Numerically Modelling the Spatial Distribution of Weather Windows: Improving the Site Selection Methodology for Floating Tidal Platforms

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Abstract **— This paper examines the impact of MetOcean conditions on weather window availability and duration for tidal energy operations and maintenance. Understanding these impacts at the initial planning stage will give a better estimation of project lifetime costs, and ensure that these costs are factored into the site selection methodology. Several sources of freely available data were input into the Delft3D modelling suite to produce spatially and temporally varying estimates of MetOcean data for the Surigao area in the Philippines. This data was validated where possible, with the generated tidal heights and flow speeds seeing a good fit to adjacent tide gauge and acoustic data. A Dijkstra's Algorithm was applied to generate an optimum route to shore that accounted for depth restrictions. Weibull persistence statistics were successfully applied to the MetOcean characteristics at each point along this route, to calculate the probability of vessel limitations being exceeded. The number of probable access and waiting hours within a month, given a required weather window length and MetOcean threshold, was calculated. Flow is seen to be the most constraining, but also the most predictable MetOcean parameter and thus can be accounted for in operational planning. Wind is seen to impact little on transit but can be constraining for longer operations. Wave conditions are seen to constrain both transit and operations weather windows significantly under the limitations examined.**

Keywords**— Tidal Stream, Site Selection, Weather Windows, Numerical Modelling**

Nomenclature

ADCP	Acoustic Doppler Current Profiler
α	Boundary Reflection Coefficient
b	Weibull Scale Parameter
D	Duration (time period of analysis)
DA	Dijkstra's Algorithm
EMEC	European Marine Energy Centre
GEBCO	General Bathymetric Chart of the Oceans
H_S	Significant Wave Height
JONSWAP	Joint North Sea Wave Project
k	Weibull Shape Parameter
LCoE	Levelised Cost of Energy
N_{Acc}	Number of Access Hours within Duration
N_ω	Number of Weather Windows within Duration
N_{Wait}	Number of Waiting Hours within Duration
O&M	Operations and Maintenance
P_W	Weibull Probability of Exceedance
SME	Sustainable Marine Energy Ltd.
PLAT-I	Platform for Inshore Applications
SWAN	Simulating Waves Nearshore
T_{Acc}	Average Length of Accessible Weather Window
T_P	Peak Wave Period
UTM	Universal Transverse Mercator
V_D	Depth-Averaged Velocity
WGS	World Geodetic System
W_S	Wind Speed

I. Introduction

To capitalise on a limited number of appropriate deployment locations and offset the costs of an emerging technology, the tidal stream industry has opted towards a site selection methodology that seeks primarily to maximise power output [(1,2)]. This means that high resource sites are often prioritised, without full understanding of the impacts of MetOcean characteristics on lifetime costs such as Operations and Maintenance (O&M).

Previous work by the authors [(3)] has demonstrated that not appropriately accounting for MetOcean conditions at hypothetical exposed and sheltered sites would have a significant impact upon a project's Levelised Cost of Energy (LCoE). For this previous study a 20-year deployment of the Sustainable Marine Energy Ltd. (SME) floating tidal energy converter, PLAT-I (PLATform for Inshore applications), was used as a case study. The paper concluded that when choosing between potential deployment sites, the impact of distance from shore and exposure to wave climate had a more significant impact on LCoE than maximising resource (power). This paper seeks to build upon the previous work, by establishing a more thorough estimation of the MetOcean characteristics at a real potential tidal energy deployment site. Consequently, this allows for an accurate approximation of the constraining effects of MetOcean conditions on marine operation success rates, expected durations and the subsequent project costs.

When assessing a new site, temporally and spatially varying MetOcean data is invaluable. However, it can be difficult to attain early on in a tidal energy development. Additionally, performing spatially varying site assessments at the required level of detail can be lengthy and expensive. This paper explores the possibility of using freely available data and numerical modelling software to provide first-pass MetOcean information to assess site suitability for further investigation. With this information available, more holistic and informed

decisions can be made regarding choice of installation location. An improved site selection methodology that incorporates these decisions will not only help to minimise early stage project costs, but also provide quantifiable estimates of lifetime costs between locations, therefore minimising the LCoE of floating tidal energy and facilitating the sector's transition towards commercial maturity.

II. Methodology

In order to quantify and assess the MetOcean conditions at a site a numerical modelling approach was used. Models were developed to assess bathymetry, tidal height, flow speed, wave conditions, wind conditions, and vessel routing.

The Delft Dashboard graphical user interface forms the backbone of the numerical modelling in this paper. The Delft3D-FLOW module, TPXO 7.2 Global Inverse Tidal Model and GEBCO '08 (General Bathymetric Chart of the Oceans) bathymetry data were used to generate approximations of tidal flow velocities and heights. The Delft3D-WAVE module contains the SWAN (Simulating Waves Nearshore) software and was utilised alongside historic wind data taken from the DHI MetOcean Data Portal to produce estimates of significant wave height. The aforementioned data and modelling software can therefore be used to simulate depth, flow, wind, and wave conditions at any location.

A Dijkstra's Algorithm was applied to estimate the optimum route between ports and potential deployment sites. For each grid cell along this route, Weibull persistence statistics were utilised to estimate probabilities of flow speed, wind speed and wave height operational limit exceedance. This allowed for the estimation of the occurrence of weather windows of a required duration, and the likely waiting time for these weather windows.

A. Case Study

Surigao Strait is a channel in the South Eastern Philippines that is suspected of having tidal energy potential. This area was used as a case study, due to adjacent tide gauge stations and existing Acoustic Doppler Current Profiler (ADCP) confirming its potential as a tidal energy deployment location. This area has been identified through initial site selection methodology, detailed in [(4)], to be specifically appropriate for SME's PLAT-I platform, with further understanding of the site therefore required. The modelling methods described above were therefore used to determine the MetOcean conditions at this location. Whilst long term data sets and simulation are preferable, due to computational and data availability constraints the simulation was initially run for a single month from April – May 2016.

