# Wake Characteristics of a Natural Submerged Pinnacle and Implications for Tidal Stream Turbine Installations

Paul Evans[#1], Eli Lazarus[+2], Allan Mason-Jones[#3], Daphne O'Doherty[#4], Tim O'Doherty[#5]

[#] *Cardiff Marine Energy Research Group, School of Engineering, Cardiff University, The Parade, Cardiff, CF24 3AA, UK*

[1]Evansps3@cf.ac.uk

[3]Mason-JonesA@cardiff.ac.uk

[4]OdohertyDM@cf.ac.uk

[5]Odoherty@cf.ac.uk

[+] *School of Earth and Ocean Sciences, Cardiff University, Main Building, Park Place, Cardiff, CF10 3AT, Wales, UK*

[2]Lazarused@Cardiff.ac.uk

***Abstract*— Measurements of tidal velocities in the vicinity of natural submerged features are rare given the cost and difficulties of collecting data in these hostile environments. This has pushed much of the research to laboratory and numerical modelling studies. However, understanding how these natural features affect flow fields has important implications for tidal stream turbine (TST) deployment, particularly those pertaining to tidal turbine arrays; siting TSTs too close to one another affects their performance and creates undesirable structural loadings.**

**This paper quantifies the wake characteristics of a submerged pinnacle in a macrotidal strait, using Ramsey Sound, Wales, UK as a field site. Vessel-mounted ADCP surveys were undertaken as a set of three transects downstream of this natural pinnacle during the flood tide to examine the streamwise and cross-channel wake extents.**

**The results of this research suggest that wake recovery of submerged pinnacles is controlled by both velocity magnitude in the principal flow direction and the local bathymetry. The latter has a more significant effect on wake migration from the centreline, which is an important consideration when designing array configurations.**

***Keywords*— Tidal energy, island wake, ADCP observations, Ramsey Sound, hydrodynamics, tidal stream turbines, site assessment.**

## I. INTRODUCTION

Investigations of shallow water wakes around bluff bodies in a body of fluid of finite depth are significant for a number of environmental and geophysical applications [1]. Chen and Jirka [2] noted that there is a need for improved understanding of shallow wakes (from either submerged or surface-piercing objects) to help understand the likely circulation patterns of pollutants behind islands or headlands, as well as predicting sedimentation patterns and the accumulation of nutrients or fish habitats. For this study, understanding the wake characteristics of a natural submerged feature is considered important as it has implications for tidal energy extraction.

Flow in the vicinity of submerged obstacles has been studied extensively through laboratory experiments and numerical modelling studies. However, the characteristics of these flows are generally still poorly understood because of the complexity of 3-D unsteady flow and the sensitivity to a relatively large number of parameters, including relative submergence, Reynolds number, obstacle characteristic length scale, aspect ratio, boundary layer characteristics, and free stream turbulence ([3], [4]). Furthermore, given the importance for aspects such as the prediction of nutrients, sediments, and biological particle transport paths ([5], [6]), as well as local flushing rates whereby water remains trapped in the recirculation region downstream ([7], [8]), there have been relatively few studies examining wake characteristics of natural bathymetric features. Lueck and Mudge [9] and Kunze and Toole [10] examined turbulence in the vicinity of seamounts, Klymak and Gregg [11] investigated variable depth sills, Nash and Moum [12] focussed on a shallow water continental shelf bank, Althaus *et al*. [13] observed the interactions of large-scale tides with a deep ridge, Edwards *et al*. [14] studied sidewall ridges, and Dewey *et al*. [15] studied stratified tidal flow over an isolated submerged topographic feature. Oceanic currents are generally associated with stratified flow; the ebb and flood of a tide over coastal features adds greater complexity.

In shallower water, a number of studies have examined flow in the vicinity of coastal features. Wolanski ([7], [16]) made observations and numerically modelled the tidal flow in the vicinity of Rattray Island within the Great Barrier Reef, north-east Australia; noting that the wake eddies were subject to vertical circulations with shear zones either side of the island. Deleersnijder *et al*. [17] created a numerical model of Rattray Island and noted two counter-rotating eddies in the wake with upwelling in their centres. A number of other studies (observational and numerical) relating to shallow sea wakes have been undertaken ([5], [6], [18]-[36]).

Neill and Elliott ([31], [32]) noted that island wakes generated by obstacles of order 1000 m wide (i.e. Rattray Island, Australia) are generally characterised by two counter-rotating eddies with a central return flow, while wakes produced by islands with length scales of order 100 m (i.e. Beamer Rock, Firth of Forth; small islands in Rupert Bay, northern Quebec, Canada) [26] are generally characterised by a von Kármán vortex street with eddies shedding alternately from both sides of the island. Neill and Elliott ([31], [32]) observed and numerically modelled Beamer Rock, a 50 m wide island in the Firth of Forth. They found that the island produced a von Kármán vortex street wake, the pattern of which differed between both the ebb and flood tides, and spring/neap conditions. They also noted the formation of eddies in the lee of islands as flow separated at the boundary layer, transferring fluid subject to high vorticity within the interior of the flow, as observed by Signell and Geyer [28].

Tidal stream turbines (TSTs) differ from natural oceanic features by extracting the kinetic energy from the tidal flow, reducing the flow velocity downstream [37], as well as modify the turbulence. Immediately downstream of a device, or a submerged pinnacle, the flow reduction will be at its greatest with high shear forces at the wake boundary [37]. The wake widens and the velocity increases as downstream distance increases until wake recovery occurs. An important question that still remains unanswered is: what is the optimal TST spacing in an array to maximise power-output without compromising performance, while retaining the structural integrity of a device? This question has been partly answered experimentally ([38]-[42]) and numerically ([43], [44], [45], [46], [47], [48]), or a combination of both ([49], [50]), however, given the relative infancy of tidal stream energy exploitation, very few field-based measurements have been made.

Although the geometry of the natural bathymetric feature under investigation here is dissimilar to a TST, quantifying its wake is important as it has important implications for TST design. For instance, examining shallow wake behaviour in coastal environments provides tidal energy developers with an insight into how an artificial feature may influence the flow field. The quantification of island wakes is also important for numerical model validation.

A wake is defined as a region of non-zero vorticity downstream of an obstacle [51]. A natural or artificial obstruction creates two principal wake regions: the near and far wake. The near wake exists immediately downstream of an obstruction and experiences reduced flow and negative velocities (flow reversals). In order to conserve momentum, the transition from the near wake region to the far wake is characterised by wake expansion and mixing with the ambient flow field, resulting in the shear layer moving towards the wake centreline [52].

In 1883, Osborne Reynolds conducted experiments to investigate the transition of laminar to turbulent flow. These experiments demonstrated that turbulence was controlled by the fluid velocity, viscosity, and a length scale, and in doing so introduced the dimensionless Reynolds number ($R_e$): a measure of the ratio of inertial force (resulting from fluid acceleration) to the viscous force (due to the friction between fluid particles moving past each other) acting on a water particle [52].

The diameter Reynolds number ($Re_d$) [51] is appropriate for flow past an object because the island or object diameter will dictate the largest turbulent length scale, defined by:

$$Re_d = \frac{UD}{v} \qquad [1]$$

where $D$ is the cylinder diameter and $v$ is the kinematic viscosity of the fluid (1.14x10$^{-6}$ m$^2$s$^{-1}$ for water) [52].

