A Methodology for Near-Shore Wave Resource Assessment

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Abstract

Accurate estimates of the available wave power resource are essential for the commercialisation of wave energy converters. Wave resource assessment is needed for site selection, power generation forecasting, research and development and market valuation, all of which have different accuracy requirements.

For this reason, Aquamarine Power is working towards creating a standardised method of wave resource modelling and calculation, specifically tailored towards Aquamarine Power's Oyster technology. The methodology outlined in this paper provides a framework for providing resource assessments which are fit for purpose, whilst making the best use of computational and personnel resources.

A four tier assessment system has been developed in which increasingly detailed modelling and calculations provide increasingly accurate estimations of the exploitable wave resource, and the predicted energy generation at a site.

Wave models developed in DHI's MIKE21 spectral waves software, are used to provide time varying wave conditions across the frequency and directional spectrum. A wave resource calculation methodology has been developed to interpret modelled results using a combination of linear, Stokes and Cnoidal wave theories, and results from tank testing of scale wave energy converters.

Together, the wave modelling and calculation methods provide estimates of the raw wave resource present at a site, and the forecast power produced at that site by a wave energy converter. This provides information which is essential to the development of the wave power industry.

Keywords: capacity factor, resource assessment, wave power

1. Introduction

As the wave power industry develops, there is a need to describe the wave resource available at different locations, in order to determine the energy available for a wave energy converter to capture. Wave resource assessment inputs into a number of functions, including; valuing the market available for wave energy converters, specifically Aquamarine Power's Oyster device; selecting sites for development and providing energy forecasts for sites in development; optimally positioning devices within a site; and informing the design of future devices.

Each requirement for resource assessment has a different specification in terms of the information needed and the accuracy required. In addition to quantifying the average wave power available, it is important to be able to estimate the time varying wave power at the predominant wave frequency, and the frequency and directional spectral characteristics of the waves. Furthermore, it is necessary to understand how the Oyster device performs in varying wave conditions, based on results of tank testing of scale models. This informs both projections of future energy generation at potential sites, and the potential available for future devices to exploit. As computing and personnel resources are highly valuable, it is also necessary to carry out resource assessment in the most efficient way.

To this end, Aquamarine Power is working towards creating a "Best Practice" method of wave resource modelling and calculation, specific to the Oyster device. A four tier system has been developed to provide increasingly accurate estimations of the available wave resource, from high level global estimates, to highly detailed, locally calibrated and verified results.

2. Background

Aquamarine Power is developing the Oyster wave energy convertor, a bottom hinged flap which is fixed to the sea-bed. Power is generated as the flap is forced back and forwards by the surge motion of the waves. Oyster is located in the near-shore environment at approximately 10-15m water depth.

The first demonstration scale Oyster device was deployed at the European Marine Energy Centre (EMEC) in Orkney, during summer 2009. The next generation of Oyster devices is currently under development, and they will ultimately be deployed in clusters, as commercial wave farms.

Understanding the exploitable wave resource is crucial to the commercialisation of wave energy converters, as energy projections feed directly into the selection of sites for development.

3. Resource Assessment Classification

Wave power resource estimates are classified according to the level of detail involved in the resource assessment process. As the highest level of assessment is very costly in terms of computing requirements and data collection, it is reserved for sites which are under development or have a high probability of being developed in the near future. The wave resource at less critical sites is estimated in less detail, with compromises made in the spatial resolution of the wave modelling, and the accuracy of model input data.

Levels A to C estimates are calculated using the results from in-house modelling, while level D estimates are calculated from external global or regional models such as the National Oceanographic and Atmospheric Administration Wave Watch III (NOAA WWIII) models.

The four levels of resource assessment are summarised in Table 1, and defined in more detail in the following descriptions. Level A represents the most detailed study, and Level D the least detailed.

	A	B	C	D
Model Type	MIKE 21	MIKE 21	MIKE 21	External
Coastal Resolution	<50m	<100m	<2 km	<0.5°
Boundary Wave Data	Fully spectral	Fully spectral	Parameterised	--
Calibration	Yes	No	No	No
Predominant wave power theory	5th order Stokes/ Cnoidal	Linear	Linear	Linear

Table 1: Summary to key features of resource assessment classification levels.

A. Modelled in house, with a coastal resolution not exceeding 50m, and bathymetric data of at least this resolution. Wave boundary forcings from fully spectral buoys, or fully spectral modelled data with scatter indexes not exceeding 0.3. Calibration and verification from Acoustic Doppler Current Profilers (ADCPs), spaced not more than 2 km from areas of interest, deployed for at least 1 year.