Considerable effort was made to ensure model accuracy, but it is worth noting that the modelling outputs utilised in this paper are not designed to be a perfect recreation of complex natural phenomena. They were designed to allow a tidal developer to make an initial decision between deployment locations; providing quantifiable inputs to a decision that was previously either burdened with a lack of data and high uncertainties or was erroneously not taken into consideration. This is particularly important when targeting lesser known or more remote sites, unlike areas in the UK and Europe which have a large portfolio of data such as EMEC [(5)].

B. Bathymetry & Grid Generation

The GEBCO bathymetry data is a continuous high-resolution terrain model [(6)]. The bathymetry portion of the grid was generated largely from the interpolation of multiple databases of ship-track soundings and satellite data. This gives a good resolution of detail for an initial site assessment, though it is limited in areas that are not frequented by vessels, or areas of complex bathymetry as these features will not be detected. The GEBCO data was imported into Delft Dashboard, using the WGS'84 (World Geodetic System), UTM (Universal Transverse Mercator) Zone 51N coordinate system and chart datum.

Two bathymetric grids were generated for the area in question. The first was a larger, coarser grid comprised of 130x130 1km grid cells, while the second was smaller and finer, comprised of 60x70 200m grid cells (Figure 1). The smaller grid was nested inside the larger, such that the boundary inputs for both FLOW and SWAN models were taken as outputs from the larger grid. The location of operating tide gauge data stations are also shown (1. Hinun, 2. Surigao, 3. Dahi). The island in the centre right of the smaller grid domain is known as Rasa Island, and the narrow channel behind it is Rasa Strait.

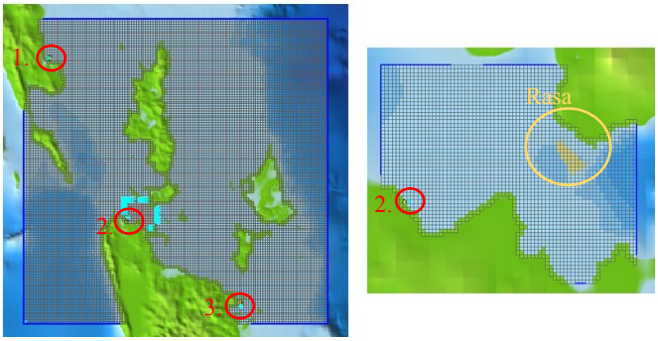

Figure 1. Coarse (left) and fine (right) bathymetry grids at Rasa strait

C. Tidal Velocity

Delft3D-FLOW is a multidimensional hydrodynamic simulation program for non-steady flows driven by tidal and meteorological forcing [(7)]. The boundaries of the larger grid were forced astronomically using the TPXO 7.2 Global Inverse Tidal Model. This model generates gridded tidal coefficients by interpolating between confirmed constituents from the world's active tide gauge stations, while accounting for latitude [(8)]. The main alterations to the model defaults were the setting of the model Time Step (or Courant Number) at 0.2 for model run stability and an increase in the boundary reflection coefficient (α) to 10000 in order to account for the large size of the grid and mass of water attempting to leave through the open Direchlet boundaries. These alterations were deemed to be appropriate based on existing literature [(9,10)] and prior experience with the Delft software.

By forcing a change in sea surface height at the boundaries of the larger grid, the variation in depth averaged velocity (V_D) through the smaller grid was estimated spatially across the domain and temporally at hourly intervals; an example of the result is shown in Figure 2. Highest flows are seen in the deepest water, and constrictions due to bathymetry also produce increases in flow speed.

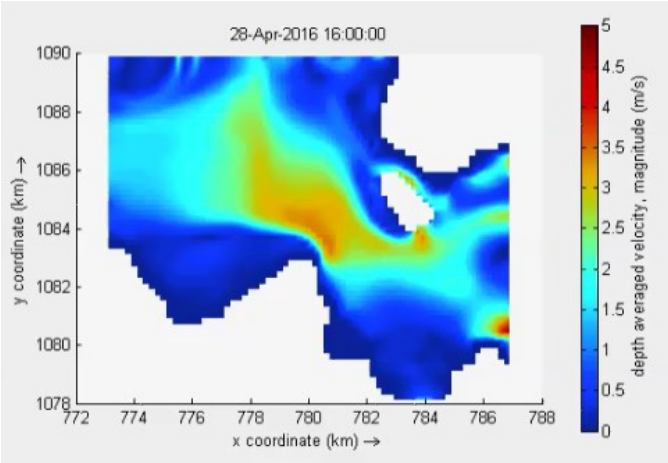

Figure 2. Delft3D-FLOW output for fine grid of depth-averaged velocity

The Delft3D-FLOW model has been validated against real tidal height data at three adjacent tide gauges (Figure 3). The location of each of the tide gauges is shown in Figure 1.

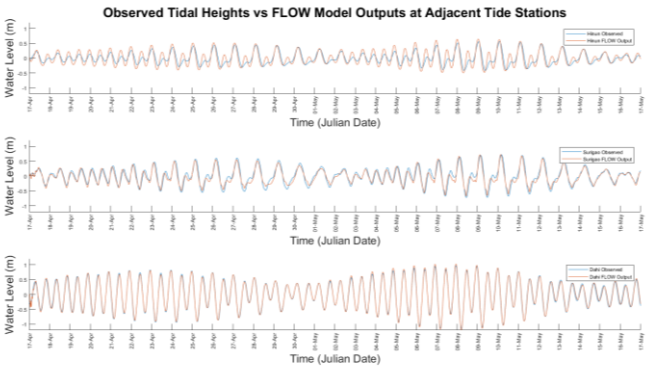

Figure 3. Delft3D-FLOW tidal height validation against raw tide gauge data

All three locations show a very strong correlation in terms of phase. The Dahi station shows the closest correlation in terms of magnitude, while Hinun is seen to be the weakest. The Surigao station is the most relevant to the objectives of this paper, as it is located within the finer grid and is at the same geographical position as the DA shortest path start point. This station shows strong correlation in terms of both phase and magnitude. The FLOW model does under predict the diurnal elements of the tidal height in some situations, however, this under prediction is only of in the order of magnitude of 0.1m and thus is deemed to be an acceptable reconstruction. Logic dictates that if the tidal height is correct in terms of size and magnitude, and the size and shape of the basin modelled is approximately correct, then the flow speeds through the basin must also be relatively accurate.