## II. Case Location: Ramsey Sound

### A. Geographical and hydrodynamic setting

Connected to the Irish Sea, Ramsey Sound (Fig. 1) is a strait approximately 3 km long and 500–1600 m wide, separating Ramsey Island from the Pembrokeshire coastline near St. David's headland, Wales. Water depth in the strait is typically between 20 – 40 m below CD (where 0 m CD is approximately the level of Lowest Astronomical Tide, LAT), but reaches a maximum depth of 66 m CD within a north–south trending trench. A submerged pinnacle known as Horse Rock dominates the north-eastern quadrant of the strait. Roughly conical, this natural obstruction to flow has an estimated diameter of 100 m at its base (50 m at half its height) and is approximately 23 m higher than the seabed around it. The crest pierces the water surface and dries (according to the Admiralty Chart) at approximately +0.9 m CD during spring-tide lows. It should be noted that the data presented here has been reduced to Chart Datum so that all measurements refer to the same reference point, rather than depth below the water surface.

The area experiences a strong, semi-diurnal tidal regime with a range of approximately 1.6 – 5 m from mean neap to mean spring, and includes zones of high turbulence [53]. Charted tidal streams indicate current speeds of up to 6 knots (~ 3 ms$^{-1}$). Although the general tidal dynamics in Ramsey Sound has been known for decades, very few studies have characterised the hydrodynamics of this area, particularly the effect of Horse Rock on the tidal dynamics. The aim of this paper is therefore to address the general lack of knowledge and understanding of the influence these submerged features have on tidal flow in energetic macrotidal straits using Ramsey Sound as a field site. Although this study focuses on a single site, many potential tidal energy sites in the UK exhibit similar characteristics to Ramsey Sound, such as the Pentland Firth; a strait lying between the Scottish mainland and the Orkney islands in Scotland (with tidal currents exceeding 7 ms$^{-1}$), Yell Sound; a strait running between Yell and Shetland in Scotland [54], and Kyle Rhea; a strait of water between the Isle of Skye and the Scottish mainland, for example.

### B. Tidal stream energy extraction in Ramsey Sound

In 2011, Tidal Energy Ltd. (TEL), a UK-based commercial energy company, was granted permission to trial their DeltaStream tidal-stream turbine device (TST) [55] in Ramsey Sound (Fig. 1), estimated to have an energy potential of approximately 75 GWhyr$^{-1}$ [56]. The original 1.2 MW DeltaStream unit supported three 15 m diameter horizontal axis tidal turbines mounted on a triangular frame with the centre of the hubs set 12 m from the seabed. However, to prove the technology without overcomplicating the design, a decision was made to install a single 400 kW turbine on one of the smaller foundations, which will still greatly contribute to the energy demands of the communities in St David's [57]. The tip of DeltaStream's turbine at Top Dead Centre (TDC) will be approximately set at 30 m below CD (Chart Datum), so not to restrict boating activity [55]. The constructed prototype device is currently at Pembroke Dock, Wales, awaiting a weather and tidal window for deployment. The device is to be installed as part of a one year demonstration project to test its integrity and power-output capabilities. If successful, the device will be scaled up to full commercial scale and suitable locations identified for a turbine array.

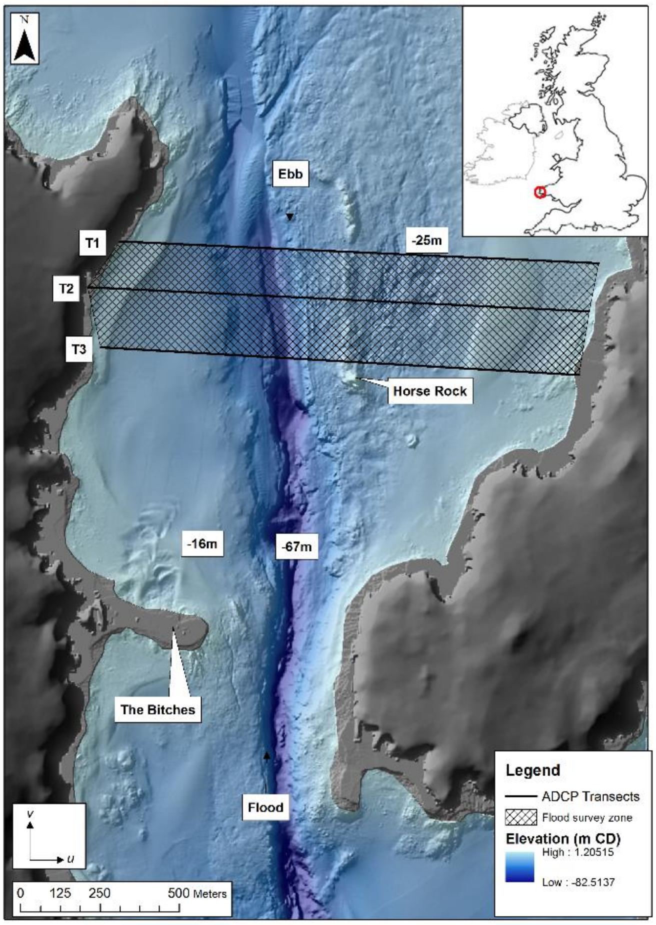


Fig. 1 Location map of Ramsey Sound, Pembrokeshire (UK). Bathymetric contours show seabed elevation. ADCP survey transects are represented by black lines.

## III. Methodology

### A. Survey equipment and design

To measure the tidal velocity data, a four-beam 600 kHz broadband Workhorse Sentinel acoustic Doppler current profiler (ADCP) unit, manufactured by Teledyne RD Instruments, was gunwhale-mounted on Cardiff University's Research Vessel, *Guiding Light*. The acoustic Doppler current profiler (ADCP) transducers were placed 1.4 m below the water surface; water column measurements presented here begin at a depth of 2.75 m. Streamwise (north-south, $v$), cross-channel (east-west, $u$), and vertical ($w$) velocity components of tidal flow were recorded at 1 Hz. Depth to the seabed was measured using the built-in bottom-tracking system, which was also used to calculate the vessel speed. Vessel position and heading data were logged using an external Coda Octopus F180 heading sensor with a horizontal accuracy of 1.5 m, along with the ADCP's self-contained tilt sensor, which has a range of ± 15° with accuracy ± 0.5°, precision ± 0.5°, and resolution ± 0.01° [58].

Surveying across the central portion of Ramsey Sound (Fig. 1) was conducted in June 2012, just prior to a peak spring tidal cycle. Flood-tide velocities were recorded in one day over a half tidal cycle at a set of three transects (T1 – T3) downstream of Horse Rock (downstream with respect to flow on the flood tide, and so sited north of the feature). No upstream transects were made because of the navigational hazard of collecting velocity data upstream of this feature. Downstream distance from Horse Rock were 50 m (T3), 250 m (T2), and 400 m (T1). The transects covered the northern portion of the Sound, encompassing the deeper north-south trending trench as well as the shallower outer margins. Each set of transects were surveyed in a continuous, five-hour circuit from one hour after slack (Slack+1) until one hour before slack (Slack+5). Although each three-transect circuit took approximately 30 minutes to complete, the simplifying assumption made here is that the data recorded during each circuit are representative of one twelfth of a given tidal cycle. Vessel transect time is a well-known limitation of vessel-based surveys relative to bottom-mounted instrumentation. However, the temporal and spatial resolution of the velocity measurements and transects employed herein are consistent with vessel-based methods used in previous studies of this type ([59], [60]).

