

# Hydrodynamic Characteristics of Macrotidal Straits and Implications for Tidal Stream Turbine Deployment

By

**Paul Stephen Evans** 

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## ABSTRACT

National efforts to reduce energy dependency on fossil fuels have prompted examination of macrotidal nearshore zones around the UK for potential tidal stream resource development. Although a number of prospective tidal energy sites have been identified, the local hydrodynamics of these sites are often poorly understood.

Tidal-energy developers rely on detailed characterisation of tidal energy sites prior to device field trials and installation. Although first-order appraisals may make macrotidal tidal straits appear attractive for development, detailed, site-specific hydrodynamic and bathymetric surveys are important for determining site suitability for tidal stream turbine (TST) installation. Understanding the ways in which coastal features affect tidal velocities at potential TST development sites will improve identification and analysis of physical constraints on tidal-energy development.

Ramsey Sound (Pembrokeshire, Wales, UK) will soon host Wales' first TST demonstration project. However, the local hydrodynamics of the sound have been underexamined. Ramsey Sound experiences a marked tidal asymmetry, with local bathymetric features that affect flow fields which are spatially heterogeneous in three dimensions.

Using Ramsey Sound as a case study, this thesis has three objectives: (1) to examine the wake created by submerged objects through field- and laboratory-based measurements, (2) to experimentally investigate the effect of submergence on wake development and decay downstream of a conical island, and (3) to develop a TST suitability tool, which examines the effects of velocity, water depth and bed slope on power availability within a macrotidal coastal area.

Laboratory experiments have shown that submergence level is an important parameter controlling wake structure and extent, and that changes in submergence level affect both the 3-D flow structure in the near wake and the 2-D far wake of islands. Analysis of physical and hydrodynamic characteristics in Ramsey Sound, including tidal velocities across the swept area of the pilot TST, vertical shear in the stream flow, estimated power output, water depth and bed slope, suggests that the spatial and temporal variability in the flow field may render much of Ramsey Sound unsuitable for tidal power extraction. Although the resource potential depends on velocity and bathymetric conditions that are fundamentally local, many prospective tidal energy sites are subject to similar physical and hydrodynamic constraints. Results of this study can help inform site selection in these complicated, highly dynamic macrotidal environments.

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## NOMENCLATURE

Α	cross-sectional flow area (m <sup>2</sup> )
$A_p$	projected area of obstruction (m <sup>2</sup> )
С	speed of sound (m s <sup>-1</sup> )
В	channel width (m)
CD	Chart Datum (m)
$C_D$	drag coefficient
CFD	computational fluid dynamics
D	object diameter at base (m)
$D_f$	total drag force (kg m s <sup>-2</sup> )
$D_{50}$	object diameter at its half height (m)
FD	Doppler shift
Fr	Froude number
$F_s$	frequency of transmitted sound (Hz)
g	gravitational acceleration (m s <sup>-1</sup> )
Н	water depth (m)
h	object height (m)
k	turbulent kinetic energy $(m^2 s^2)$
$K_z$	vertical eddy diffusion coefficient (m <sup>2</sup> s <sup>-1</sup> )
l	turbulent length scale (m)
OD	Ordnance Datum (m)
Р	island wake parameter
$Q_{vol}$	volumetric flow rate (m <sup>3</sup> s <sup>-1</sup> )
$R_l$	recirculation length (m)
$R_w$	recirculation width (m)

Re	Reynolds number
$Re_d$	Reynolds number based on the objects diameter
Reн	Reynolds number based on the flow depth
St	Strouhal number
TST	tidal stream turbine
U	approach, or free-stream velocity (m s <sup>-1</sup> )
$\overline{U}$	time- and depth-averaged velocities (m s <sup>-1</sup> )
$\overline{u_d}$	depth-averaged longitudinal velocity (m s <sup>-1</sup> )
$U_{def}$	velocity deficit (m s <sup>-1</sup> )
$U_{ref}$	reference velocity (m s <sup>-1</sup> )
$\overline{u_v}$	average longitudinal velocity over the vertical diameter of a TST swept area (m s <sup>-1</sup> )
$u_{vol}$	volumetric averaged velocity (m s <sup>-1)</sup>
<i>u</i> , <i>v</i> , <i>w</i>	instantaneous longitudinal, lateral and vertical velocity components (m $\ensuremath{\mathrm{s}}^{\mbox{-1}}$ )
$\bar{u}, \bar{v}, \overline{w}$	time-averaged longitudinal, lateral and vertical velocity components (m $\ensuremath{s^{\text{-1}}}\xspace$ )
<i>u</i> ', <i>v</i> ', <i>w</i> '	turbulent fluctuations in the time-averaged longitudinal, lateral and vertical velocity components (m $\rm s^{-1})$
V	relative velocity between source and receiver (m s <sup>-1</sup> )
w	base width of (m)
<i>x</i> , <i>y</i> , <i>z</i>	distances along the longitudinal, lateral and vertical axes (m)
ε	dissipation
ρ	fluid density (kg m <sup>-3</sup> )
μ	dynamic viscosity (kg m <sup>-1</sup> s <sup>-1</sup> )
v	kinematic viscosity $(m^2/s^{-1})$

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## **1 INTRODUCTION**

#### 1.1 Context

#### 1.1.1 Global energy

Global energy usage has increased markedly over the past five decades and is a trend that is likely to continue with direct consequences for fossil fuel stores and changing climate (Woolf *et al.* 2014). Total global energy use at the beginning of the century was estimated to be 12 TW (Royal Commission on Environmental Pollution, 2000) with a United Kingdom (UK) energy requirement of 310 GW. At present, combustion of fossil fuels is the primary provider for global energy requirements (O'Rourke *et al.* 2010; Tang *et al.* 2014). In 2007, the contribution of fossil fuels to total primary energy consumption was 88%, consisting of 35.6% oil (3952.8 million tonnes of oil equivalent, mtoe), 23.8% natural gas (2637.7 mtoe), 28.6% coal (3117.5 mtoe), 5.6% nuclear (622 mtoe) and 6.4% hydro-electricity (709.2 mtoe) (International Energy Agency, 2007). In 2012, total energy consumption from natural sources was 206.3 mtoe, 2% higher than in 2011 (DECC, 2013a). However, in 2012, the contribution from renewable energy sources increased for both electricity generation and bioenergy consumption.

Global climate change is becoming more widely acknowledged and as such, policy makers worldwide are recognising the importance of greenhouse gas emission reductions. Consequently, there is an international shift towards clean renewable technologies for electricity generation (Denny, 2009). Furthermore, the finite nature and geographical constraints associated with fossil fuels is motivating this movement towards finding long term clean and renewable alternatives.

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#### 1.1.2 Renewable energy targets in the UK

The UK 2020 target of 15% from renewable energy introduced in the 2009 EU Renewable Energy Directive suggests a 34% reduction in emissions is required (DECC, 2012). A significant investment will be required if this target is to be met, particularly in new on- and offshore wind, as well as the UK's abundant wave and tidal energy resource potential (Iyer *et al.* 2013). Despite this, electricity generation in the UK from renewable sources increased by approximately one fifth between 2011 and 2012, reaching 41.3 TW-h, while capacity grew by more than one quarter to 15.5 GW (DECC, 2013b). Furthermore, the contribution of all renewable electricity sources to that generated in the UK was around 11.3% in 2012 (1.9% higher than 2011) (DECC, 2013b). Official figures recently released have shown that electricity from renewables increased by 30% over 2013, now representing 14.9% of total electricity generation; a rise of 3.6% from 2012 figures, which equates to a total generation of 4.2 GW (DECC, 2014). This increase has been driven by the Renewables Obligation (RO), which is designed to incentivise the generation of electricity from renewable sources by placing an obligation on licenced electricity suppliers to generate a greater proportion of electricity from renewable sources.