D. *Wind Velocity*

Hourly averages of wind speed (W_S) and direction at 10m above sea level at the geographical location of Surigao City (Position 2, Figure 1) were taken from the DHI MetOcean Data Portal [(11)] and input into the model at the boundaries of the larger grid. The data was consistent spatially across the domain but varied temporally in hourly intervals. Spatial variations due to meteorological or topographical conditions within the domain are therefore not accounted for within this model.

E. *Significant Wave Height*

SWAN is a phase-averaging wave model that is used here to obtain estimates of significant wave height (H_S). The model is based on the wave action balance equation which accounts for sources and sinks of energy, the largest of each being wind inputs and frictional dissipation [(12)].

The DHI MetOcean wind speed and direction at the location of Surigao City were input at the boundaries of the larger grid, along with reasonable estimates for existing wave parameters. The majority of the parameters were set as the model defaults though some parameters were changed. The main alterations were: a decrease in wet grid point accuracy from 98% to 95% to allow for model run times within 48 hours; setting the obstacle reflection coefficient to 0.5 to represent a steep beach; applying diffraction; and altering the boundary wave conditions to H_S = 1m and T_P = 4s in order to represent a previously existing moderately developed sea state [(13)].

The resulting waves were propagated across the domain of the larger grid according to these wind conditions and the bathymetric characteristics. Variations in H_S can therefore be estimated within the smaller grid at high resolution, (Figure 4). The refraction and sheltering effects of coastline and islands are clearly visible, with the highest waves being found in the deepest waters with the longest fetch. Unfortunately, due to data unavailability, no validation could be performed on the SWAN wave predictions. However, the results closely reflect observations made during site assessments at the same time of year as this analysis in terms of magnitude, direction and general sea state behaviour.

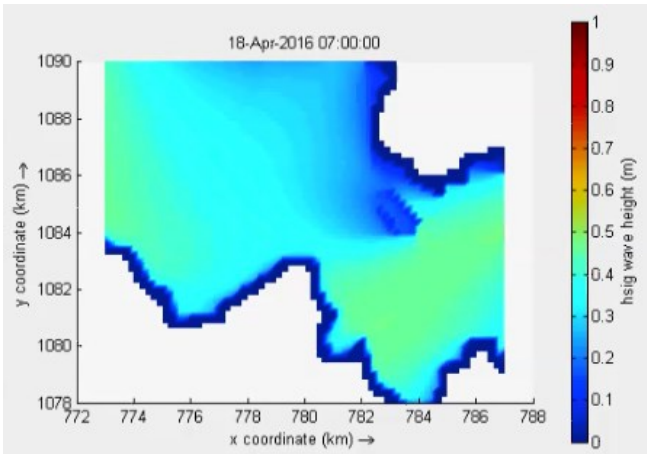

Figure 4. SWAN output of significant wave height

F. Operational Limitations

1) Path from Port to Site: Rasa Strait is expected to have relatively high flows (Figure 2) while also being sheltered from the majority of waves (Figure 4), making it a suitable potential site for SME's PLAT-I device. It was therefore designated as the deployment location for this paper.

To install and maintain PLAT-I an appropriately equipped maintenance vessel and port is needed. Within the domain designated in the smaller grid, the only such port is in Surigao City. In order to estimate the transit distance and time for a marine operation, as well as the likely MetOcean conditions encountered, it is necessary to designate an efficient route to site.

Dijkstra's Algorithm (DA) has been utilised to find the shortest weighted path between two valid points on the grid. In this instance, valid criteria are designated as a) not land, and b) deep enough to transit through (5m depth). The weighting, or mobility of the DA is the ease with which the algorithm will progress to the next point. Depth is used as a mobility parameter to ensure the vessel keeps to a shallow and typically sheltered route. It is utilised here to make deeper water less favourable, thus mimicking a realistic route from port to site, where a vessel will transit adjacent to the coastline where possible (Figure 5).

At each grid cell node along the algorithm path, the flow speed, wind speed and significant wave height were output for every hour of the simulation. The probability of the transit limits being exceeded at any single node along the transit route, and the operational limits exceeded at the deployment site node, can then be estimated.

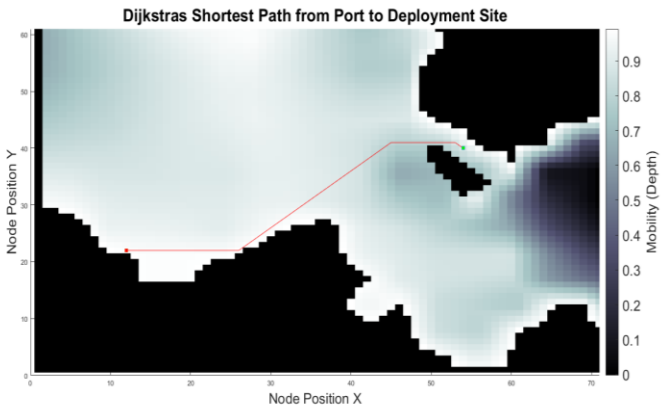

Figure 5. Dijkstra's Shortest Path Algorithm

2) Vessel Characteristics: In order to calculate an approximation for weather window occurrences and durations, it is necessary to input these transit limits and other operational constraints into the model. These primarily take the form of safety and equipment limitations for the vessel during the transit to and from site, and during an operation.