### B. Data post-processing

Instantaneous velocity measurements ($u$, $v$, $w$) for each transect were spatially averaged with a sliding 5 m window ($\overline{u}$, $\overline{v}$, $\overline{w}$), equating to an averaging interval of approximately 5 – 10 s; a filter size significantly smaller than the width of the strait and one that still allows the hydrodynamics downstream of Horse Rock to be captured, to reduce uncertainty/standard deviation. This is consistent with the averaging approach adopted by others ([31], [59]). This post-processing step reduced the standard deviation ($\sigma$) of the velocity data from ± 0.07 $ms^{-1}$ to ± 0.04 $ms^{-1}$. Therefore, a velocity of 2 $ms^{-1}$ represents a random error of ± 2%. Many ADCPs automatically average the velocity data over 5-10 s, however, it was considered important to capture data at the maximum sampling rate (1 Hz) of the ADCP so that the data could be averaged to a user-defined value during post-processing. Increasing the averaging period further could mask important flow/eddy structures, however, there are no pre-determined rules for an appropriate averaging period as it ultimately depends on the application, i.e. longer averaging periods of circa 5-10 minutes are generally used for moored ADCP data [61] because the instrument is sampling over the same portion of the water column. However, moving platform applications require a much shorter averaging period. The vertical resolution of the data (1 m) remained unchanged to allow the velocity profiles to be determined with a meaningful resolution. Dialogue with a Field Service Supervisor at Teledyne RD Instruments (Grangier, July 2012, pers. comm.) confirmed that these averaging intervals were appropriate for this study.

### *C. Velocity analyses*

The reduction in the streamwise velocity downstream of a natural or artificial (i.e. a TST) obstruction is termed a wake. Quantifying wake recovery is useful for determining the appropriate streamwise distance between TSTs in a farm in order to ensure velocities and device-generated turbulence have recovered to an acceptable level upstream of the downstream device to ensure sufficient power-output, while avoiding unnecessary structural loading [62]. The streamwise wake recovery can be defined by the non-dimensional 'velocity deficit' [63]:

$$U_{def} = 1 - \frac{\bar{v}}{U} \qquad [3]$$

where $\bar{v}$ is the mean streamwise velocity and $U$ is the undisturbed free-stream, an approach velocity. A $U_{def}$ value of 0 signifies that the wake velocity has recovered back to free-stream, while a $U_{def}$ of 0.25 is equivalent to 75% of the free-stream velocity. Translating this approach to "real" velocity data in the vicinity of natural obstructions, such as Horse Rock is challenging given the varying bathymetry and velocities within the Sound. Determining the free-stream velocity ($U$) and $U_{def}$ is therefore difficult. This issue was also observed by Neill and Elliott [31]. Accurately quantifying the free-stream velocity without any influence from this pinnacle would either require transects to be run simultaneously both upstream and downstream of Horse Rock using two vessels, or through the deployment of moored ADCPs far enough upstream to measure the undisturbed velocities but close enough to determine the free-stream velocity without being significantly affected by the bathymetry. The former was not possible due to the navigational hazards associated with surveying upstream of this pinnacle while the latter would require one or ideally more seabed-mounted ADCPs spaced evenly across the Sound in order to determine the free-stream velocity.

It was concluded that the only practical way of examining the wake created by Horse Rock was to use a reference velocity ($U_{ref}$); instead of the free-stream velocity ($U$), given by $\bar{v}/U_{ref}$: This reference velocity was taken at the half-height of Horse Rock at the same location along T3 to the east of Horse Rock. This reference velocity (which varied for each phase of the tide) was subsequently used to normalise the streamwise velocities. Wake recovery is therefore defined here as the relationship between the mean streamwise velocity and the reference velocity ($\bar{v}/U_{ref}$). A varying reference velocity was chosen because it provided a more accurate representation of wake recovery, i.e. taking the mean of all the reference velocities over the tidal cycle would result in an inaccurate assessment of wake recovery. Typically, a normalised velocity value of 0.9 is equivalent to a local velocity of 90% of the reference velocity. However, quantifying "full recovery" back to the free-stream (or upstream) velocity downstream of an obstruction (natural or artificial) is difficult in coastal areas with strong currents due to the spatial variability of the tidal velocities, which are largely dictated by the local bathymetry. For example, if a moored ADCP was positioned upstream of Horse Rock to measure the approach velocity for the same time period as the vessel-mounted surveys, it is likely (even without the existence of Horse Rock), that the undulating bathymetry away from this pinnacle influences the flow in such a way that the velocities 400 m downstream would differ from those 400 m upstream and would therefore render the "free-stream" velocity as meaningless.

The normalised streamwise velocities ($\bar{v}/U_{ref}$) at the half-height of Horse Rock (~ -10 m CD) were used as they allow a more direct comparison of the wake extent, both in the streamwise and cross-channel directions at different tidal phases. Southerly flow denotes flow reversals immediately downstream of Horse Rock and is represented by negative values ($\bar{v}/U_{ref} < 0$). The coordinate system has been non-dimensionalised by dividing by the diameter of the conical island at its half-height ($D$). For instance, a streamwise distance of 400 m downstream of Horse Rock is represents by $y/D$ = 8, while a cross-channel distance of 50 m is denoted by $x/D$ = 1.

## IV. RESULTS

The data presented here represents velocities at a depth of -10 m CD, which translates to a distance of 10.9 m below the crest of Horse Rock (≈ +0.9 m CD). This elevation was chosen as it represents the half-height of Horse Rock, which represents an average rock diameter of approximately 50 m. This is consistent with the methodology adopted by Lloyd and Stansby [64]. Table 1 provides a summary of the relative submergence ($H/h$) of Horse Rock at various phases of the flood tide, as well as the reference velocities ($U_{ref}$) and associated diameter Reynolds number ($Re_d$) as given in Eq. [1].

TABLE I
SUMMARY OF HYDRODYNAMIC CONDITIONS IN THE VICINITY OF HORSE ROCK OVER A TYPICAL SPRING FLOOD HALF TIDAL CYCLE

| | **Depth over Horse Rock (m)** | **Water depth (m)** | **Reference velocity ($ms^{-1}$)** | **Diameter Reynolds number** |
|---|---|---|---|---|
| Slack+1 | 2.7 | 25.6 | 2.2 | $9.65 \times 10^7$ |
| Slack+2 | 3.3 | 26.2 | 2.8 | $1.23 \times 10^8$ |
| Slack+3 | 3.6 | 26.5 | 3.0 | $1.32 \times 10^8$ |
| Slack+4 | 3.3 | 26.2 | 2.1 | $9.21 \times 10^7$ |
| Slack+5 | 2.9 | 25.8 | 1.5 | $6.58 \times 10^7$ |

A wake characteristic that is important in the planning and placement of multiple turbines within an array is its cross-channel displacement: the cross-channel distance of the wake from the flow axis of a turbine, or in this case, from the centreline of Horse Rock. To assess the cross-channel wake migration, a north-south orientated line was drawn through the centre of Horse Rock. The cross-channel displacement was represented as the distance from this line to the centre of the wake, measured at 50 m and 20 m intervals in the streamwise (downstream of this pinnacle) and cross-channel planes over the various phases of the flood and ebb tide, and again at the half-height of Horse Rock in order to examine wake migration under a variety of velocities.

Cross-channel profiles of the normalised streamwise velocities ($\bar{v}/U_{ref}$) as a function of the downstream distance from Horse Rock are presented in Fig. 3 for a range of $U_{ref}$ velocities; representing different phases of the flood tide. Positive cross-channel displacement values indicate an easterly migrating wake, while negative values denote a westerly displacement. These plots are also useful for determining the approximate point at which the wake recovers back to the reference velocity ($U_{ref}$). These plots show that for each phase of the tide, the greatest velocity deficit is found immediately downstream of the pinnacle. Furthermore, these plots suggest that at $x/D$ = 8, recovery back to the reference velocity does not occur for any phase of the flood tide.