Within the UK, various constraints, such as hydro-power plant suitability and the amount of sun hours generally restricts renewable energy options to wind, wave and tidal power (Walkington and Burrows, 2009). Although these forms of technologies are crucial to meet future energy demands, certain technologies, such as solar, wind and wave generation are variable since the amount of electricity produced is ultimately dependent on weather conditions (Denny, 2009). These particular renewables also require the resource to be exploited as and when it is available (Walkington and

Burrows, 2009). Although alternative forms of energy, such as tidal streams, are more locally focussed and perhaps more promising, they cannot alone provide 12 TW (Woolf *et al.* 2014).

Although tides are intermittent they have the advantage over other forms of renewable energy of being predictable over long timescales (Cave and Evans, 1984). Tidal energy generation (once the technology has been proven) should therefore be less challenging than other, less predictable forms of renewable energy technologies (Denny, 2009).

Wales does not have devolved renewable energy targets, however, the Welsh Government is being proactive in the transition to a low-carbon economy (DECC, 2012). Wales has significant renewable energy sources, particularly onshore and offshore wind, wave, tidal, and solar with scope for biomass and hydro, as well as existing nuclear sites (Welsh Government, 2012). Wales also benefits from a having a good highway network, railways, deep ports, and electrical and gas grid infrastructure to help streamline the transition to a low carbon economy.

The renewable energy sector in Wales is continuing to grow with renewable generation increasing by 58% between 2004 and 2010 (Welsh Government, 2012). Currently, 62% of renewable energy generation in Wales is sourced from wind (with existing operational wind farms having a capacity of 562 MW) and solar, 25% from thermal and 13% from hydro generation (Welsh Government, 2012). Wales has 1200 km of coastline, which makes it ideally suited for harnessing the power of the sea. The Welsh Government has therefore set the following marine energy targets to help achieve this low carbon economy (Welsh Government, 2010):

3

- Offshore wind To deliver a further 15 kWh per day per person by 2015/16.
- Tidal stream and wave To capture at least 10% (~ 8 kWh per day per person) of the potential tidal stream and wave energy off the Welsh coastline by 2025.

Meeting the tidal stream energy target requires a better understanding of the tidal resource in Wales by constraining estimates of tidal power through site-specific velocity measurements (Willis *et al.* 2010; Evans *et al.* 2013; Fairley *et al.* 2013) and through full hydrodynamic oceanographic numerical modelling (Blunden and Bahaj, 2007; Walkington and Burrows, 2009; Hashemi *et al.* 2012; Serhadlıoğlu *et al.* 2013).

#### 1.2 Tidal currents

The physics of tides is well-established; however, few studies have examined the tidal resource within macrotidal sites where there are strong and variable currents (Woolf *et al.* 2014). This section provides a description tides in the context of energy exploitation. Pugh (1987) provides a more comprehensive description of tides.

Oceanic tides are very long period waves. The periodic rise and fall of the water surface generates a horizontal movement of water known as tidal currents. These tidal variations can be exploited to generate electricity. In coastal areas where water is driven through narrow channels and around headlands, tidal currents are accelerated. These currents generally flow in two directions: flood currents propagate landwards and ebb currents recede seawards. Tidal velocities typically vary from zero at slack water to maximum in between these slack waters. Unlike tidal streams, which are forced by gravity alone, tidal currents can be affected by meteorological forcing (Charlier and Finkl, 2009), however, for the purposes of this study these terms will be used synonymously.

Typically, tidal currents of less than 1 m s<sup>-1</sup> are generally insufficient for economic power generation (Couch and Bryden, 2006). Tidal energy fluxes at shelf edges that reach 300 kW m<sup>-1</sup> could be considered substantial; however, this is the sum total potential and kinetic energy contained within the wave over the full water depth (typically 200 m near the edge of the shelf). A more appropriate value is the kinetic energy flux passing across a plane perpendicular to the flow (Woolf *et al.* 2014). The available power within a tidal system is proportional to the cube of the current velocity; a velocity of 1 m s<sup>-1</sup> will generate a power density of just 500 W m<sup>2</sup> (Griffin and Hemer, 2010). A minimum velocity of 1 m s<sup>-1</sup> is optimistic for economic viability and as such, relatively few suitable areas for tidal energy extraction exist (Couch and Bryden, 2006).

Couch and Bryden (2006) note a few exceptions where currents exceed 1 m s<sup>-1</sup> in reasonably accessible locations. They identify three classes: resonant systems, hydraulic currents and tidal streaming. Very fast currents are encountered in resonant systems, such as the Bristol Channel, UK and the Bay of Fundy, Canada. Resonant systems occur when a standing wave is established with the incoming tidal wave encountering the reflected tidal wave. A hydraulic current is generated by a water level difference at two locations connected by a waterway. The greatest difference in water level coincides with the maximum flood/ebb tide. Slack water occurs when the level difference is approximately the same. Chesapeake and Delaware Canal connecting the Chesapeake and Delaware Bays is an example of a hydraulic current system. Tidal

streaming refers to a local acceleration of flow due to a constriction, i.e. where a headland or island directs the flow.

## 1.3 Tidal energy

### 1.3.1 Global marine energy resource

Numerous sites with sufficiently strong currents for economic viability are being recognised across the world (Edmunds *et al.* 2014) with a number of grid connected prototype devices in operation in UK waters (see Table 1).

Table 1 – Full scale tidal stream energy devices installed or currently operating in UK waters (EMEC, 2014)

Operator	Device	Location
Alstom (formerly TGL)	DeepGen (1 MW)	Fall of Warness, EMEC
Andritz Hydro Hammerfest	HS1000 (1 MW)	Fall of Warness, EMEC
Atlantis Resources Corporation	AR1000 (1 MW)	Fall of Warness, EMEC
Marine Current Turbines	Seagen (1.2 MW)	Strangford Lough, Northern Ireland
OpenHydro	Open Centre turbine (250 kW)	Fall of Warness, EMEC
Scotrenewables Tidal Power	SR250 (250 kW)	Fall of Warness, EMEC
Voith Hydro	HyTide 1000 (1 MW)	Fall of Warness, EMEC

The Bay of Fundy located between New Brunswick and Nova Scotia in Canada has the potential to produce 30 GW of tidal energy (The Gaia Project, 2014). China also has abundant resources of tidal energy, estimated to be in the region of 3.5 GW (Atlantis, n.d.). Other countries with significant tidal power potential include the USA, Argentina, Russia, France, Australia, New Zealand, India and South Korea. Figure 1 shows the distribution of the global tidal stream energy resource.



Figure 1 – Global tidal stream resource (Atlantis, n.d.)

At a European scale, electricity production provides approximately 0.02% of Europe's energy needs (European Commission, 2013). However, global tidal stream energy has been predicted to theoretically supply more than 150 TW-h per year, which is much greater than all domestic electricity consumption in the UK and represents a potential tidal global market of up to 90 GW of generating capacity (Atlantis, n.d.).

#### 1.3.2 Tidal energy resource in the UK

The UK has a combined wave and tidal energy potential to deliver 20% of the UK's current electricity demand, equating to an installed capacity of 30-50 GW (DECC, 2013c). This resource has meant that the UK currently dominates the global tidal energy industry, with France and Canada rapidly closing the gap.

Black and Veatch (2011) define a number of tidal resources:

- the *total resource* is the 'total energy that exists within a defined tidal system';
- the *theoretical resource* is the 'maximum energy that can be harvested from tidal currents in the region of interest without consideration of technical, economic or environmental constraints';
- the *technical resource* is the 'energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment';
- the *practical resource* accounts for key external restrictions (e.g. shipping, fishing, MOD etc.). The practical resource therefore refers to a proportion of the technical resource.