Table 1 shows constraints for three different types of marine operation, based on SME operational experience with work boats and marine contractors. These values were used to conduct the weather window assessment using the method described. However, due to the sheltered nature of the site and the use of a relatively calm month for analysis, though the method worked the results did not highlight the impact of this research. As such hypothetical constraints were applied to operation, to accentuate the effectiveness of this model. The values in brackets indicate where harsher constraints than those typically used were implemented into the model. This was to provide proof of the Weibull Persistence method in the event of especially calm conditions.

It is assumed that the cable laying is required to be completed in one operation and will follow the DA shortest path to site for ease of comparison. In reality it could be performed in multiple operations and would potentially make landfall sooner depending on grid connection options.

The DA shortest path is deemed to be identical for the transit to and from site, and the time for this crossing is calculated as a function of the vessel speed and distance. The impacts of MetOcean conditions on transit time (travelling against flow/waves) is not accounted for at this juncture but is planned for future iterations. The length of each task is deemed to be the required weather window length for each part of the operation. Note that when towing PLAT-I or during the cable laying operations, the MetOcean restrictions are more stringent than the return journey to port as the constraints are driven by the tidal platform, rather than those of the installation vessel.

Table 1. Operational and Vessel Constraints

Installation Operational Constraints

Limiting Parameter	Transit to Site	Operation	Transit to Port
Tidal Flow Speed (m/s)	1	1	2
Wind Speed (m/s)	15 (7.5)	15 (7.5)	20
Significant Wave Height (m)	1 (0.25)	1 (0.25)	2
Vessel Maximum Speed (m/s)	2	-	3
Distance (m)	8800	-	8800
Total Length of Task (hours)	1.22	4	0.81
Total Operation Length (hours)		**6.04**	

Maintenance Operational Constraints

Limiting Parameter	Transit to Site	Operation	Transit to Port
Tidal Flow Speed (m/s)	2	1	2
Wind Speed (m/s)	15	15 (7.5)	20
Significant Wave Height (m)	2	1 (0.25)	2
Vessel Maximum Speed (m/s)	3	-	3
Distance (m)	8800	-	8800
Total Length of Task (hours)	0.81	2	0.81
Total Operation Length (hours)		**3.63**	

Cabling Laying Operational Constraints

Limiting Parameter	Transit to Site	Operation	Transit to Port
Tidal Flow Speed (m/s)	1	1	2
Wind Speed (m/s)	15 (7.5)	15 (7.5)	20
Significant Wave Height (m)	1 (0.25)	1 (0.25)	2
Vessel Maximum Speed (m/s)	2	-	3
Distance (m)	8800	-	8800
Total Length of Task (hours)	1.22	1	0.81
Total Operation Length (hours)		**3.04**	

G. Operational Windows

1) Weibull Probability of Exceedance: With time-varying MetOcean parameter data at each point along the transit route, it is possible to calculate the probability of an operational threshold being exceeded at any point during the journey, according to a Weibull Persistence Method (14,15). The Weibull distribution was chosen because of its flexibility and applicability to parameters that may follow different distribution shapes. By applying a Weibull Fit to the probability of exceedance of the MetOcean data, it is possible to identify the shape (k), scale (b) and location (X_0) parameters. The k parameter alters the shape of the distribution, such that it could take on the appearance of a bell curve, or exponentially tend towards zero or one. The scale parameter b is similar to a peak enhancement factor, focusing the density of the probability distribution into a smaller area. Finally, the location parameter shifts the distribution along the x-axis. It is defaulted to 0 and is only altered to provide a better fit to the raw probability of exceedance data.

Having identified the Weibull Parameters, the Weibull Probability of Exceedance (P_W) can then be calculated (Equation 1).

$$P_W(M > M_{Acc}) = \mathrm{e}^{\left(-\left(\frac{\mathrm{M_{Acc}}-\mathrm{X_0}}{b}\right)^k\right)} \qquad \text{Equation 1}$$

Where M is a MetOcean parameter such as V, W_S or H_S and M_{Acc} is the threshold operational limit for that parameter (Table 1).

2) Average Weather Window Length: From the Weibull Probability of Exceedance, it is possible to calculate the average length of an accessible weather window (τ_{Acc}) with designated operational constraints (Equation 2).

$$\tau_{\mathrm{Acc}} = P_W(M > M_{Acc}).\frac{D}{N_\omega} \qquad \text{Equation 2}$$

Where D is the duration of the time frame (in this case 720 hours in the month), and N_ω is the number of weather windows within the time frame (if a threshold operational limit was only exceeded twice separately during a month, the N_ω value would be three).

3) Probability of Persistence: The probability that an accessible weather window will persist for a (natural log normalised) required duration (X_i) can be calculated using Equation 3:

$$P(X_i > X_{Acc}) = \mathrm{e}^{(-C_{Acc}(X_{Acc})^{\alpha_{Acc}})} \qquad \text{Equation 3}$$

Where C_{Acc} is occurrence of accessible conditions as derived from the distribution shape (Equation 4) and α_{Acc} is the relationship between the mean MetOcean value $\bar{M}$ and the threshold operation value (Equation 5), assuming a linear correlation characteristic [(16)].

$$C_{Acc} = \left[\Gamma\left(1 + \frac{1}{\alpha_{Acc}}\right)\right]^{\alpha_{Acc}} \qquad \text{Equation 4}$$

$$\alpha_{Acc} = 0.267\gamma\left(\frac{M_{Acc}}{\bar{M}}\right)^{-0.4} \qquad \text{Equation 5}$$

The γ coefficient (Equation 6) and $\bar{M}$ (Equation 7) are both derived from the Weibull distribution shape, scale and location parameters.