Fig. 3a displays the cross-channel extent of the wake one hour after slack water. The wake is relatively symmetrical at $y/D$ = 2, however, as downstream distance increases the wake migrates to the east as the flow follows the path of least resistance, i.e. away from the north-south trending ridge to the north of Horse Rock. At $y/D$ = 8, the cross-channel displacement is approximately by $y/D$ = 0.4 from the centreline.

Two hours after slack water (Fig. 3b), $x/D$ increases to 0.8 at $y/D$ = 8. Based on these plots, it would be expected that as the mean streamwise velocity ($\bar{v}$) increases, the cross-channel displacement would also increase. However, the cross-channel profiles during the lower velocity phases of the tide, i.e. four (Fig. 3d) and five (Fig. 3e) hours after slack water, display relatively large cross-channel displacements. This suggests that the migration from the centreline of Horse Rock is not significantly affected by velocity magnitude; instead the bathymetry appears to be the major controlling factor of cross-channel displacement. This is dissimilar to the length of the wake in the streamwise direction, which is predominantly controlled by the mean streamwise ($\bar{v}$) velocity.

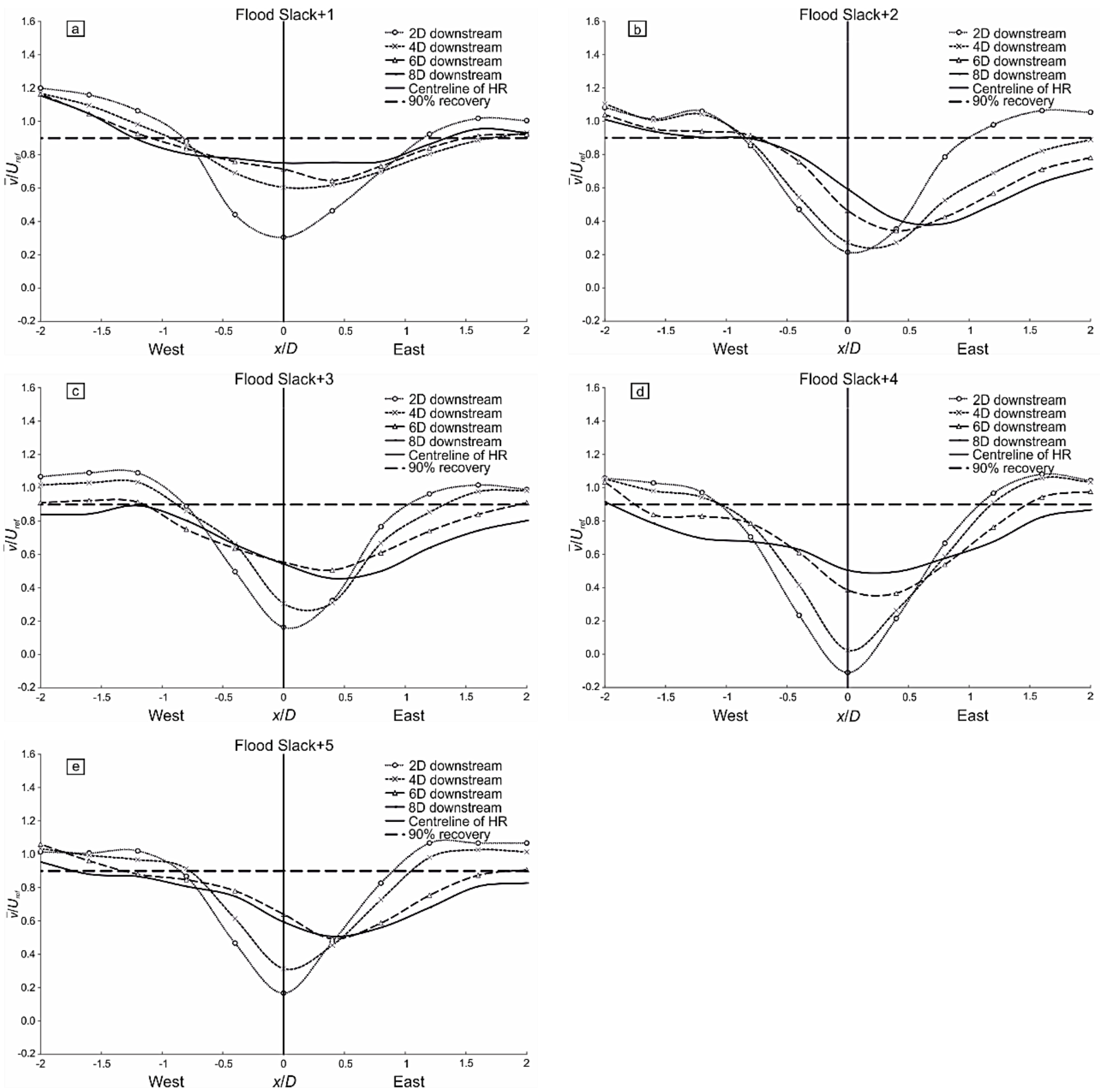

Fig. 2 Cross-channel profiles of streamwise velocity deficit ($\bar{v}/U_{ref}$) downstream of Horse Rock ($y/D$) at the pinnacle half-height at Slack+1 (a); Slack+2 (b); Slack+3 (c); Slack+4 (d); and Slack+5 (e) during the flood tide

Mean streamwise velocity profiles along the wake centreline are presented in Fig. 4a and 4b at $y/D$ = 2 and 8 respectively. Due to a highly aerated water column two hours after slack water, it was not possible to acquire data immediately downstream of Horse Rock ($y/D$ = 2) during the flood tide. Flow reversals occur immediately downstream of Horse Rock ($y/D$ = 2) for all phases of the flood tide, with the strength of this recirculation zone generally greatest at mid water depth. Around maximum flood these flow reversals peak at 3 $ms^{-1}$, suggesting the presence of an eddy structure since the flow nearer the surface experiences positive velocities. As the flood tidal velocities decrease, the profiles display a more uniform shape indicating that the strength of the flow reversals is a function of the longitudinal ($\bar{v}$) velocity. As the downstream distance increases ($y/D$ = 8), the velocities away from the peak flood conditions also display a more uniform profile. Around peak flood, however, the velocities continue to fluctuate with depth. The absence of negative values in these profiles suggests that the eddy present at $y/D$ = 2 does not extend this far downstream.

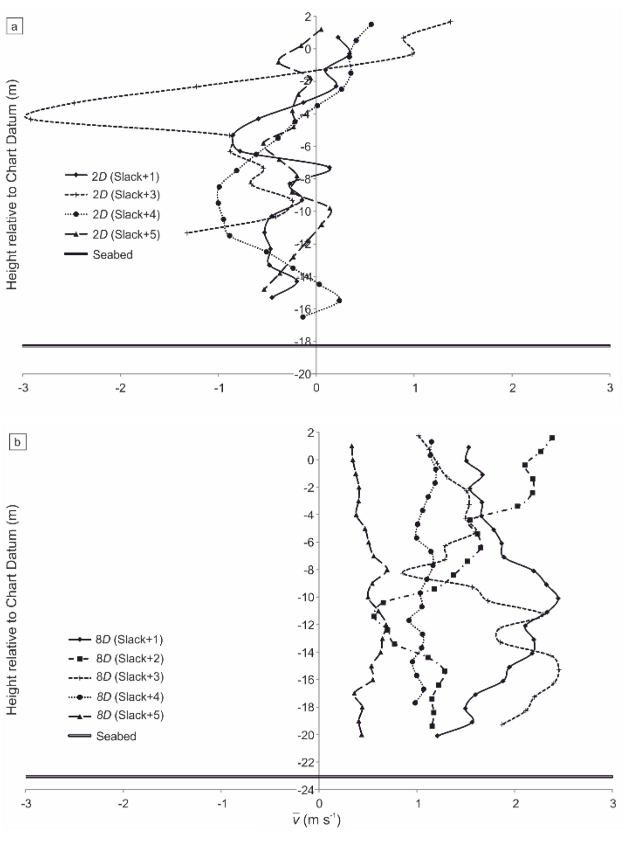


Fig. 3 Streamwise velocity profiles ($\bar{v}$) in $ms^{-1}$ at $y/D$ = 2 (a) (i.e. 2 diameters downstream of Horse Rock) and $y/D$ = 8 (b) (i.e. 8 diameters downstream of Horse Rock) along wake centreline for each flood tidal phase