The total theoretical resource from tidal stream (marine current) energy in the UK is estimated to be in the order of 95 TW-h year<sup>-1</sup> (32 GW) (Crown Estate, 2012), which accounts for around 50% of Europe's tidal energy, 25% of which can be found in Scotland. However, approximately 20% of this total (20.6 TW-h year<sup>-1</sup>) is deemed to be extractible (Woolf *et al.* 2014). A practical resource must include external constraints and therefore each site must be evaluated on a site-by-site basis. Almost half of the practical resource (~ 10 TW-h year<sup>-1</sup>) is calculated for the deep Pentland Firth, Scotland. Of particular importance is temporal variability, or intermittency of tidal currents, which results in variability of the available power. The phase relationship between high water and peak flood varies, but peak flood and ebb flows will usually be separated by slightly more than 6 hours. For example, although each 1 GW of capacity could supply nearly 9 TW-h year<sup>-1</sup> from steady strong currents, 10 TW-h year<sup>-1</sup> will be generated from a farm rated at 4.2 GW (Black and Veatch, 2011).

The total installed tidal generation capacity in the UK was approximately 10 MW in 2011 (RenewableUK, 2011).

The majority of the UK's tidal stream resource (Figure 2) is found in the north of Scotland, however, other key areas include Alderney, Anglesey, Pembrokeshire and the Strangford Lough area in Northern Ireland (Sustainable Development Commission, 2007). Table 2 shows the distribution of the tidal energy resource across the UK, while Table 3 summarises the tidal stream resource potential of the top UK sites.

Туре	Location	Indicative annual energy (TW-h year <sup>-</sup> <sup>1</sup> )	Indicative maximum power (GW)
	England	34	11
	Wales	28	9.5
<b>Tidal stream</b>	Scotland	32	11
	Northern Ireland	1	0.5
	Total	95	32
	England	57	27
Tidal range: barrage	Wales	23	8
schemes	Scotland	16	10
	Total	96	45
Tidal range: lagoon schemes	England	14	8
	Wales	7	3.5
	Scotland	4	2.5
	Total	25	14

 Table 2 – Distribution of tidal energy resources across the UK (Crown Estate, 2012)

Site name	Area	<b>Resource</b> (TW-h year <sup>-1</sup> )
Pentland Skerries	Pentland Firth	3.9
Stroma	Pentland Firth	2.8
Duncansby Head	Pentland Firth	2.0
Casquets	Alderney	1.7
South Ronaldsay	Pentland Firth	1.5
Hoy	Pentland Firth	1.4
Race of Alderney	Alderney	1.4
South Ronaldsay	Pentland Firth	1.1
Rathlin Island	North Channel	0.9
Mull of Galloway	North Channel	0.8

Table 3 – Tidal stream resource potential of top UK sites (Sustainable Development Commission, 2007)



Figure 2 – UK tidal stream resource (Sustainable Development Commission, 2007)

A key document for policy and planning decisions regarding feasibility studies and site leasing is the Atlas of UK Marine Renewable Energy Resources (ABPmer, 2008), which offers regional-scale descriptions of possible marine energy resources. However, the resolution of the Atlas is too coarse to capture the tidal dynamics of complicated nearshore zones such as high-velocity straits. Tidal amplitude and current velocities are functions of coastal physical geography and local bathymetry (Bryden *et al.* 2007; Easton *et al.* 2012); therefore this lack of local-scale hydrodynamic data suggests large uncertainties exist in tidal resource estimates (O'Rourke *et al.* 2010; Cooper, 2011).

#### 1.3.3 Tidal energy resource in Wales

The coast of Wales is subject to some of the largest tides in the world as well as a significant wave climate with potential for substantial electricity production. There is potential for 6.4 GW (over 10 GW with the inclusion of the Severn Estuary) of installed marine energy capacity in Wales (Welsh Government, 2012). Table 2 shows the tidal energy resource potential in Wales.

Several resource assessments (Black and Veatch, 2005; PMSS, 2006; ABPmer, 2008; Crown Estate, 2012) have identified three primary locales for tidal stream energy development along the coast of Wales: Anglesey, Pembrokeshire, and the Bristol Channel (including the Severn Estuary). The latter is restricted due to navigational constraints, limited depths, a large tidal range (potential turbine exposure at low spring tides) and relatively low velocities (see Willis *et al.* 2010). Furthermore, a potential Severn Barrage is still being explored and therefore relatively little tidal stream research is being undertaken here. The Pembrokeshire coast in west Wales has a significant wave and tidal stream climate. The coastline to the west is exposed to waves from the North Atlantic and comprises an abundance of headlands, islands and various promontories that accelerate tidal currents.

#### 1.4 Tidal stream energy extraction

Extracting energy from tides using tidal mills is a practice that dates back to Roman times (Charlier and Menanteau, 1997; Charlier and Finkl, 2009). At high tide, water flows through sluice gates into a pond, which is protected by a dyke. As the tide recedes the water flows out of the storage area through a gate, which turns a hydraulic wheel. Barrages operate on a similar principle but on a much larger scale by impounding water within a large embayment. As the tide recedes the head loss across the barrage causes the water to flow through the turbines and generate electricity.

Developers have started to recognise an apparent gap in the renewable energy market, however, tidal energy devices on a commercial scale are currently generally limited to tidal barrage schemes. Given the scale of this technology, there is uncertainty regarding the potential environmental impacts, namely water level and velocity changes outside and within the enclosed basin, siltation, habitat loss, changes in hydrodynamics and sediment transport regimes, as well as the barrier they pose to fish and shipping (Wolf *et al.* 2009). Consequently, there has been a recent shift towards harnessing the kinetic energy of tidal currents using turbines (Watchorn and Trapp, 2000).

In the UK, extracting the kinetic energy from tides is gaining momentum. There are a number of tidal stream turbine (TST) technologies in existence (see Hardisty, 2009) with a number of tidal stream schemes being considered off the coast of Wales (e.g. SeaGen, Anglesey Skerries, Anglesey) and planned (DeltaStream, Ramsey Sound, Pembrokeshire). Table 1 shows the full scale tidal energy devices installed or operating in UK waters. According O'Rourke *et al.* (2010), there are two principal TST types:

- Horizontal axis the blades rotate in the horizontal plane, parallel to the direction of the flow.
- Vertical axis the blades rotate in the vertical plane, perpendicular to the direction of flow. This device can operate with currents approaching from any direction.

A typical horizontal TST consists of blades attached to a hub (collectively termed a rotor), a gearbox, and a generator (O'Rourke *et al.* 2010). As the tidal currents flow past the blades the rotor rotates, which turns the generator. The gearbox converts the rotational speed of the rotor to the desired output speed of the generator shaft (O'Rourke *et al.* 2010). A tower supports the turbine and is sized to withstand the environmental loadings that exist in these inhospitable environments. There are three principal support structure options for TSTs, these include a gravity structure, a piled structure, or a floating structure (O'Rourke *et al.* 2010). Gravity-based devices are of sufficient mass to remain fixed on the seabed without any extra attachments. Piled devices are attached to a pole that is fixed to the seabed. Floating platforms have the benefit of easy installation and maintenance, but can disrupt navigation.

The tidal and well-established wind energy industries display similarities (Couch and Bryden, 2006). The wind industry can teach the marine energy industry many lessons; however, several key technological differences exist. Water is approximately 800 times denser than air; therefore the energy available in water is much greater since the kinetic energy flux per unit area will be significantly larger. Tidal currents have the benefit of long-term prediction compared with winds. However, tidal energy devices, depending on their scale, are affected by both a static bottom boundary (the seabed) and a dynamic surface boundary (the water surface), while a wind-power device is only subject to a bottom boundary.

Although TST technology is still relatively new (Robert, 2004) and approximately 10 – 15 years behind the wind technology industry (O'Rourke *et al.* 2010), TSTs are a highly attractive renewable energy source given the predictable power generation and limited environmental impact. Strangford Lough, Ireland hosted the first UK grid connected tidal stream device in 2008 (Fraenkel, 2007a). These devices are generally located in regions with strong currents, typically off headlands or within relatively narrow channels.