B. Modelled in-house, with a coastal resolution not exceeding 100m, with bathymetric data along depth contours of not more than 10m intervals in depths <200m. Wave boundary data as for Level A, but no requirement for ADCP verification.

C. Modelled in-house, with a coastal resolution not exceeding 2km, and bathymetric data along depth contours of not more than 10m intervals in depths <200m. Wave boundary forcings may be from parameterised global/regional models with spatial resolution not less than 0.5° if spectral data is not available.

D. Resource assessment using the results of external global/regional models.

All levels of resource assessment provide estimates of the raw wave resource available, and the expected Oyster power generation at a site. The raw resource is typically described in terms of the predominant wave power per metre of coastline, while the Oyster power generation is given as a capacity factor (factor 0 – 1 of the total installed electrical capacity).

The capacity factor is used both as a screening parameter for site selection, and to calculate the forecast power production at a site. Power production is estimated by considering the length of coastline above the capacity factor cut off value, the average capacity factor in that region, and the density of Oyster devices which may be installed.

4. Wave Modelling

All in-house models are developed using the established MIKE21 software platform developed, supported and maintained by DHI (former Danish Hydraulic Institute). Models (MIKE21 Spectral Waves FM) are run in either fully spectral mode, where the wave action conservation equation [1]-[2] is solved, or in directionally decoupled mode, where the wave action conservation equation is parameterized in the frequency domain.

While the fully spectral mode provides results of the full directional and frequency spectrum, it is extremely computationally intensive. The directionally decoupled mode provides results at the predominant wave frequency, with an assumed spectral shape. For many near-shore applications, this is an acceptable compromise, particularly since the majority of power production from Aquamarine Power's Oyster device comes from long period swell waves. Directionally decoupled mode is typically used as the last stage in Level A modelling, where the results from a fully spectral Level C model are used as boundary forcings, and a directionally decoupled model is run over a small spatial scale, to provide high resolution results for the last step into shore.

All modelling is based around a triangular flexible mesh, which allows the spatial resolution to be varied across the model domain. Each mesh cell has a depth value associated with it, which is interpolated from bathymetric data. Calculating wave conditions in deep water is much more computationally intensive than for shallow water. Consequently, cell sizes may be increased in deep water and reduced in shallow water, which reduces model run time without losing resolution in coastal areas. An example of a flexible mesh is shown in Figure 1. Areas of particular interest have smaller cell sizes to increase the accuracy of results in those regions.

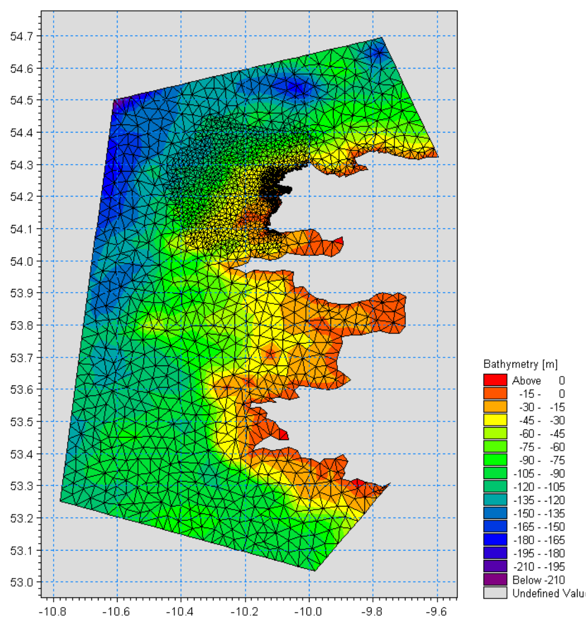

Figure 1: An example of a flexible mesh. Cell size can be increased in areas of interest. Each cell has an associate water depth which is illustrated by colours.

A model run is ideally required to span ten years or more. However, where input data is not available for this length of time, a suitability study may be conducted to assess whether a shorter model run is acceptable.

Where data is available, the model should be calibrated and verified against measured wave conditions at the site. This involves adjusting certain model parameters until a good agreement between measured and modeled results is reached. Aquamarine Power requires that calibration and verification must be carried out for Level A models, with ADCPs deployed at 2km intervals in the area of interest. For a good calibration, the scatter index (ratio of standard deviation of difference to mean of measurements) for mean wave period (T_M) and significant wave height (H_S) must not exceed 0.3.

5. Wave Power Calculation

There are several ways in which wave power can be described. The predicted power generated by the Oyster device is of primary interest to Aquamarine Power, as this determines the economic feasibility of potential sites.

It is also important to understand the raw resource at a site, which can be calculated as either the total wave power – the power contained across all frequencies and directions, or the predominant wave power – the power contained at the peak wave frequency. Knowledge of the raw wave resource available at sites around the world helps focus the development of future devices to maximise the potential power production at a wide range of sites.