$$\gamma = k + \frac{1.8X_0}{\bar{M}-X_0} \qquad \text{Equation 6}$$

$$\bar{M} = b\Gamma\left(1 + \frac{1}{k}\right) + X_0 \qquad \text{Equation 7}$$

4) Probability of Weather Window Occurrence: Combining the probabilities of Weibull Exceedance and Persistence allows for a calculation of the occurrence of a weather window with both specified MetOcean limits and required duration (Equation 8).

$$P(T > \tau_{\mathrm{Acc}}) = P(X_i > X_{Acc}).P_W(M > M_{Acc}) \quad \text{Equation 8}$$

5) Access and Waiting Hours: The Weibull distribution can be utilised to not only estimate the likelihood of a weather window occurring, but also the number of access hours (N_{Acc}) in a given duration that such windows will occur for (Equation 9), and how long it is likely that an operation will have to wait (N_{Wait}) before a weather window occurs (Equation 10).

$$N_{Acc} = \mathrm{D}.P(T > \tau_{\mathrm{Acc}}) \quad \text{Equation 9}$$

$$N_{Wait} = \frac{(\mathrm{D}-(N_{Acc}.\tau_{Acc}))}{N_{Acc}} \quad \text{Equation 10}$$

The Weibull persistence method is seen to be well suited for this application, due to its relative computational simplicity compared to time-based methods [(16)]. The equations described here can be performed quickly over a large number of grid points, without needing to iterate through the thousands of generated time series for different operation start times.

III. Results

A. Weibull Persistence Method

Figure 6, Figure 7 and Figure 8 are examples of the sensitivity of weather windows to each of the MetOcean parameters (V, W_S, H_S) and the required length of the operation. In all figures, it is seen that increasing the operational limit and decreasing the required window length increases the number of access hours per month.

The different graph shapes and steepness infer much about each parameter. Flow velocity constrains the number of access hours, even when high V operational limits are set. The main contributor is clearly the length of the required operation. If it is under two hours then the number of hours available within the month increases dramatically due to the semi-diurnal nature of the tide at the Rasa strait site.

Compare this to the wind and wave figures, which follow a much steeper gradient with increasing operation time requirement. Keeping the operational length low is still seen to be beneficial, but it is only when the MetOcean operational limit is set to be very low that the length requirement becomes constraining. For example, if the required operational window is set to only one hour (favourable) but a H_S limit of <0.15m is applied, then a weather window will simply not occur. At higher W_S or H_S, the required operational length again becomes the dominant factor.

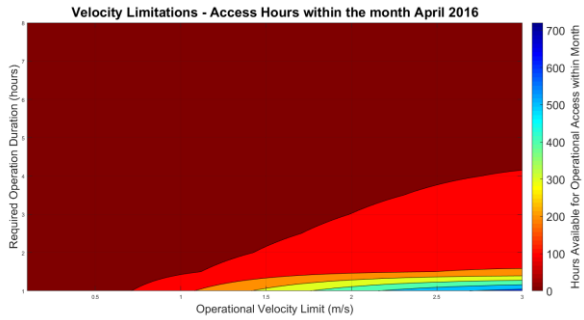

Figure 6. Access Hours accounting for velocity operational limitations

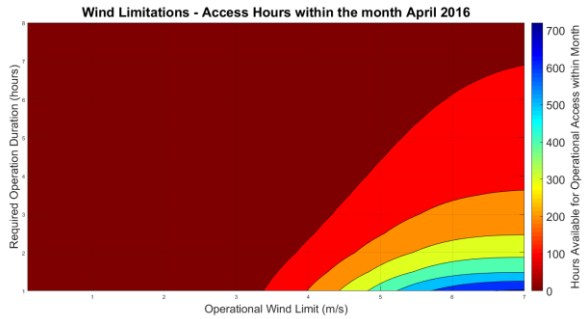

Figure 7. Access Hours accounting for wind speed operational limitations

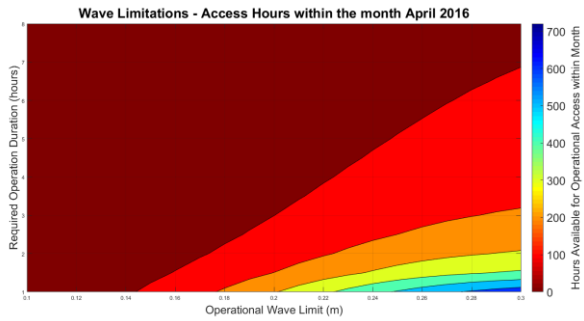

Figure 8. Access Hours accounting for wave height operational limitations

Figure 9, Figure 10 and Figure 11 show the likely number of waiting hours per month for the required weather window length and MetOcean limitation.