The first dedicated test centre for the testing of TSTs: The European Marine Energy Centre (EMEC), based in Orkney, Scotland has been operational since May 2005. The test centre is located in an area with extremely favourable marine energy conditions and was created to provide marine energy developers with a site to test grid-connected prototype devices at full-scale.

#### **1.5** Literature review

Flow in the vicinity of submerged obstacles has been studied extensively through laboratory experiments and numerical modelling. 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 (Baker, 1980; Martinuzzi and Tropea, 1993).

#### 1.5.1 Flow around an obstruction

Investigations of shallow water wakes around bluff bodies are significant for a number of environmental and geophysical applications (Kahraman *et al.* 2002). Chen and Jirka (1995) noted that there is need for improved understanding of shallow wakes (from either submerged and / 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 and the effect of submergence is considered important from a tidal energy perspective.

A wake is defined as a region of non-zero vorticity downstream of an obstacle (Batchelor, 1967). 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 (Bahaj and Myers, 2013).

Shamloo (1997) divide this wake into three regions:

- Recirculation region or closed wake exists immediately downstream of an object and is caused by the velocity difference between the free-stream and wake velocities. This region is characterised by flow reversals, vortex formation, growth and shedding. Velocity is greater at the separation line of the obstruction compared with the average velocity.
- Near-wake region Shear layer and wall effects are important in this region.
   Both the recirculation and near-wake region are often termed the 'near wake'.
- 3. **Far wake region** This zone is not solely dependent on the obstruction with the velocity deficit becoming small in comparison with the free-stream velocity.

The form of the wake is affected by two distinct physical processes: flow separation at the boundary of the obstacle, and shear instability along the separation boundaries (Zulberti, 2010). These processes have been extensively studied through laboratory experiments, especially in flow past isolated cylinders. Many experiments use cylinders to represent 'ideal' islands and therefore represent a simplification of the physical processes that naturally occur. Nevertheless, these studies provide insight into the complex flow patterns in the immediate vicinity of islands, which is challenging via field measurements. 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 (Re): 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 (Douglas *et al.* 2005), given by:

$$Re = \frac{\rho U l}{\mu} \tag{1}$$

where  $\rho$  is the fluid density (approximately 1000 kg m<sup>-3</sup> for water), *U* is the velocity of the free-stream, *l* is the length scale (the channel's hydraulic radius or flow depth is usually used as the length scale in open channel flows, while the pipe diameter is often used for pipe flow), and  $\mu$  is the dynamic viscosity (approximately 1.14 x 10<sup>-3</sup> kg m<sup>-1</sup> s<sup>-1</sup> for water) (Douglas *et al.* 2005). In pipe flow, the Reynolds number for laminar flow is < 1000-3000 with turbulent flow thought to occur at *Re* values > 5000-10000 (Chanson, 2004). In open channel flow, laminar flow has a relatively low Reynolds number (*R<sub>e</sub>* < 500) with viscous forces dominating, while for a turbulent flow, the Reynolds number (*R<sub>e</sub>* > 1000) is higher and are dominated by inertial forces (Chadwick *et al.* 2013).

The diameter Reynolds number ( $Re_d$ ) (Batchelor, 1967; Tomczak, 1988; Kundu and Cohen, 2008) is more appropriate for flow past an object because the island or object diameter will dictate the largest scale of the turbulence length, defined by:

$$Re_d = \frac{UD}{v}$$
[2]

where *D* is the cylinder diameter and *v* is the kinematic viscosity of the fluid  $(1.14 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ for water})$  (Douglas *et al.* 2005).

Friction (or viscous) drag caused by the boundary of an object results in a reduction of velocity as the flow passes the obstruction, as shown in Figure 3. Frictional drag therefore increases as the total surface area of the obstruction increases.

The pressure difference across an obstruction in the longitudinal (x) direction results in form drag, which is controlled by the projected area ( $A_p$ ) of the obstruction at higher Reynolds numbers: the larger the obstruction the greater the form drag. The total, or profile drag, is a combination of both frictional and form drag (Douglas *et al.* 2005), defined by:

$$D_f = \frac{1}{2} C_D \rho U^2 A_p \tag{3}$$

where  $C_D$  is the drag coefficient, U is the free-stream velocity, and  $A_p$  is the projected area of the obstruction.

Low diameter Reynolds numbers ( $Re_d < 0.5$ ) are associated with laminar flow where energy dissipation is limited and the pressure is the same on the upstream and downstream sides of the obstruction (Douglas *et al.* 2005). Form drag at these lower  $Re_d$  values is minimal with frictional drag at the boundary layer dominating (Figure 4a). As the Reynolds number increases ( $2 < Re_d < 30$ ), bed shear is minimal with two
symmetrical counter-rotating eddies forming within the near wake region following flow separation (Figure 4b). Elongation in these fixed eddies occurs with increasing  $Re_d$  values and oscillation occurs at  $Re_d \approx 90$  (Douglas *et al.* 2005). If the free-stream turbulence is of sufficient intensity, these eddies alternately detach from the cylinder (Figure 4c) and strengthen with increasing  $Re_d$  values; forming two rows of nonsymmetric vortices known as the von Kármán vortex street (Douglas *et al.* 2005). The exact  $Re_d$  value to initiate vortex shedding for a single cylinder varies depending on the study. Williamson (1992) suggested a  $Re_d$  value of 50, while Gerrard (1978) suggested a range between 55 and 70, and Douglas *et al.* (2005) proposed a value of 90, as shown in Figure 4. The frequency of the vortex shedding causes each shedded vortex to circulate, exerting an intermittent lateral force on the cylinder (Douglas *et al.* 2005). The Strouhal number is a dimensionless value that can be used to analyse the frequency at which vortices are shed in fluid flow, and is expressed by:

$$St = \frac{\omega l}{U}$$
[4]

where  $\omega$  is the oscillation frequency and *l* is the characteristic length (the diameter of the cylinder).

At even higher  $Re_d$  values, high shear rates cause these vortices to diminish, being replaced by a highly turbulent wake. Form drag now dominates. As  $Re_d$  values approach 2 x 10<sup>5</sup> (Figure 4d) the cylinder's boundary layer is laminar, but at higher values the boundary becomes turbulent prior to separation, which occurs slightly further downstream (Figure 4e). Acceleration occurs as flow travels past an obstacle. The stagnation point is characterised by lower velocities at the upstream face (Figure 3) with energy dissipation in the turbulent wake zone immediately downstream of the obstruction, creating a low pressure zone. A recirculation zone dominated by flow reversals, vortices and a separation point exists downstream of the obstruction and is caused by the drag force opposing the flow direction and frictional forces on the boundary (Douglas *et al*, 2005). The turbulent nature of this wake zone is dependent on the Reynolds number.



Figure 3 – Flow regimes around an immersed body (Douglas et al. (2005)

As turbulence is produced in the wakes of an obstruction, mean kinetic energy is converted to turbulent kinetic energy (k): large turbulent structures are converted to smaller structures (Wilson and Shaw, 1977). The turbulent kinetic energy per unit mass is a bulk measure of the total turbulence, defined by:

$$k = 0.5(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$
 [5]



Figure 4 – Fully turbulent wake development with increased diameter Reynolds number for flow past a cylinder (adapted from Douglas *et al.* 2005). 'S' denotes the separation points.

Lloyd and Stansby (1997a) used the diameter Reynolds number ( $Re_d$ ) to describe the free-stream flow in the wakes of surface-piercing islands of conical shape, however, Lloyd and Stansby (1997b) used the depth Reynolds number ( $Re_H$ ) to describe the free-stream flow in submerged conical island wake studies, defined by:

$$Re_H = \frac{UH}{v}$$
[6]

where H is the flow depth.