## V. Discussion

In an idealised system, such as a numerical model or laboratory experiments that comprises a flat bottom, the free-stream ($U$) velocity is relatively straightforward to determine. However, when a complicated bathymetry and coastline are present, the "free-stream" velocity (away from the influence of a feature such as Horse Rock) is spatially variable making it difficult to determine. Furthermore, the constrained nature of this tidal strait results in a relatively narrow corridor either side of Horse Rock for the flow to pass, resulting in a laterally constrained wake. Again, this presents problems when trying to quantify the free-stream velocity since the flow either side of this feature will be accelerating. Although a comprehensive seabed-mounted ADCP survey of the tidal velocity field both upstream and downstream of Horse Rock may help identify the "free-stream" velocity and therefore its wake characteristics, these devices should be deployed with a minimum spacing of 80 m to avoid interference from the 20° beam angles (Grangier, April 2013, personal communication). This relatively coarse grid of devices is unlikely to have sufficient spatial resolution to capture the wake velocities in as much detail as the vessel-mounted approach used to inform this paper. Furthermore, although these moored units would continuously measure the same portion of the water column, it has been shown that due to the irregular bathymetry within Ramsey Sound, the velocities are highly spatially variable and as such, sampling at a single location is unlikely to provide a representative "free-stream" velocity.

Despite this, the wake created by Horse Rock has been examined using a reference velocity ($U_{ref}$) to determine both its streamwise ($y$) and cross-channel ($x$) extent. Streamwise velocity magnitude largely dictates the wake extent in the longitudinal plane ($y/D$), as well as the recirculation length with greater velocities resulting in a longer recirculation zone. Higher reference velocities resulted in an increased longitudinal wake extent, suggesting that wake recovery is a function of streamwise ($y$-direction) velocity, i.e. as the approach velocities (or reference velocity in this case) increase, the recovery rate is longer. The wake recovery rate is therefore partly controlled by the longitudinal velocity, i.e. lower reference velocities ($U_{ref}$) are generally associated with a faster recovery. This is consistent with Malki *et al*. [46] who demonstrated through a combined Blade Element Momentum – Computational Fluid Dynamics (BEM-CFD) model that velocity deficit profiles downstream of a 10 m diameter TST blade recover back to the free-stream velocity at a faster rate with lower inlet velocities. This is also consistent with experimental wake study downstream of porous discs [65]. These studies, however, represent idealised cases with uniform velocity profiles at the inlet and no bathymetry. In reality, however, these devices will be deployed in areas where tidal currents experience strong spatial variability (in the streamwise, $y$, cross-channel, $x$, and vertical, $z$, planes) due to the irregular seabed and coastline configuration, and temporal variability as the tidal velocities fluctuate over the tidal cycle. Experimental and numerical modelling studies provide an insight into wake recovery and are a cost-effective alternative to measuring the wake of full-scale devices. However, given the complicated hydrodynamics associated with the energetic, fast-flowing sites being proposed for TST exploitation, these full-scale measurements are required in order to quantify wake recovery with any level of detail and confidence. Bahaj and Myers [37] noted that in the far wake, wake velocity recovery is primarily controlled by the ambient turbulence intensity and geometry of the device / channel. The length scale ambient turbulence is relatively long and the turbulence intensity high in strong tidal flows [66] compared to smaller scale numerical and experimental studies. This is likely to facilitate more complete wake mixing (dissipation) such that velocity recovery downstream of an obstruction (natural or artificial) is more rapid, allowing closer device spacing. This is likely to be true for Ramsey Sound given the turbulent nature of the surface waters in the vicinity of Horse Rock, particularly on the flood tide. Tidal energy sites are, however, unique with regards to tidal forcing and turbulence-generating bathymetric features. As opposed to offshore wind farms, TST spacing should therefore be considered on a site-by-site basis. Placing a structure, such as a TST device, in a complicated tidal region such as this is likely to result in an unsymmetrical wake. This has implications on spacing requirements for TST arrays. However, excessive increases in the lateral spacing of devices within a single row will result in an inefficient use of space since the majority of tidal energy sites are generally constricted [47]. As the technology matures, it is likely that arrays will become larger with more complicated configurations. The physical and hydrodynamic characteristics of a tidal energy site should therefore be fully understood prior to the installation of TST devices.

With increasing downstream distance, the flow profile of the wake velocities ($\bar{v}$) tended towards the reference velocity ($U_{ref}$), which is consistent with the findings of previous experimental ([37], [47], [65], [67]) and numerical ([46], [48]) studies related to TSTs. Regardless of the reference velocity or elevation in the water column, the greatest velocity deficit occurred immediately downstream of the pinnacle. Again, consistent with the aforementioned numerical and experimental investigations. The velocity profiles in the wake of Horse Rock also revealed the existence of an eddy structure. This flow structure is comparable to that described by White and Wolanski [36] as 'diverging flow', which is described as 'surface water depletion replaced by upwelled water'. The velocity profile four hours after slack is of a similar shape to that observed by Neill and Elliott [31] at a similar downstream distance during a wake study of Beamer Rock, an emergent island in the Firth of Forth, Scotland.

Flow depth and the strength of vertical velocities can have a significant effect on wake length. Previous work presented by Myers *et al*. [68] concluded that a different wake is generated by TSTs operating in shallow fast-flowing water compared with devices deployed in deeper water. It is likely that until the technology is proven, many first generation TSTs will be located in shallow water and will therefore create longer wake lengths compared with deeper sites [69]. In order to reduce wake length, the most optimal turbine diameter to flow depth ratio is 0.25 [69]. Sites located outside this optimum depth range are likely to be subjected to increased wake length. Wake length is also controlled by flow mixing at the shear layer; the boundary between the slower wake velocities and the accelerated free-stream flow beyond the horizontal shear layer.

There are currently only a few deployment initiatives underway to investigate TST performance ([70] - [72]). Given the costs involved in and significant risks of deploying these devices, the majority of the preliminary investigations into turbine performance have been through laboratory and numerical modelling studies. These controlled environments aid the understanding of turbine performance in various conditions to maximise return on the investment without compromising the integrity of the turbines themselves. However, understanding the effect of natural obstructions on tidal velocities using field data allows parameters such as vertical and horizontal variation in velocities, as well as turbulence to be captured. The influence of bathymetry and coastline configuration is also captured through field-based measurements, which can be a challenge via experimental ([47], [65], [69], [73]) and numerical [46] studies, which generally rely on uniform flow profiles and flat beds. Furthermore, the far wake is an experimentally difficult region to investigate since the velocity differences are very small [73].