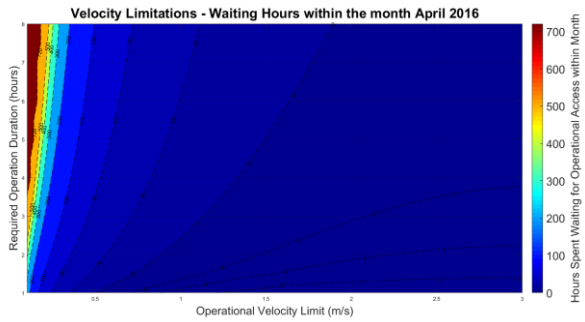

Figure 9. Waiting Hours accounting for velocity operational limitations

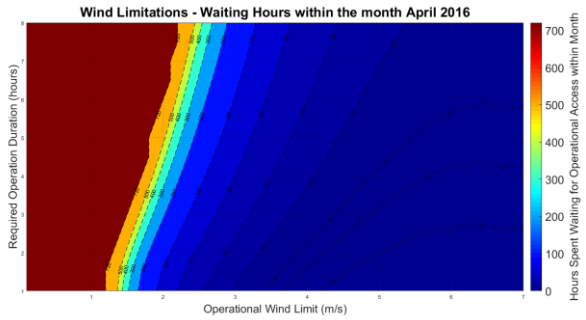

Figure 10. Waiting Hours accounting for wind speed operational limitations

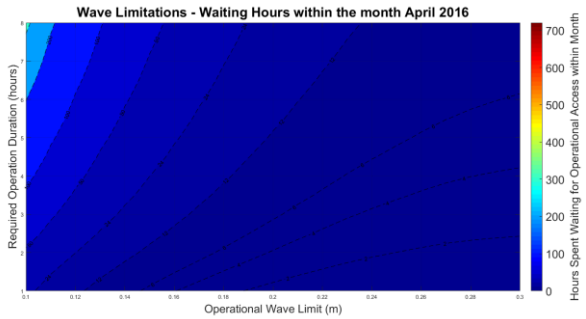

Figure 11. Waiting Hours accounting for H_S operational limitations

If a velocity limitation of >1.5m/s is utilised, then the operation will rarely need to wait longer than one day because high flow speeds will not persist for long except during spring tides. Setting an especially high velocity limit reduces the likely waiting time to almost zero.

Contrast this to the wind resource which implies that an operation will be waiting for the entire month (720 hours) if the wind limit is set below 1m/s. However, there is also a very rapid transition towards low waiting times, implying that wind speeds rarely exceed 3m/s at this location. This is confirmed by analysis of the DHI wind data, thus the results are representative.

The wind and especially wave plots are characteristic of a parameter that changes rapidly and dynamically. The majority of occurrences are low and calm, and do not impact upon the waiting time, even if the required operational length is long. However, the data sets are also clearly prone to occasional extreme, or higher magnitude events. This means that statistically, the likelihood of waiting long for a weather window is low, but the likely number of access hours within a month is also relatively low. The rare events which exceed the operational thresholds cannot be ignored by the persistence statistics and reduce the overall amount of access time within the month.

Note also that the Weibull persistence statistics are unable to make predictions for data which is not present within the distribution. At no point along the DA shortest path route do waves exceed 0.5m, and therefore attempting to account for the occurrence of such waves is not possible. It is assumed here that if an operational limit is set so high as to be above the maximum value that occurred within the data set, then the amount of access hours is set to be the full duration (720 within a month) and the number of waiting hours is set to zero.

Because the wind and wave conditions that occur within the model domain are below the operational limits typically utilised by SME, the limits were adjusted to the values given in brackets in Table 1 in order to show the potential impacts of the MetOcean parameters on access/waiting hours and prove the viability of the statistical methods utilised here. In the future, other potentially more energetic sites can be explored using the same method, but with the limits altered to reflect more tolerant O&M constraints.

IV. Case Study

The limitations and durations of three common marine operations (Table 1) were input into the Weibull persistence statistics model, and the likely access and waiting hours for each aspect of the three marine operations were output.

A. Installation Operation

The first case study investigated was an Installation operation. Figure 12 shows the access hours for each aspect of the operation for each node, or position, along the DA shortest path route (Figure 5).

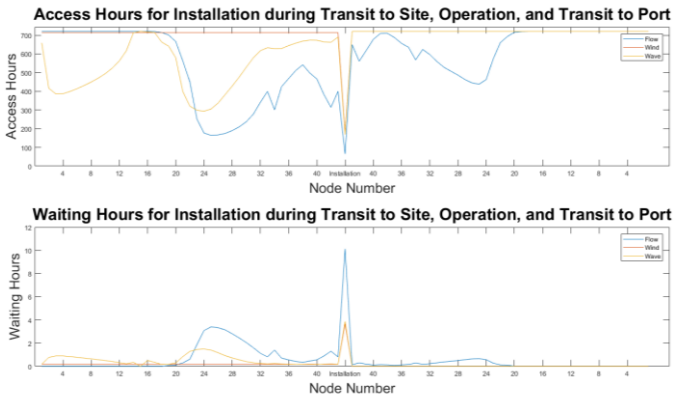

Figure 12. Access and Waiting Hours during an Installation Operation

Towing a PLAT-I to site would require relatively calm MetOcean conditions. The actual installation would occur over a 4h period requiring calm conditions for the duration, and finally the installation vessel would return to shore with only minor restrictions applied during the crossing.

Flow is shown to be constraining in terms of access and waiting hours at three key instances during the operation. The first is the deepest section of the channel during transit to site, node 24, where the highest modelled flow speeds are observed. The short 1h window is likely to require a relatively long, 4h period of waiting, implying that the vessel must only wait for a slack period for transit to site. The second instance is the return journey to port, where a similar pattern is observed, but with lessened impact on access hours due to relaxed operational limits. The waiting time is seen to be very low, implying that the vessel isn't even required to wait for a slack period to return to port. Waves are seen to limit the number of access hours at similar locations along the route (node positions 24 & 25). This location is deep and exposed and is likely to see the highest

waves due to the ENE prevailing winds at the modelled time of year. The nature of the wave distribution implies that waiting time will not be long for this very short transit window, but that the limit is exceeded relatively frequently (41% access time).

Wind is not seen to be constraining in terms of access hours at any point during transit, to or from site, but is seen to be a limiting factor during the installation operation itself. This is interesting, because it shows that even with relaxed operational limits, the duration of the operation begins to be a factor. This is true at the third key instance not just for wind, but for all three MetOcean parameters when on site. Requiring 4h of low flow for the installation operation reduces the number of access hours to just 9%, implying that this operation could only realistically be performed in neaps to ensure success. The waiting hours reflect this, in that it is likely that an operation will have to be postponed by at least 11 hours (or practically 1 working day) on any given day to ensure that 4h at the required flow speed limit are found. Similarly, wind and wave both see a reduction in access hours down to approximately 24% during the installation on site.