Flows around 3-D bed-mounted obstacles have been studied to a lesser extent than 2-D obstacles due to their complexity (Lacey and Rennie, 2012). Figure 5 and Figure 6 qualitatively identify the complex 3-D vortical structures associated with flow in the vicinity of submerged obstacles. Flow separation occurs upstream of the obstacle and a horseshoe vortex is formed (Lacey and Rennie, 2012). The horseshoe vortex propagates downstream forming two counter-rotating vortices. Longitudinal tip vortices form at the sides and apex (tip) of the obstacle (Hajimirzaie, 2013). The tipgenerated vortices were observed by Calluaud et al. (2005) for cubes to form into hairpin-like structures. These hairpin-like structures were also observed by Acarlar and Smith (1987) and Martinuzzi (2008) in a study of bed-mounted hemispheres and pyramids respectively. An arch vortex also exists; shedding periodically from the obstacle sides (Lacey and Rennie, 2012). The behaviour of the wake is dictated by the flow conditions upstream of the object; a reduction in the extent of the recirculation zone occurs when a turbulent boundary layer develops upstream of an obstacle (Lacey and Rennie, 2012). Given its relevance to this study, the flow structure in the vicinity of a cone or pyramid is discussed in more detail in the following section.



Figure 5 – Flow around a bed-mounted cube (Martinuzzi and Tropea, 1993)



Figure 6 – 3-D vortex topology surrounding an obstacle (AR = 1) at high relative submergence (Pattenden *et al.* 2005)

# 1.5.2 Flow around a cone or pyramid

Interestingly, few surface-piercing (Lloyd and Stansby, 1997a) and submerged (Martinuzzi and Tropea, 1993; Lloyd and Stansby, 1997b; Martinuzzi and AbuOmar, 2003; Martinuzzi, 2008) studies have examined the flow structure in the vicinity of

conical or pyramid shaped islands. The wake flow structure for objects with pyramid geometries is poorly understood (Martinuzzi and AbuOmar, 2003).

Martinuzzi (2008) found that vortex shedding can be classified into four conditions depending on the pyramid apex angle. This is contrary to the findings of Lloyd and Stansby (1997a) who noted that modifying a conical island's side slope from 8.0 to 33.1° had little effect on the wakes produced. This could be because the slope was too small.

Identifying vortex structures via surface pressure measurements or single-point velocity measurements is difficult (Martinuzzi, 2008); however, the latter can be addressed by increasing the measurement grid density. The velocity field along the side face of the pyramid studied by Martinuzzi (2008) is shown in Figure 7. Downstream of the tip, a large vortex develops and extends to the wake vortex forming a hairpin structure (Martinuzzi, 2008).



Figure 7 – PIV streamlines obtained with for  $\zeta = 60^{\circ}$  (*AR* = 1.73) and Reynolds number of 33000 (Martinuzzi, 2008)

#### 1.5.3 Effect of relative submergence

Relative submergence (H/h) and its effect on the wake of an obstacle is considered important for a wide variety of applications. With the exception of a few studies (Lloyd and Stansby, 1997a; Lloyd and Stansby, 1997b; Shamloo *et al.* 2001; Ozturk *et al.* 2008; Sadeque *et al.* 2008; Sadeque *et al.* 2009; Lacey and Rennie, 2012), little is known about the effect of relative submergence on the 3-D wake of objects, such as a conical island.

Lloyd and Stansby (1997b) used a particle tracking velocimetry (PTV) system to examine the surface velocities in the vicinity of four submerged conical islands of varying side-slope angles at different levels of relative submergence. In the submerged conical island case, vigorous vortex shedding was observed when the depth above the apex was relatively small (H/h = 1.02) (for slopes 8.0° to 33.1°). It was revealed that

the instability of shear layers between the lower near wake velocities and the accelerated flow across from the apex caused this horizontal shedding. Increasing the water depth caused the low near wake velocity region to narrow with a corresponding decrease in the velocity deficit and less vigorous vortex shedding. Well-organised shedding diminished at a critical depth ( $H/h \approx 1.13 - 1.18$ ).

Shamloo *et al.* (2001) investigated the hydrodynamics associated with hemispheres under varying relative submergence (*H*/*h*) ranging from 0.62 to 4.27 and proposed a classification of flow conditions based on relative submergence, as shown in Figure 8. They defined relative submergence regimes one through four (*H*/*h* > 4, 1.3 > H/h > 4, 1.0 > H/h > 1.3, H/h < 1.0, respectively). In regime one (Figure 8), flow at the surface did not interact with the island wake. For *H*/*h* ranging between 1.3 and 4, the surface water layer did not mix with the island wake layer but surface waves were induced (Figure 8c). For submergence levels ranging between 1.1 and 1.3, the free shear layer mixed through the whole depth (Figure 8d). For submergence levels less than 1 (Figure 8e), a Kármán vortex street was observed in the wake. Shamloo *et al.* (2001) suggested that relative submergence (*H*/*h*) is highly influential with regards to wake geometry, velocity, bed shear stress, and scour.



Figure 8 – Details of flow regimes for hemispherical object (Shamloo et al. 2001)

Sadeque et al. (2008) and Sadeque et al. (2009) evaluated the turbulent wake structure around a vertical cylinder with submergence levels ranging from H/h = 0.73 - 4. Cylinder height varied while the flow depth remained constant during the experiments. At low submergence (H/h = 0.73), Sadeque *et al.* (2008) observed a recirculating wake throughout the water column. When the obstruction was only marginally submerged (H/h = 1.1), the recirculation zone was longer and wider in extent compared to when the object was surface piercing (H/h = 0.73). Horseshoe vortex structures were observed closer to the submerged cylinders than the surface-piercing cylinder. Increases in relative submergence resulted in the upstream boundary layer separation point moving closer to the obstruction; resulting in a reduction in the size of the horseshoe vortex system. At greater relative submergences (H/h = 1.8, 4), Sadeque et al. (2008) observed in the area immediately downstream of the cylinder, a 3-D flow recirculation with fluid flowing over the apex disrupting the vortex street in the wake region. Since the object height varied and the flow depth remained constant, the shortest structure (H/h = 0.73) was comparatively slender (height >> width) compared with the tallest object (H/h = 4), which was relatively squat (height ~  $\frac{1}{2}$  width), making comparisons between the experiments more difficult. For example, the length of the recirculation zone was greater at H/h = 1.8 than at H/h = 4 but this could been due to a taller obstacle for H/h = 1.8. The studies by Sadeque *et al.* (2008) and Sadeque *et al.* (2009) are useful when examining the effect of submergence level on the flow structure around different length cylinders, however, in a coastal system, objects remain constant with a fluctuating free surface over a tidal cycle.

Lacey and Rennie (2012) examined the effect of submergence on a bed-mounted cube. They observed that changes in submergence level have a significant influence on the 3-D flow structure of submerged bed-mounted obstacles.

Despite the numerous wake studies that have been undertaken in relation to flow around obstacles of varying geometries, very few have examined in detail the influence of submergence of a conical island on the far and near wake. Therefore, information relating to the effect of relative submergence on wake extent, both longitudinally and laterally, and the 3-D flow structure and turbulence characteristics of the near wake is lacking in previous studies of this nature.

# 1.5.4 Natural island wakes

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 influences the flow. The quantification of island wakes is also important for numerical model validation.

The preceding sections have focused on fluid flow past idealised objects, however, in reality this is rarely the case. Given the importance for aspects such as the prediction of nutrients, sediments, and biological particle transport paths (Wolanski and Hamner, 1988; White and Deleersnijder, 2007), as well as local flushing rates whereby water remains trapped in the recirculation region downstream (Wolanski *et al.* 1984a; Lloyd

*et al.* 2001), there have been relatively few studies into wake quantification of natural bathymetric features. In addition, although the biological enrichment that occurs around oceanic islands, termed the 'island mass effect', there have been few studies that have examined the exact physical cause of this phenomenon (Barton, 2001).