The relatively large spacing between these transects meant that wake recovery could be investigated, while preventing a loss of temporal resolution and preserving a high spatial resolution. This survey approach made it difficult to capture the detailed flow structures within the near wake region. These areas are subjected to stronger vorticity and are more complex than the far wake region. Reducing the longitudinal spacing, decreasing the lateral extent and increasing the number of survey transects downstream of these features would enable the flow structures in the near wake to be captured in more detailed. However, this wake study was primarily concerned with the quantification of the far wake extent (both longitudinally and laterally). Despite this, capturing these near wake flow structures via vessel-mounted ADCP surveys alone will always be challenging given the temporal variability of the tides. Unless multiple survey vessels are available, deploying a grid of moored ADCPs could help capture the dynamic near wake system in greater detail. As previously mentioned, a minimum spacing of 80 m between these moored devices is required to prevent beam interference. This presents problems with attempting to understand the flow field of the near wake for features of this scale since the obstructed wake is confined to a relatively narrow corridor, which could be missed altogether. Adopting a similar approach to Dewey *et al*. [15] using both moored and vessel-mounted ADCPs could improve the resolution of the dataset, however, it should be noted that the feature under examination during their study had a half-height radius of around 400 m, as opposed to Horse Rock, which has a half-height radius of approximately 25 m. Therefore, fully understanding the processes in operation in the near wake region may not be viable through in-situ field measurements alone. Supplementing these data with laboratory and / or numerical modelling (CFD) studies would bridge the gap in understanding. For example, Neill and Elliot [31] used measured and modelled data to examine the wake created by a 50 m wide surface-piercing island using a series of ADCP transects.

Although this study focuses on a single site, there are other comparable prominent natural obstructions to flow off the coast of Wales, including Wolves Rock to the north-west of Flat Holm Island in the Severn Estuary and the Mixon Shoal to the south of Mumbles Head, Swansea Bay. The local bathymetric configuration and hydrodynamics will differ at these locations, however, the results of this study provide an insight into the complicated tidal flow regime in the vicinity of such features, which until now has been lacking. Furthermore, many potential tidal energy sites in the UK exhibit similar characteristics to Ramsey Sound, such as the Pentland Firth, Scotland, and Kyle Rhea; a strait of water between the Isle of Skye and the Scottish mainland, for example. Marine current energy resource is generally limited to relatively narrow sites where flow spatially constrained between islands (as is the case for Ramsey Sound), around headlands, or estuarine-type inlets [65]. These areas are usually subjected to bi-directional, spatially variable tidal currents and often exhibit a complicated bathymetric configuration.

Coastline configuration also controls the magnitude and direction of the tidal velocities. For example, Ramsey Sound comprises multiple headlands and promontories, which deflect tidal flow creating two counter-rotating recirculation zones exist on both sides of the Sound during the flood and ebb tides. The Bitches reef acts as a barrier to flow on both the flood and ebb phases of the tide. During the flood tide, flow is constrained through the narrow passage to the east and as such, the tidal velocities accelerate as they pass through this channel. A proportion of this northward-flowing body of water subsequently encounters the shallow reef at the north-eastern tip of Ramsey Island, whereby the velocities are significantly reduced and are deflected to the west before flowing in a southerly direction along the western margin of the Sound. The velocities associated with these opposing currents are then reduced by the presence of The Bitches, which deflect the flow to the east before converging with the principal northward-flowing body of water to form a large counter-clockwise recirculation zone. During the ebb tide, the flow is again forced through the narrow passage between The Bitches and the mainland, although a proportion of the flow is deflected to the west as it encounters this reef and flows in a northerly direction before re-joining the dominant southerly currents to form a clockwise recirculation cell.

TEL has consent to install a TST device within the northern portion of Ramsey Sound; the optimum depth to reduce wake length based on the rotor diameter / flow depth ratio given by Giles *et al*. [69] is 60 m (using a rotor diameter of 15 m), which therefore limits the favourable locations to the deep north-south trending channel. This area has been promoted for marine energy extraction and as such, having an understanding of the wake characteristics created by natural features in fast-flowing, macrotidal straits helps to determine the effects of installing a device of a similar scale (without energy extraction) on the local flow field. The relationships identified here can therefore serve as a predictor of the likely levels of wake interference in highly dynamic flows. Sites with strong tidal flows (such as Ramsey Sound) exhibit bi-directional flow characteristics. Longitudinal wake extent is therefore important as this will affect row spacing, i.e. devices will need to be located far enough downstream to ensure the velocities have recovered to a sufficient level and that turbulence levels are not excessive [65]. Lateral wake extent is equally important as this will determine the extent to which the wake migrates from the centreline. From a TST perspective, this is important as it determines the lateral spacing requirements of devices so that the wake created by an upstream device does not affect the efficiency of a device downstream. Examining the wake of a natural feature in an energetic strait therefore helps to understand its development, migration and decay over a variety of flow conditions. Furthermore, numerical models of this area can subsequently be calibrated for a more accurate representation of wake development in these energetic environments. As this technology matures, demonstration and pre-commercial scale devices will be replaced by commercial scale arrays in order to maximise power-output to help meet growing energy demands. When deploying a TST array, the wake velocity structure will be important when determining the array layout and configuration [69]. Developers will therefore have to carry out a cost-benefit exercise in order to decide the most appropriate lateral and longitudinal configuration; too close and device efficiency will be compromised while over-spacing will prevent maximisation of the tidal site [47]. The local hydrodynamics and bathymetric configuration of each potential marine energy extraction site should therefore be characterised on a site-by-site basis in order to understand the tidal system prior to installing a TST or array.

## VI. Conclusions

This paper has identified through field-based measurements that Ramsey Sound exhibits a complicated tidal flow regime, which is highly influenced by the local bathymetry and coastline configuration. Wake recovery of submerged pinnacles is controlled by both velocity magnitude in the longitudinal direction and the local bathymetry. The latter has a more significant effect on wake migration from the centreline.

Recognising the intricacies of energetic straits and the influence of naturally-occurring features on the local flow field is important as it has implications for TST deployment by helping to understand how an artificial structure of a similar scale could affect the flow regime, albeit without any energy extraction. It also allows for the calibration and validation of numerical models examining wake recovery, which are typically based on idealised conditions (flat bed and uniform velocity profiles). This should facilitate improved predictions of wake recovery as well as the energy availability in these dynamic tidal straits

In addition to providing a greater understanding of the effects natural structures have on the local flow field, which has important implications for TST design, it is also important to characterise prospective tidal energy sites prior to installation. This information is crucial as it identifies the hydrodynamic and physical barriers to deployment.

## ACKNOWLEDGMENT

This work was undertaken as part of the Low Carbon Research Institute Marine Consortium (www.lcrimarine.org). The authors wish to acknowledge the financial support of Welsh Government, the Higher Education Funding Council for Wales, the Welsh European Funding Office and the European Regional Development Fund Convergence Programme.

## REFERENCES


[1] A. Kahraman, B. Sahin, and D. Rockwell, D, "Control of vortex formation from a vertical cylinder in shallow water: Effect of localized roughness elements," *Experiments in Fluids*, vol. 33, pp. 54-65, 2002.

[2] D. Chen and G. H. Jirka, "Experimental study of plane turbulent wakes in a shallow water layer," *Fluid Dynamics Research*, vol. 16, pp. 11-41, 1995.

[3] C. J. Baker, "The turbulent horseshoe vortex," *Journal of Wind Engineering & Industrial Aerodynamics*, vol. 6, pp. 9-23, 1980.

[4] R. Martinuzzi and C. Tropea, "The flow around surface-mounted, prismatic obstacles placed in a fully-developed channel flow," *Journal of Fluids Engineering*, vol. 115, pp. 85-92, 1993.