The Installation part of the operation is clearly the most limiting, due to its relatively stringent operational limitations and the long length of time these limitations must not be exceeded. This suggests that reducing operation times will significantly benefit the likelihood of success, and therefore cost, of a marine operation.

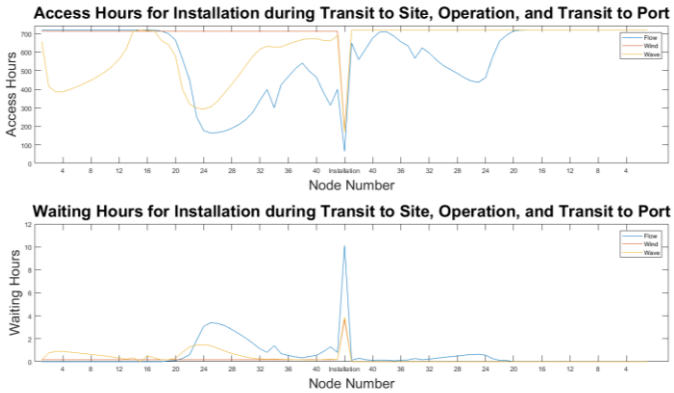

Figure 13. Access & Waiting Hours during an Installation Operation

B. Maintenance Operation

Similar results can be observed during the Maintenance operation (Figure 13) Low flow speeds must be observed for 2h during the maintenance task itself. This condition persisting for just 2h leads to only 14% of the month being available for the operation and a likelihood of 6h of waiting for the flow window. The strict wind and wave limitations during the operation on site also lead to access being limited to 51% and 44% respectively. However, the vast majority of wind and wave data at this location are relatively low in magnitude and only exceed the operational limit intermittently. This, in conjunction with the short length of the operation, means that only 2h of waiting is likely for the 2h of actual maintenance.

Contrast this to the journey to and from site, where these limitations are removed due to a lessened safety requirement during the transportation of personnel compared to the operation itself. Wave and wind are not likely to cause any loss of access to and from site, and no waiting for a window is likely to occur. Only flow provides a limit to access, with 61% of hours in the month being accessible and only 1h of waiting time expected. Essentially this portion of the operation is likely to go ahead as long as the vessel is not sent out during the peak of tide flow conditions. As with the Installation, the Maintenance part of operation is clearly the most limiting, due to its relatively strict operational limitations, but also the length of time these limitations must not be exceeded for.

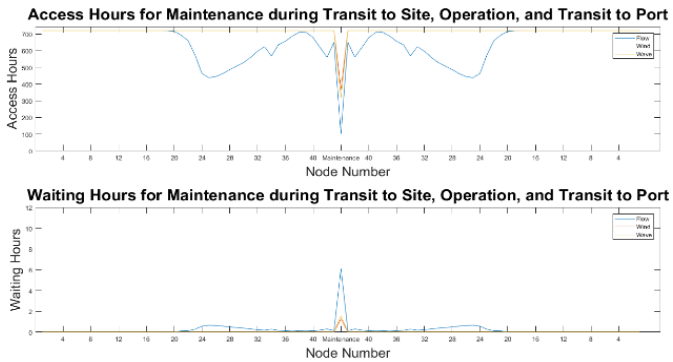

Figure 14. Access & Waiting Hours during a Maintenance Operation

C. Cable Laying Operation

Finally, a slightly different operation examined is that of cable laying (Figure 14). The cable laying aspect of the operation occurs during the journey to site, and very little time is spent on station at any one node. Each of the three aspects of the operation are approximately 1h, meaning that none of the conditions are required to persist for longer than 1h. This means that the cable laying portion of the operation, while slower than a regular transit to site, isn't any less constraining in terms of persistence than a journey to site during Installation. This again highlights the model sensitivity to persistence or required duration of a weather window. If the transit distance and therefore time were longer, then the access and waiting hours would become far less favourable. Similarly, if the vessels maximum speed was decreased or problems occurred with the cable laying such that it had to be done more slowly, the likelihood of decreased access hours, longer waiting time and therefore operational cancelation would drastically increase.

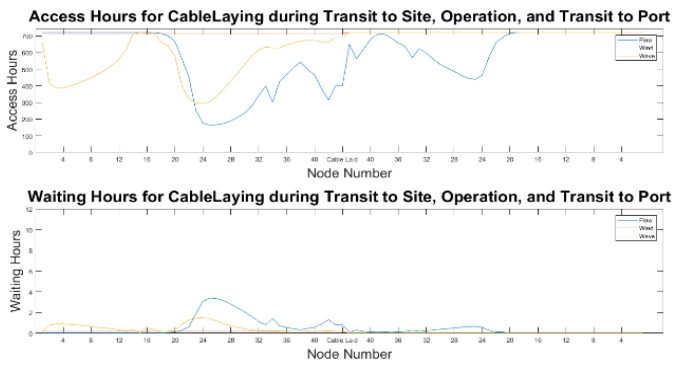

Figure 15. Access & Waiting Hours during a Cable Laying Operation

D. Discussion

The results as discussed are summarised in Table 2, which shows the number access/waiting of hours and percentage of the available time in the month.

The worst-case node for each aspect of the operation is the value used in Table 2 (the minimum access and maximum waiting time along the route). This assumption is pessimistic, in that it dictates that all points along the route have the conditions of the least favourable point. However, this assumption is reflective of reality. An operation would not go ahead without a forecasted weather window longer than the time required.

It is worth noting here that daylight hours and other practical limitations are not yet taken into account, so the actual number of available hours is likely to be even lower and waiting time for these access windows considerably longer.