Lueck and Mudge (1997) and Kunze and Toole (1997) examined turbulence in the vicinity of seamounts, Klymak and Gregg (2001) investigated variable depth sills, Nash and Moum (2001) focussed on a shallow water continental shelf bank, Althaus *et al.* (2003) observed the interactions of large-scale tides with a deep ridge, Edwards *et al.* (2004) studied sidewall ridges, and Dewey *et al.* (2005) studied stratified tidal flow over an isolated submerged topographic feature. Oceanic studies tend to concern stratified flow with weaker tidal currents. The ebb and flood of a tide over coastal features adds greater complexity.

In shallower water, a number of studies have been undertaken to examine flow in the vicinity of coastal features. Wolanski (1984a; 1988) 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.* (1992) 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 include: Hogg (1980); Pingree and Maddock (1980); Falconer *et al.* (1985; 1986; 1987); Simpson and Tett (1986); Wolanski (1986); Black and Gay (1987); Ingram and Chu (1987); Tomczak (1988); Wolanski and Hamner (1988); Signell and Geyer (1991); Davies and Mofor (1990); Middleton

*et al.* (1993); Dietrich *et al.* (1996); Neill and Elliott (2004a); Neill and Elliott (2004b); Blaise *et al.* (2007); Dong and McWilliams (2007); White and Deleersnijder (2007); White *et al.* (2008); White and Wolanski (2008)

Historically, detailed field observations of ocean circulation have relied on direct measurements through moored current meters and radar-tracked drogues (Wolanski *et al.* 1984a, 1984b). Remotely sensed aerial, x-band radar and satellite imagery have also been employed to examine surface features, including eddies, jets and shear zones (Maxwell, 1968; Van Dyke, 1982; Wolanski *et al.*, 1984a; Ingram and Chu, 1987; Pattiaratchi *et al.* 1987; Bell, 2008). More recently, acoustic Doppler current profilers (ADCP) have been utilised to measure oceanic currents, having the added benefit in their ability to measure three-dimensional (3-D) current velocities through the water column.

Neill and Elliott (2004a) 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 (Neill and Elliott, 2004a; 2004b); small islands in Rupert Bay, northern Quebec, Canada (Ingram and Chu, 1987)) are generally characterised by a von Kármán vortex street with eddies shedding alternately from both sides of the island.

Neill and Elliott (2004a; 2004b) 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 (1991).

In idealized laboratory experiments, molecular friction controls the frictional boundary layers (Tomczak, 1988), however, turbulent viscosity dominates in the ocean (Neill and Elliott, 2004b). Using the Reynolds number, Re, which is based on the kinematic viscosity, for the prediction of an oceanic unsteady or steady wake is therefore not possible (Dietrich *et al.* 1996; Neill and Elliott, 2004b). The island wake parameter, P, (Wolanski, 1984a) was therefore developed for the prediction of island wakes:

$$P = \frac{UH^2}{K_z l} \tag{7}$$

where U is the free-stream velocity, H is the water depth,  $K_z$  is the vertical eddy diffusion coefficient (which when depth-integrated is 0.01H|U|), and l is the characteristic length scale, which in this case is the cross-stream island length.

The island wake parameter is therefore a balance between the vorticity flux being transferred to the eddy at the separation point and the vorticity flux extracted from within the eddy, assuming that the eddy is of a similar scale to the island width (Neill and Elliott, 2004b). For  $P \ll 1$ , friction dominates and quasi-potential flow occurs, for  $P \sim 1$ , a stable wake results, and for  $P \gg 1$ , bottom friction is negligible and the wake is of a similar nature to that of flow around obstacles in the laboratory at high *Re* values (Wolanski, 1984a). Values of *P* for islands varied from 1.3 to 5 in Rupert

Bay (Ingram and Chu, 1987) with evidence of a vortex street, while values of 0.8 were observed for flow past Lundy Island, Bristol Channel (Pattiaratchi et al. (1987) when no wake was evident, two vortices at P = 1.7 and a vortex street at P = 2 (Neill and Elliott, 2004b). Tusker Rock in the Bristol Channel had a P value of 7 and displayed a narrow steady wake, while Grassholm Island had a P value of 169 with the evidence of a vortex street (Pattiaratchi et al. (1987). Cramp et al. (1991) calculated a P value of 2.3 for Flat Holm Island in the Bristol Channel and predicted an unsteady wake. Table 4 shows the island wake parameter for a number of naturally-occurring islands, including the one pertinent to this study using a velocity of 3 m s<sup>-1</sup> (peak flood) and 1.1 m s<sup>-1</sup> (peak ebb), a depth of 23 m, a depth-integrated  $K_z$  value of 0.69 m<sup>2</sup> s<sup>-1</sup> and 0.25 m<sup>2</sup> s<sup>-1</sup>, and a width of 50 m. Neill and Elliott (2004b) note that a limitation of the island wake parameter is that without measured data, values of  $K_z$  are difficult to define and can vary from 0.01 m<sup>2</sup> s<sup>-1</sup> in Rupert Bay (Ingram and Chu, 1987) to 0.25 m<sup>2</sup> s<sup>-1</sup> in the Bristol Channel (Cramp et al. 1991). Therefore, using this parameter to predict island wakes is questionable. Furthermore, selecting a suitable value for U can be difficult through field measurements, as will be shown later in this thesis.

Location	<i>l</i> (m)	Р
Beamer Rock neap/flood	50	60
Beamer Rock neap/ebb	50	60
Beamer Rock spring/flood	50	60
Beamer Rock spring/ebb	50	60
Tusker Rock	100	7
Grassholm Island	370	169
Flat Holm	700	2
This study (Horse Rock) spring/flood	50	46
This study (Horse Rock) spring/ebb	50	46

Table 4 – Island wake parameter, P, for a number of naturally-occurring islands (adapted from Neill and Elliott, 2004b)

TSTs differ from natural oceanic features by extracting the kinetic energy from the tidal flow, reducing the flow velocity downstream (Bahaj and Myers, 2013), 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 (Bahaj and Myers, 2013). 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 / structural integrity of a device?

Few studies have examined wakes created by TSTs in coastal environments (Boake, 2011). Experimental studies into the characterisation of TST wakes have been conducted (Myers and Bahaj, 2009; Maganga *et al.* 2010; Rose *et al.* 2011a; Stallard *et al.* 2011). Numerical studies comparing experimental data with Computational Fluid Dynamics (CFD) models have also been performed (Mycek *et al.* 2011; Rose *et al.* 2011b). Pure numerical modelling studies have also been undertaken (Ghidaoui *et al.* 2006; Mason-Jones, 2010; Malki *et al.* 2011; Myers and Bahaj, 2012). Tedds *et al.* (2014) provides a summary of the experimental and numerical TST wake studies undertaken to date.

# 1.5.5 Tidal resource characterisation

Marine energy resource assessments are fundamental in order to determine the suitability of an area based on parameters such as velocity magnitude (particularly in the longitudinal, x, direction), velocity shear, vertical velocity, and directionality. These assessments serve to quantify the power available within a system, which can

subsequently be used to determine the device-dependent extractable power. Pacheco *et al.* (2014) noted that a number of rudimentary analytical models have been established; however, these models assume a non-divergent volume flux. This assumption therefore neglects spatial variability along the channel. It will be shown later in this thesis that spatial variability in tidal velocities is resultant from irregularities in both bathymetry and coastline configuration. Designing a TST array therefore requires site-specific velocity measurements (ideally over a one lunar month period) in order to establish the local hydrodynamics, including the oscillations in forces on TST devices (Pacheco *et al.* 2014).

