddy Simulation model and the ambient turbulence is taken into account with a Synthetic Eddy Method. Because this work was also part of the OCEANQUEST project, the Hydroquest© tidal turbine was selected for the study. It is a vertical axis tidal turbine consisting of four 3-bladed rotors.

Some of the most recent works using this approach have focused on studying interactions between turbines [46]. The objective was to predict the behavior of small-sized farms in order to optimize turbine placement and thus maximize energy production. Farms consisting of three and four Hydroquest© turbines have been studied with various spacing between turbines. The way velocity deficit accumulates in aligned arrays is one of the most significant observation. Figure 14 illustrates the phenomenon for three aligned turbines.

The model is currently undergoing improvements through the implementation of a wall model for non-moving parts. Palabos grid resolutions for turbine-scale models and regional scale models are of the same order of magnitude so an ALM-LBM-LES simulation

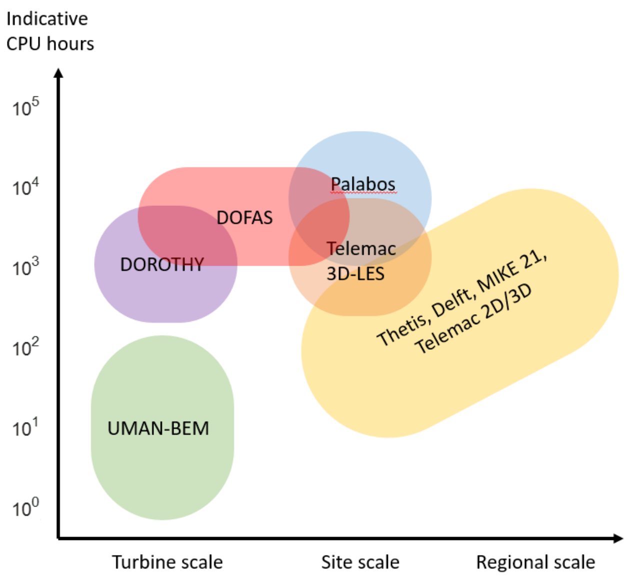


Fig. 15. Indicative scales and computational requirements for numerical models used in TIGER.

of a small tidal farm incorporating a realistic seabed morphology is feasible with the computational resources currently available.

V. Discussion and conclusions

This paper has provided an overview of the numerical models used within the TIGER project. The work conducted showcases the range of spatial and temporal scales that can be assessed using currently available tools. In many cases, the models have been used to provide information to technology and site developers to aid in their design process. This feeds into one of the key goals of TIGER, which is to accelerate the development of the tidal sector, faster and more effectively than would be possible without support from Interreg.

The models described in this paper cover a wider range of spatial and temporal scale, and are intended to be used for different purposes. Broadly speaking, the regional-scale models provide the lowest resolution data, but over the largest spatial and temporal scales, whereas site-scale models provide higher-resolution data regarding fine-scale flow over the site, but for smaller areas and shorter durations. Similarly, the interaction between the flow and individual turbines is covered at various levels of fidelity in the turbine-scale and site-scale models, with corresponding implications for computational cost. A high-level schematic of the scales and indicative computational cost of each model is shown in Figure 15. The computational requirements can vary significantly between particular applications of each model, the domain size, resolution, number of cases considered, etc. However, the indicative ranges show that computational requirements vary by several orders of magnitude. The higher fidelity models provide some information that is not available from the lower-fidelity models, but at higher computational cost.

Data from the models has also been used to inform high level strategic techno-economic considerations for the tidal energy industry. In particular, data from several models has been used to support the ORE Catapult in developing the report “Cost Reduction Pathway of Tidal Stream Energy in the UK and France” [47].

The TIGER “Data Collection & Survey Best Practice Report” [48], discusses general requirements for tidal resource assessment. The report highlighted the key importance of numerical modelling as part of any resource assessment study. This paper has also highlighted the capability of the range of numerical models, regarding different oceanographic inputs, including bathymetry, depth-dependant tidal currents, turbulence, wind and wave effects, as well as the inclusion of the tidal turbine(s) themselves. As such, this paper should assist researchers, practitioners and decision-makers in the selection of suitable modelling approaches and tools to cover the spatial and temporal domain required for their needs. Given the different capabilities and computational costs, a combination modelling approaches could be applied to cover the regional, site and turbine domains, for time periods of minutes to years.

The research, resources and applications presented here and conducted as part of the TIGER project, will feed into the overall advancement of the sector, by providing the highest quality modelling input for engineering, environmental and financial decision-making.

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