Table 2. MetOcean induced Access and Waiting Hours

Installation Operational Access and Waiting Hours

Limiting Parameter		Transit to Site	Operation	Transit to Port
Access Hours	Tidal Flow Speed	164 (23%)	65 (9%)	438 (61%)
	Wind Speed	720 (100%)	168 (24%)	720 (100%)
	Significant Wave Height	294 (41%)	168 (24%)	720 (100%)
Waiting Hours	Tidal Flow Speed	4	11	1
	Wind Speed	0	4	0
	Significant Wave Height	2	4	0

Maintenance Operational Constraints

Limiting Parameter		Transit to Site	Operation	Transit to Port
Access Hours	Tidal Flow Speed	438 (61%)	102 (14%)	438 (61%)
	Wind Speed	720 (100%)	370 (51%)	720 (100%)
	Significant Wave Height	720 (100%)	319 (44%)	720 (100%)
Waiting Hours	Tidal Flow Speed	1	6	1
	Wind Speed	0	2	0
	Significant Wave Height	0	2	0

Cabling Laying Operational Constraints

Limiting Parameter		Transit to Site	Operation	Transit to Port
Access Hours	Tidal Flow Speed	164 (23%)	438 (61%)	438 (61%)
	Wind Speed	720 (100%)	720 (100%)	720 (100%)
	Significant Wave Height	294 (41%)	720 (100%)	720 (100%)
Waiting Hours	Tidal Flow Speed	4	1	1
	Wind Speed	0	0	0
	Significant Wave Height	2	0	0

In all operation cases, flow is seen to be the most constraining factor, both in transit and during operations. However, it is also the only parameter that can be predicted with a high degree of accuracy. Through harmonic analysis of even just a month of data, it is possible to identify the approximate timings of springs and neaps years in advance [(17)]. The access hours relating to flow limitations that occur within one month will be grouped into the neap tide period. When considering the planning of when an operation should occur a frequency approach is not ideal for the prediction of access windows and the waiting hours reflect this. Even if the operational limits are adjusted to be high (3m/s) then the waiting time alters very little. This is because the flow will follow a 6-12h semi-diurnal regime, and it is extremely likely (even during neaps) that the flow will exceed the operational limit at some point during this cycle. This means that practically for operational planning, the required operational length is the more constraining factor in terms of waiting hours and potential cancellations, as when the access hours occur can be predicted with high certainty.

The frequency approach remains a strong indicator of how constraining the tide is in terms of number of available access and waiting hours, and thus is highly useful for a first pass assessment of a location's suitability and its sensitivity to operational limitations. Assuming tidal prediction can be achieved, and that the neap period can be identified, then the duration of the Weibull persistence can be adjusted to be just the neap period. The constraining factors to operational planning then become just the wind and waves.

In this study, wind and wave cannot be treated independently as the waves are directly driven by the wind input. The only waves represented in this model are those locally generated and therefore when calculating a probability of overall access hours due to multiple constraining parameters only the least favourable of the wind or wave probabilities of weather window should be used. For all examples considered waves are seen to be more constraining in terms of access and waiting hours than wind. Waves are only constraining to transit when in the deepest most exposed areas of the channel, and when a vessel is forced to remain on station for an extended period, such as the Installation operation.

This implies that decreasing required operational window length increases the number of access hours and has a significant positive impact on the waiting hours. With the exception of very low operational limits, it is the window length that drives waiting time. Increasing the H_S limit means that more conditions can be operated in, and shortening the required window means that the sporadic occurrence of higher waves has a lessened impact on operational planning, as they are less likely to occur during shorter operations.

It would be necessary to discern swell waves from those locally generated as it is possible that the wind could theoretically be a constraining factor while the waves are not, and vice versa. However, discerning swells from local waves based on their direction and form has only been achieved with very long datasets [(18)]. It is unlikely that any meaningful results could be discerned from a month of data, especially

when the wind directly drives the generated wave data and does not vary spatially.

V. Further Work

The next stage of this work will focus on increasing the model duration and applying the model at multiple locations. Currently, only 1 month of data has been modelled due to computational and time constraints but a full year is desirable to account for potential seasonality. This would not only allow greater understanding of the MetOcean conditions at Rasa Island but would also enable operational planning to be concentrated on calmer months, and the impact of unplanned maintenance during less favourable months to be investigated.

With costing applied, it will also be possible to incorporate LCoE into the selection of the route to and from site. With a more thorough understanding of the site parameters, it may prove to be operationally beneficial to take a longer path to site that avoids areas of high flow and inclement weather, rather than the most geographically direct route.

The next immediate step will be to apply cost metrics to the number of accessible and waiting hours. This will involve applying the daily flat costs of vessels and staff, as well as researching the cost implications of operational cancellation and keeping contracted vessels on standby. Over a project lifetime, the implications of these MetOcean induced O&M costs can be assessed in terms of LCoE.

VI. Conclusions

This paper has examined the impact of MetOcean conditions on weather window availability and duration. Understanding a site at the initial planning stage is essential to prevent the deployment of a tidal energy device in an area with economically unviable lifetime costs, such as O&M.

The method proved to be computationally efficient and easy to implement. The results are shown to be highly informative to the operational planning of tidal energy deployments. The constraining impact of the tide in terms of access hours has been quantified, and the importance of minimising operational length for decreased waiting hours has been identified.

The impact of requiring calmer wind or wave conditions to persist for an extended period has also been quantified in terms of likely access and waiting hours. The clear implication for all case study operations investigated was that increasing the operational MetOcean limitation increases the number of access hours, but operational window length has greater impact. Even relatively relaxed MetOcean conditions are likely to be exceeded if the duration of the operation is too lengthy.

Incorporating these MetOcean impacts early on in the planning stage will give a better estimation of project lifetime costs and ensure that these costs are factored into the site selection methodology.

Acknowledgments

The authors wish to acknowledge the companies and funding bodies who have enabled the collection and interrogation of the data used in this paper, as well as allowing for its publication. Sustainable Marine Energy Ltd. and SCHOTTEL Hydro have provided invaluable case study data and expertise. The software developers at Delft and DHI have provided invaluable modelling tools and data. The Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE) and its contributing funding bodies have provided the authors with the facilities and financial backing to produce this paper.

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