Considerable work has centred on characterising the tidal resource of various locations worldwide in the interest of marine energy extraction, particularly that pertaining to tidal stream energy. Carballo *et al.* (2009) studied the tidal resource in a coastal embayment: the Ría de Muros, north-west Spain using an ADCP-validated numerical model (Delft3D-FLOW). Stevens *et al.* (2012) used both moored and vessel-mounted ADCP measurements as well as a Vertical Microstructure Profiler manufactured by Rockland Scientific International Inc. to examine the velocities and turbulence statistics in the Karori Rip area of Cook Strait, New Zealand. Ramos and Iglesias (2013) tested the performance of two TST designs against a novel site-specific turbine efficiency parameter using the Ría de Arousa, a large estuary in north-west Spain, as a case study. Fairley *et al.* (2013) used tidal velocity data collected via vessel-mounted ADCP measurements to calculate the tidal energy flux within Ramsey Sound and the Bishop and Clerks, Pembrokeshire, Wales. Palodichuk *et al.* (2013) used moored and vessel-mounted ADCP measurements to help understand the flow characteristics in north-rest Marinely Inlet, Puget Sound, Washington, USA. Ramos *et al.* (2013; 2014)

developed a high-resolution numerical model (validated with moored ADCP measurements) of the Ría de Ribadeo in north-west Spain, while Sanchez et al. (2014) examined the effects of TSTs (floating and bottom-fixed) on the estuarine circulation within the Ría de Ortigueira. Serhadlioğlu et al. (2013) numerically modelled the tidal energy potential of the Anglesey Skerries, Wales. Easton et al. (2010; 2011; 2012), Adcock et al. (2013), Goddijn-Murphy et al. (2013), Draper et al. (2014) and Martin-Short *et al.* (2015) examined the tidal resource of the Pentland Firth, Scotland through a combination of direct measurements and numerical modelling, while Neill et al. (2014) numerically examined the tidal resource of Orkney, Scotland and the highlighted the role of tidal asymmetry on the net power output. Gunawan et al. (2014) used acoustic Doppler velocimeter (ADV) measurements to assess the tidal resource in the East River tidal strait, near Roosevelt Island, New York. O'Rourke et al. (2014) studied the tidal resource associated with the Bulls Mouth and the Shannon Estuary, Ireland using a combination of measured and modelled data. Tang et al. (2014) used a combination of moored and vessel-mounted ADCP measurements as well as a numerical model to characterise the tidal resource along the coast of New Jersey, USA. Thiébot et al. (2015) created a 2D hydrodynamic model of the Alderney Race, France to help understand the effects of TSTs on the local hydrodynamics and sediment transport.

Harmonic analysis of vessel-mounted ADCP measurements can also be performed (Geyer and Signell, 1990; Simpson *et al.* 1990; Vennell, 1994; Carrillo *et al.* 2005; Murphy and Valle-Levinson, 2008; Epler, 2010, for example).

There are many challenges facing the tidal energy industry, including physical, political, social, environmental and financial factors. It is beyond the scope of this thesis to discuss all of these issues; instead the physical factors will be discussed henceforth.

Tidal stream energy devices occupy a much greater overall flow depth (up to 70%) compared to wind turbines (Sustainable Energy Ireland, 2008). Extracting more than 10 - 15% of the tidal stream resource is considered to be detrimental; increasing exponentially (Sustainable Energy Ireland, 2008). Given the relative infancy of this technology, first generation devices are likely to be located in coastal areas with favourable marine environments and vessel navigation, however, as TST technology matures, an increase in conflicts with local shipping, higher turbulence levels and velocity shear with depth is likely (Mason-Jones *et al.* 2013).

Other issues limiting TST technology are deployment and maintenance, electricity transmission, and environmental impacts (O'Rourke *et al.* 2010). The harsh conditions in which these devices are to be deployed, coupled with the limited slack water time (only a few minutes between tides in some cases) means that TSTs must be designed so they can be deployed swiftly.

One of the biggest issues currently facing the tidal energy industry is scarcity of field data. Although costly, field data is imperative for the accurate characterisation of tidal energy sites. This information is also important for the validation of numerical models to ensure confidence in the modelled outputs in order to obtain a better representation of the environment, i.e. velocity profile, turbulence, seabed roughness, bathymetry and waves.

Maintenance and servicing access is essential to ensure the design life of a TST is not compromised. Vessels will be required to perform this, which in itself is hazardous and challenging. The turbine of MCT's SeaGen device can be raised above sea level to allow for maintenance.

Transmission of electricity ashore is another issue facing the industry, with greater cabling distances anticipated as the technology matures and is able to withstand the pressures associated with being deployed in deeper water. The proximity of TSTs from the shore will therefore have cost implications (Bryden *et al.* 1998). Grid connection is another issue facing the industry. Although costly and likely to be opposed by the general public, upgrading the grid network may be required to transmit the tidally-generated electricity.

TSTs operate in harsher conditions than wind turbines and are subject to higher structural loadings. The higher density of seawater means that TSTs generate a much larger thrust (Bahaj and Myers, 2003), which will require stronger, more costly materials (O'Rourke *et al.* 2010). TSTs can also be affected by biological fouling from marine life, increased material corrosion from salts and the potential for blade cavitation in shallow water (Douglas *et al.* 2008). Blade vibrations from velocity fluctuations around a TST rotor can also lead to failure. Although difficult to measure and quantify through field data, turbulence levels must be accounted for when designing a TST (O'Rourke *et al.* 2010). The difficulties associated with taking in-situ

turbulence measurements means that at present the effect of turbulence on a TST is limited to experimental studies and numerical modelling.

The inherent nature of TST deployment sites means that they are often located in close proximity to shipping lanes, with vessel draughts in some areas reaching 14.5 m (Willis *et al.* 2010). For instance, the Bristol Channel has a number of potentially attractive TST sites, however, this waterway is heavily shipped for various activities, which may prevent the deployment of a device at a site. Furthermore, the Bristol Port Company (BPC) has proposed plans to expand Avonmouth Docks to include a deep water berthing facility for container ships with a maximum draught of 16 m (Willis *et al.* 2010).

Fujita (2000) noted that a distance of within 1 km of the coastline and at a depth of between 20 - 30 m is optimal for a TST site. Furthermore, tidal velocities are generally high in shallower coastal areas, such as estuaries, coastal lagoons, and constricted channels (Pacheco *et al.* 2014), but many of these areas are vertically constrained, as observed in the Bristol Channel (Willis *et al.* 2010) and can therefore impede or even preclude TST deployment. These spatial constraints greatly reduce the available resource, particularly since early devices (i.e. prior to 2010) cannot operate in depths exceeding 50 m (Sustainable Energy Ireland, 2008). Practically, jack-up barges used to install these devices can only operate in maximum depths of 40 m, which limits first generation devices to shallower water (Sustainable Energy Ireland, 2008). A number of demonstration devices have been installed worldwide, with a limited number of full-scale prototypes (SeaGen, Strangford Lough, Northern Ireland; OpenHydro, Orkney, Scotland, for example) (Pacheco *et al.* 2014). The majority of these

demonstration devices are horizontal axis devices, however, given the depth constraints at many potential tidal energy sites, there has been a recent shift towards vertical axis and floating tidal energy devices.

It has been suggested that the optimum tidal velocity is between  $2 - 2.5 \text{ m s}^{-1}$ ; slower currents tend to be uneconomic while higher velocities can lead to blade loading problems (Soares, 2002). This was reinforced in the Offshore Renewables Resource Assessment and Development (ORRAD) Project (PMSS, 2010), which stated that mean peak spring flow speeds must exceed 2 m s<sup>-1</sup>; and is consistent with Sustainable Energy Ireland (2008). It is, however, expected that the velocity required for economic viability will reduce with advances in TST technology. Developers are starting to design devices capable of operating economically in tidal velocities peaking at approximately 1.5 m s<sup>-1</sup> (Sustainable Energy Ireland, 2008). Figure 9 shows the total UK tidal stream resource for a range of velocities and water depths. Currently, TSTs are being designed to be deployed in areas with depths ranging between 30 – 40 m (Black and Veatch, 2005), however, the tidal stream resource is greater for depths > 40 m. Designing TST devices that can harness tidal stream energy at these depths, while withstanding the pressures associated with these depths, will allow greater energy generation and reduce the reliance on fossil fuels.