[5] E. J. Wolanski and W. M. Hamner, "Topographically controlled fronts in the ocean and their biological influence," *Science*, vol. 241, pp. 177-181, 1988.

[6] L. White and E. Deleersnijder, "Diagnoses of vertical transport in a three-dimensional finite element model of the tidal circulation around an island," *Estuarine, Coastal and Shelf Science*, vol. 74, pp. 655-669, 2007.

[7] E. Wolanski, J. Imberger and M. L. Heron, "Island wakes in shallow coastal waters," *Journal of Geophysical Research*, vol. 89, pp. 10553-10569, 1984.

[8] P. M. Lloyd, P. K. Stansby, and D. Chen, "Wake formation around islands in oscillatory laminar shallow-water flows. Part 1. Experimental investigation," *Journal of Fluid Mechanics*, vol. 429(1), pp. 217-238, 2001.

[9] R. G. Lueck and T. D. Mudge, "Topographically induced mixing around a shallow seamount," *Science*, vol. 276, pp. 1831-1833, 1997.

[10] E. Kunze, E and J. M. Toole, "Tidally driven vorticity, diurnal shear, and turbulence atop Fieberling Seamount," *Journal of Physical Oceanography*, vol. 27, pp. 2663-2693, 1997.

[11] J. M. Klymak and M. C. Gregg, "The three-dimensional nature of flow near a sill," *Journal of Geophysical Research*, vol. 106(C10), pp. 22295-22311, 2001.

[12] J. D. Nash and J. N. Moum, "Internal hydraulic flows on the continental shelf: High drag states over a small bank," *Journal of Geophysical Research*, vol. 106, pp. 4593-4612, 2001.

[13] A. Althaus, E. Kunze, and T. Sanford, "Internal tide radiation from Mendocino Escarpment," *Journal of Geophysical Research*, vol. 33, pp. 1510-1527, 2003.

[14] K. A. Edwards, P. MacCready, G. Moum, G. Pawlak, J. M. Klymak, and A. Perlin, "Form drag and mixing due to tidal flow past a sharp point," *Journal of Physical Oceanography*, vol. 34, pp. 1297-1312, 2004.

[15] R. Dewey, D. Richmond, and C. Garrett, "Stratified tidal flow over a bump," *Journal of Physical Oceanography*, vol. 35, pp. 1911-1927, 2005.

[16] E. Wolanski, "Island wakes in shallow waters," *Journal of Geophysical Research*, vol. 93, pp. 1335-1336, 1988.

[17] E. Deleersnijder, A. Norro, and E. Wolanski, "A three-dimensional model of the water circulation around an island in shallow water," *Continental Shelf Research*, vol. 12, pp. 891-906, 1992.

[18] N. G. Hogg, "Observations of internal Kelvin waves trapped around Bermuda," *Journal of Physical Oceanography*, vol. 10, pp. 1353-1376, 1980.

[19] R. D. Pingree and L. Maddock, "The effect of bottom friction and Earth's rotation on an island's wake," *Journal of the Marine Biological Association of the UK*, vol. 60, pp. 499-508, 1980.

[20] R. A. Falconer, E. Wolanski, and Mardapitta-Hadjipandeli, L. 1985. Numerical simulation of secondary circulation in the lee of headlands, in: *Proc. Int. Conf. Coastal Engineering*, vol. 3, pp. 2414-2433, 1985.

[21] R. A. Falconer, E. Wolanski, and L. Mardapitta-Hadjipandeli, "Modelling tidal circulation in an island's wake," *Journal of Waterway, Port, Coastal and Ocean Engineering*, vol. 112(2), pp. 234-254, 1986.

[22] R. A. Falconer and L. Mardapitta-Hadjipandeli, "Bathymetric and shear stress effects on an island's wake: A computational model study," *Coastal Engineering*, vol. 11, pp. 57-86, 1987.

[23] J. H. Simpson and P. B. Tett, "Island stirring effects on phytoplankton growth," *Lecture Notes on Coastal and Estuarine Studies*, vol. 17, pp. 41-76, 1986.

[24] E. Wolanski, "Island wakes and internal tides in stratified shelf waters," *Annales Geophysicae*, vol. 4B, pp. 425-439, 1986.

[25] K. P. Black and S. L. Gay, "Eddy formation in unsteady flows," *Journal of Geophysical Research*, vol. 92, pp. 9514-9522, 1987.

[26] R. G. Ingram and V. H. Chu, "Flow around islands in Rupert Bay: an investigation of the bottom friction effect," *Journal of Geophysical Research*, vol. 92, pp. 14521-14533, 1987.

[27] M. Tomczak, "Island wakes in deep and shallow water," *Journal of Geophysical Research*, vol. 93, pp. 5153-5154, 1988.

[28] R. P. Signell and W. R. Geyer, "Transient eddy formation around headlands," *Journal of Geophysical Research*, vol. 96, pp. 2561-2575, 1991.

[29] P. A. Davies and L. A. Mofor, "Observations of flow by an isolated island," *International Journal of Remote Sensing*, vol. 11, pp. 767-782, 1990.

[30] J. H. Middleton, D. A. Griffin, and A. H. Moore, "Oceanic circulation and turbulence in the coastal zone," *Continental Shelf Research*, vol. 13, pp. 143-168, 1993.

[31] S. P. Neill and A. J. Elliott, "In situ measurements of spring–neap variations to unsteady island wake development in the Firth of Forth, Scotland," *Estuarine, Coastal and Shelf Science* vol. 60(2), pp. 229-239, 2004.

[32] S. P. Neill and A. J. Elliott, "Observations and simulations of an unsteady island wake in the Firth of Forth, Scotland," *Ocean Dynamics*, vol. 54, pp. 324-332, 2004.

[33] S. Blaise, E. Deleersnijder, L. White, and J. Remacle, "Influence of the turbulence closure scheme on the finite-element simulation of the upwelling in the wake of a shallow-water island," *Continental Shelf Research*, vol. 27, pp. 2329-2345, 2007.

[34] C. Dong and J. C. McWilliams, "A numerical study of island wakes in the Southern California Bight," *Continental Shelf Research*, vol. 27, pp. 1233-1248, 2007.

[35] L. White, E. Deleersnijder, and V. Legat, "A three-dimensional unstructured mesh finite element shallow-water model, with application to the flows around an island and in a wind-driven, elongated basin," *Ocean Modelling*, vol. 22, pp. 26-47, 2008.

[36] L. White and E. Wolanski, "Flow separation and vertical motions in a tidal flow interacting with a shallow-water island," *Estuarine, Coastal and Shelf Science*, vol. 77, pp. 457-466, 2008.

[37] A. S. Bahaj and L. E. Myers, "Shaping array design of marine current energy converters through scaled experimental analysis," *Energy*, vol. 59, pp. 83-94, 2013.

[38] L. E. Myers and A. S. Bahaj, "Near wake properties of horizontal axis marine current turbines," in: *Proc. 8th European Wave and Tidal Energy Conference (EWTEC)*, Uppsala, Sweden, 2009.

[39] F. Maganga, G. Germain, J. King, G. Pinon, and E. Rivoalen, "Experimental characterisation of flow effects on marine current turbine behaviour and on its wake properties," *Renewable Power Generation*, vol. 4(6), pp. 498 – 509, 2010.

[40] S. Rose, A. Good, M. G. H. Atcheson, C. Johnstone, and P. MacKinnon, "Investigating experimental techniques for measurement of the downstream near wake of a tidal turbine," in: *Proc. 9th European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK, 2011.