5.1. Oyster Power Generation

The predicted hydrodynamic and electrical power, specific to the Oyster device, can be calculated for potential sites. This is calculated using both the modelled wave climate, and the results from tank testing of a scale model Oyster device. Estimating the electrical power output also requires the modeled performance of the electrical generating system, which gives the expected losses from the hydrodynamic power to the electrical output.

Tank testing provides the hydrodynamic power captured by the device at a number of sea states, which can be interpolated across the full range of significant wave heights and wave periods to generate the hydrodynamic Oyster power curve. Testing is carried out in polychromatic simulated seas, with the Bretschneider spectral shape.

The electrical losses are then applied to give the electrical power curve, which is used as a lookup table to predict the Oyster power generation, given wave conditions at a particular site. This power curve is subject to continual revision, as the design is updated and improved. The Oyster II power curve is shown in Figure 2.

The “flat topped” shape of the power curve is caused by the maximum capacity of the generator. Any hydrodynamic power over the maximum capacity cannot be utilized.

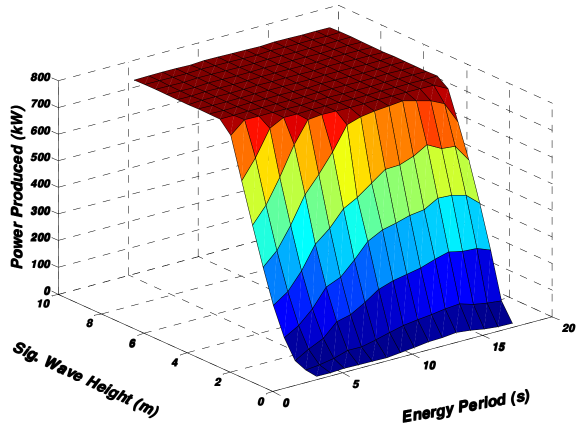

Figure 2: The Oyster power curve provides a lookup table of the Oyster power production for a particular significant wave height and energy period.

The Oyster power curve provides the estimated power generated by waves approaching the flap head on. As the flap is fixed to the sea bed, it cannot adjust to varying wave directions, and there is a consequent reduction in accessible hydrodynamic power as the difference between the wave direction and flap orientation increases. The directional reduction factor is given by Equation 1, where n is specific to the design of Oyster.

$$directional\ reduction\ factor = cos^{n}(\theta_{Flap} - \theta_{Wave}).$$

Equation 1

Where the wave height, wave period and wave direction are known, the power curve, together with the directional reduction factor, can be used to estimate the Oyster power output at a site. Where there is wave data spanning complete years (preferably 10 years or more), the average annual output of a device may be calculated. This can be related to capacity factor by simply dividing by the maximum capacity.

5.1. Predominant Wave Power

A practical measure of the raw wave resource is the predominant wave power; the power present at the predominant frequency of the wave. As this is the frequency at which a hinged oscillator such as the Oyster device will operate, it is an extremely useful quantity. It is typically presented as an annual average value.

The predominant wave power is calculated for waves approaching from all directions, and from waves within the band of directions which the Oyster can access power from. The "cropped" wave power is also calculated, to allow for the maximum capacity of the generator (as illustrated by the "flat topped" shape to the power curve in Figure 2). Waves above the threshold value are cropped at the threshold. This provides a useful metric for the extractable power, and avoids the problem of annual averages being "pulled up" by isolated storm events, where only a small proportion of the power would actually be extractable.

For all levels of wave modelling bar Level A, the predominant wave power is calculated according to Airy (linear) wave theory [3] for intermediate water depths (0.25>depth/wave length>0.05).

For Level A modelling, the predominant wave power is calculated using a combination of fifth order Stokes and Cnoidal wave theories [4]. The most appropriate wave theory is selected by assessing the non-linearity of waves. This can be determined by calculating the Ursell number (U) [5], defined in Equation 2.

$$U = \frac{L^2 H}{d^3}$$

Equation 2

Where L is the wave length (m)
H is the wave height (m)
d is the water depth (m)

Waves with a small Ursell number (defined as <<100), are only weakly non-linear, and may be well described by Airy wave theory, although higher order Stokes theory may also be used.

Waves with a larger Ursell number should be described by either Stokes theory or Cnoidal theory. Cnoidal theory is valid where the Ursell number is greater than 26, and Stokes theory for values less than this [6].

5.2.1. Irish Case Study

To illustrate the effects of higher order theories, the wave power has been calculated for a time series using both Airy wave theory, and fifth order Stokes and Cnoidal wave theories. The time series provides modelled wave conditions for a point in 12.5m water depth at a site on the west coast of Ireland, at hourly intervals for 12 years.

Figure 3 shows the cumulous distribution of the Ursell number, calculated for each time step. This shows that 46% of the time, the Ursell number is <5, where waves are only weakly non-linear and Airy wave theory gives a good approximation. For 44% of the time, the Ursell number is between 5 and 26, and Stokes theory should be used. For the remaining 10% of the time, the Ursell number is 26, and Cnoidal theory should be used.

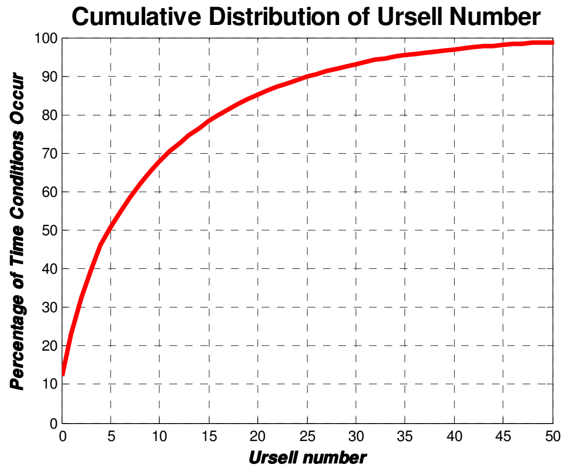

Figure 3: The cumulative distribution of Ursell number, showing the percentage of time steps which occur with Ursell number less than or equal to each value.

Table 2 shows the wave powers calculated from Airy wave theory, and a combination of Stokes and Cnoidal wave theories. Wave powers are given for omni-directional waves, and for directional waves, with the reduction in power given by Equation 1. Values are also given for the cropped power, where the powers are cropped at the wave power equivalent to the maximum capacity of the generator (as illustrated by the flat top of the power curve in Figure 2).

Wave Theory	Airy (Linear)	Stokes /Cnoidal (5^{th} order)
Omni-Directional Power (kW/m)	41.01	39.36
Directional Power (kW/m)	38.99	37.40
Omni-Directional Power (kW/m) CROPPED	26.43	26.28
Directional Power (kW/m) CROPPED	25.32	25.16

Table 2: Predominant wave powers calculated for a site 12.5m depth on the west coast of Ireland. Wave powers are calculated using both Airy wave theory (linear) and a combination of Stokes and Cnoidal wave theories (5^{th} order).

While the omni-directional wave power is 4% greater for the linear calculation than the 5^{th} order calculation, this difference decreases to 3% when the directional wave power is considered. If cropping of powers over the generator limit is included, this drops to 0.6%. This small difference between linear and 5^{th} order results provides justification for the use of Airy wave theory in Level B – D resource assessment.

5.1. Total Wave Power

The total wave power may be determined by integrating the energy density across all frequencies and directions. The total wave power is defined in Equation 3.

$$P = \rho g \int_0^\infty \int_0^{2\pi} E(f,\theta) c_g(f,\theta)\, d\theta df$$

Equation 3

Where P is the total wave power (kW/m)
ρ is the density of water (kg/m^3)
g is the gravitational acceleration (m/s^2)
E is the wave energy density (m^2/Hz/rad)
c_g is the wave group velocity
θ is direction (rad)
f is the wave frequency (Hz)

To calculate the total wave power requires fully spectral information on the wave climate, which may be from wave measurements or a fully spectral wave model. Whilst this is the theoretical raw resource available, in practice no device is currently capable of fully exploiting this quantity. Nonetheless, knowledge of the theoretical maximum wave power is important from a design perspective, to help future generations of devices maximise power generation.

6. Conclusions and Future Work

Aquamarine Power has developed a clear and logical system to assess the wave resource available at sites around the world. This fulfils a number of objectives: to assess the global wave power resource and value the potential market for the Oyster device; to provide a clear understanding of wave conditions around the world to inform future device design; to identify sites for development within the next 5 years; to optimally position devices; and to provide energy forecasts for sites in development.

The methodology outlined in the paper provides a framework for providing resource assessments which are fit for purpose whilst making the best use of computational resources. A four tier system has been developed where increasingly detailed modelling and resource calculations provide increasingly accurate resource estimates.

Moving forward, Aquamarine Power will continue to refine the resource assessment process, in particular pertaining to the wave modelling. In the near future, the input wave data sources will be examined, to assess the benefits of using higher resolution model input data from external sources. As Aquamarine Power deploys more ADCPs it will become possible to quantify the improvement in accuracy seen between different levels of modelling, which has not been possible to date due to the lack of baseline data to evaluate against.

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