[41] T. Stallard, R. Collings, T. Feng, and J. I. Whelen, "Interactions between tidal turbine wakes: experimental study of a group of 3-Bladed rotors," in: *Proc. 9th European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK, 2011.

[42] S. C. Tedds, I. Owen, and R. J. Poole, "Near wake characteristics of a model horizontal axis tidal stream turbine," *Renewable Energy*, vol. 63, pp. 222-235, 2014.

[43] M. S. Ghidaoui, A. A. Kolyshkin, J. H. Liang, F. C. Vhan, Q. Li, and K. Xu, "Linear and nonlinear analysis of shallow wakes," *Journal of Fluid Mechanics*, vol. 548, pp. 309-340, 2006.

[44] G. Bai, G. Li, Y. Ye, and T. Gao, "Numerical analysis of the hydrodynamic performance and wake field of a horizontal axis tidal current turbine using an actuator surface model," *Ocean Engineering*, vol. 94, pp. 1-9, 2015.

[45] A. Mason-Jones, D. O'Doherty, C. Morris, and T. O'Doherty, "Influence of a velocity profile & support structure on tidal stream turbine performance," *Renewable Energy*, vol. 52, pp. 23-30, 2013.

[46] R. Malki, I. Masters, A. J. Williams, and T. N. Croft, *The variation in wake structure of a tidal stream turbine with flow velocity*, in: *Proc. 4th Int. Conf. on Comp. Methods in Marine Engineering, MARINE 2011*, Springer, pp. 137-148, 2011.

[47] L. E. Myers and A. S. Bahaj, "An experimental investigation simulating flow effects in first generation marine current energy convertor arrays," *Renewable Energy*, vol. 37, pp. 28-36, 2012.

[48] A. Mason-Jones, "Performance assessment of a horizontal axis tidal turbine in a high velocity shear environment," Ph.D. thesis, Cardiff University, UK, 2010.

[49] P. Mycek, B. Gaurier, G. Germain, G. Pinon, and E. Rivoalen, "Numerical and experimental study of the interaction between two marine current turbines," in: *Proc, 9th European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK, 2011.

[50] S. Rose, S. Ordonez, K. H. Lee, C. Johnstone, C. H. Jo, and T. McCombes, "Tidal turbine wakes: small scale experimental and initial computational modelling," in: *Proc. 9th European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK, 2011.

[51] G. K. Batchelor, *An Introduction to Fluid Dynamics*, Cambridge: University Press, 1967.

[52] J. F. Douglas, J. M. Gasiorek, J. A. Swaffield, and L. B. Jack, *Fluid Mechanics*, 5th ed., UK: Longman, 2005.

[53] M. Togneri and I. Masters, "Comparison of turbulence characteristics for selected tidal stream power extraction site,", in *Proc. 9th Engineering Turbulence Modelling and Measurements Conference*, Thessaloniki, Greece, 2012.

[54] I. G. Bryden, T. Grinsted, and G. T. Melville, "Assessing the potential of a simple tidal channel to deliver useful energy," *Applied ocean Research*, vol. 26, pp. 198-204, 2004.

[55] Tidal Energy Limited, "DeltaStream Demonstrator Project Ramsey Sound, Pembrokeshire – Non-technical summary", 2009.

[56] I. Fairley, S. P. Neill, T. Wrobelowski, M. Willis, and I. Masters, "Potential array sites for tidal stream turbine electricity generation off the Pembrokeshire coast," in *Proc. 9th European Wave and Tidal Energy Conference (EWTEC)*, Southampton, UK, 2011.

[57] MEP. (2011) MEP webpage on DeltaStream device. [Online]. Available: http://www.marineenergypembrokeshire.co.uk/wales-moves-one-step-closer-to-capturing-tidal-energy-potential

[58] Teledyne RD Instruments. (2009) Workhorse Sentinel Datasheet [Online]. Available: http://www.rdinstruments.com/datasheets/wh_sentinel.pdf, 2009

[59] I. Fairley, P. S. Evans, C. F. Wooldridge, M. Willis, I. Masters, "Evaluation of tidal stream resource in a potential array area via direct measurements," *Renewable Energy*, vol. 57, pp. 70-78, 2013.

[60] M. C. Easton, A. Harendza, D.K. Wool, and A.C. Jackson, "Characterisation of a tidal energy site: Hydrodynamics and seabed structure," in *Proc. 9th European Wave and Tidal Energy Conference (EWTEC)*, Porto, Portugal, UK, 2007.

[61] Y. Yoshikawa, T. Matsuno., K. Marubayashi, and K. Fukudome, "A surface velocity spiral observed with ADCP and HF radar in the Tsushima Strait," *Journal of Geophysical Research*, vol. 112, 2007.

[62] D. M. O'Doherty, A. Mason-Jones, C. E. Morris, T. O'Doherty, C. D. Byrne, P. W. Prickett, and R. I. Grosvenor, "Interaction of marine turbines in close proximity," in: *Proc. 9th European Wave and Tidal Conf. (EWTEC)*, Southampton, UK, 2011.

[63] L. E. Myers and A. S. Bahaj, "Design of 1st-generation marine current energy convertor arrays," In: *Proc. 11th World Renewable Energy Congress XI and Exhibition*, Abu Dhabi, Dubai, 2010.

[64] P. M. Lloyd and P. K. Stansby, "Shallow-water flow around model conical islands of small side slope. I: Surface piercing," *Journal of Hydraulic Engineering*, vol. 123(12), pp. 1057-1067, 1997.

[65] A. S. Bahaj, L. E. Myers, M. D. Thomson, N. and Jorge, "Characterising the wake of horizontal axis marine current turbines, in: *Proc.7th European Wave and Tidal Energy Conference (EWTEC)*, Porto, Portugal, UK, 2007.

[66] J. Thomson, B. Polagye, M. Richmond, and V. Durgesh, "Quantifying turbulence for tidal power applications," in: *Proc. Oceans 2010*, Seattle, Washington, USA, 2010.

[67] B. Gunawan, V.S. Neary, C. Hill, and L. P. Chamorro, "Measurement of velocity deficit at the downstream of a 1:10 axial hydrokinetic turbine model," in: *Proc. Hydraulic Measurements and Experimental Methods Conference*, Snowbird, UT, USA, 2012.

[68] L. E. Myers, A. S. Bahaj, G. Germain, and J. Giles, "Flow boundary interaction effects for marine current energy conversion devices," in: *Proc. 10th World Renewable Energy Congress XI and Exhibition*, Glasgow, UK, 2008.

[69] J. Giles, L. E. Myers, A. S. Bahaj, and B. Shelmerdine, "The downstream wake response of marine current energy converters operating in shallow tidal flows," in: *Proc. 10th World Renewable Energy Congress*, Linköping, Sweden, 2011.

[70] P. L. Fraenkel, "Marine current turbines: Pioneering the development of kinetic energy converters," in: *Proc. IMechE. Part A: Journal of Power and Energy*, vol. 221(2), pp. 159-169, 2007.

[71] P. Gilson, "Altrom's first tidal in stream energy converter demonstration project," in: *Proc. 3rd Int. Conf. Ocean Energy* (ICOE), Bilbao, Spain, 2010.

[72] M. Paish, J. Giles, and B. Panahandeh, "The Pulse Stream Concept, and the development of the Pulse Stream Demonstrator," in: *Proc. 3rd Int. Conf. Ocean Energy* (ICOE), Bilbao, Spain, 2010.

[73] P. B. Johansson and W. K. George, "The far downstream evolution of the high Reynolds-number axisymmetric wake behind a disk. Part 1. Single-point statistics," *Journal of Fluid Mechanics*, vol. 555, pp. 363-385, 2006.