	B&V 2004 Total Resource (GWh/y) (% in brackets)							
Depth Range (m)	Velocity Range (m/s)					Total		
	<2.5	2.5 - 3.5	3.5 - 4.5	4.5 – 5.5	>5.5	Total		
<25	139	2806	690	0	0	3635		
	(0.1)	(2.6)	(0.6)	(0.0)	(0.0)	(3.3)		
25 - 30	82	1898	0	0	0	1981		
	(0.1)	(1.7)	(0.0)	(0.0)	(0.0)	(1.8)		
30 - 40	865	6468	10338	0	0	17671		
	(0.8)	(5.9)	(9.5)	(0.0)	(0.0)	(16.2)		
>40	2957	19262	12618	31615	19505	85957		
	(2.7)	(17.6)	(11.6)	(28.9)	(17.9)	(78.7)		
Total	4043	30434	23647	31615	19505	109244		
	(3.7)	(27.9)	(21.6)	(28.9)	(17.9)	(100.0)		

Figure 9 – B&V 2004 UK total resource distribution (Black and Veatch, 2005)

Tools to determine suitable TST sites have been introduced prior to this study. For example, Iglesias *et al.* (2012) developed a numerical Tidal Stream Exploitability (TSE) index (validated against moored ADCP data) to aid the selection of depthlimited TST sites, using the Ría de Ortigueira estuary in north-west Spain as a field site. This numerical model (Delft3D – FLOW) examined two parameters, depthaveraged tidal flow and water depth to identify suitable TST sites. Moreover, Fairley *et al.* (2011) developed a GIS-based tool to assess various constraints on TST deployment around Pembrokeshire, Wales, specifically a minimum peak spring current of 2 m s<sup>-1</sup> (based on a 3-D POLCOMS model (Holt and James, 2001)), a minimum depth requirement based on a 10 m diameter turbine, a seabed gradient within 10% of a value suggested by a TST developer, port proximity, fishing activity and Special Area of Conservation (SAC) habitats. Both studies used depth-averaged tidal velocities, which can result in unrealistic flow conditions. Furthermore, the grid resolution of the model used in the study by Fairley *et al.* (2011) was approximately 300 m, which is too coarse to accurately capture the complicated bathymetry of the area, again resulting in less accurate tidal velocities. This study relies on "real" velocity data and as such, captures the effects of bathymetry on tidal flow more realistically.

#### 1.6 Research aims and objectives

Even outside the context of tidal resource development, few field studies to date have measured directly the effects of bathymetry on current speed and 3-D velocity structure of tidal flow through narrow straits (Neill and Elliott, 2004a; Carballo *et al.* 2009; Easton *et al.* 2010; Easton *et al.* 2011; Marine Scotland, 2011; Ramos and Iglesias, 2013; Ramos *et al.* 2013, 2014; Pacheco *et al.* 2014; Sanchez *et al.* 2014) and even fewer have examined the 3-D flow structure of the wake generated by submerged islands, which would be useful for tidal energy developers trying to understand the effect of deploying a device on the local flow field. Although research into effects of TSTs on the environment and the effects of the environment on devices is becoming more prevalent, to date, few field studies have investigated the feasibility of installing these devices in areas that are subject to high current speeds (Boake, 2011), which are attractive from an energy generation perspective.

Measurements of tidal flow within Ramsey Sound are extremely limited, and few studies of a similar nature (particularly from survey vessels) have been conducted previously (Evans *et al.* 2013; Fairley *et al.* 2013). This is reinforced by Woolf *et al.* (2014, p. 6) who noted that 'tides have been the subject of long and extensive study

although, paradoxically, there have been relatively few studies in the energetic tidal channels where currents are strongest'. The complex flow within a tidal channel can be mapped effectively by a combination of vessel-mounted ADCP surveys and numerical modelling (Simpson *et al.* 1990; Valle-Levinson *et al.* 2000; Sepúlveda *et al.* 2004; Carrillo *et al.* 2005; Goddijn-Murphy *et al.* 2013, for example), but to map all tidal sites at a sufficient resolution is unrealistic.

The principal aims of this thesis are to investigate the influence of bathymetric and topographic irregularities on velocities and assess a prospective tidal energy site for its suitability for TST deployment. The motivation for this study stems from the requirement to better understand the influence of bathymetric features on tidal flow and the implications of key hydrodynamic and physical parameters on TST deployment at this critical stage before these marine renewable energy developments are installed.

These aims will be achieved through the following objectives:

**Objective 1:** To examine the influence of submerged objects on the local flow field. This information is important for the validation of numerical models as well as for an improved understanding of the complicated flow patterns in the vicinity of these structures. Understanding the principal controlling mechanisms on wake development and decay will also help tidal energy developers optimise TST array layouts to ensure the wake created by an upstream device is not compromising the performance of a device downstream. **Objective 2:** To investigate the hydrodynamic parameters pertinent to macrotidal straits. Having an understanding of the effects of bathymetry and coastline configuration on these hydrodynamic parameters will help inform tidal energy developers of the various factors to consider when locating potential TST sites.

**Objective 3:** To develop a TST suitability tool which examines the effects of velocity, water depth and bed slope on power availability within a macrotidal coastal area. This tool is considered important as it highlights the significance of these physical parameters in constraining tidal energy sites, which has implications on the nature of the TST design.

#### 1.7 Thesis structure

The structure of this thesis broadly follows the objectives set out above. Chapter 2 examines the effect of submergence on the wake of an object in idealised conditions, while Chapter 3 focuses on the influence of bathymetry and coastline configuration on tidal flow in a macrotidal strait, specifically the effect of submerged islands on the 3-D flow structure downstream. Chapter 4 evaluates the viability of macrotidal straits for TST installation by examining parameters such as vertical shear, vertical velocities, flow magnitude, bed slope and water depth. The effect of depth-averaging these data is also assessed. Conclusions are presented in Chapter 5, including recommendations for further work.

# 2 INVESTIGATION OF FLOW AROUND AN OBSTRUCTION

### 2.1 Introduction

Laboratory experiments were conducted to investigate the influence of relative submergence (H/h) on velocity and turbulent structures within the wake of a conical island for two different flow conditions: surface-piercing and fully submerged. Although flow in nature is more complicated than that found in laboratory experiments or simple numerical models (Lu and Lueck, 1999), it is important to examine the effect of relative submergence on the wake created by an obstacle in a controlled setting. Given the constantly changing sea level and tidal velocities, the effect of relative submergence on the wake form is difficult to quantify through field measurements. From a tidal energy perspective, understanding the effect of this parameter on the wake of submerged features is useful, particularly for TST design.

The motivation for undertaking these experiments was twofold: 1) to study the wake characteristics for the two flow conditions in the near wake region, and 2) to examine the effect of relative submergence on wake development and its decay in the far wake region, and how these change with submergence level, which again is challenging in the field due to the spacing between survey transects.

A natural or artificial obstruction within a fluid creates a wake comprising two distinct regions (as described in Section 1.5): the near and far wake. Flow structures within the near wake region are more complex than the far wake comprising reduced flow, flow reversals, more intense vertical velocities and turbulent flow structures (Sadeque *et al.*).

2009). Relatively few studies have been conducted to examine the near-wake characteristics. It is therefore important to study the characteristics of shallow water near-wakes behind obstructions of different levels of relative submergence.

Although vessel-mounted ADCP surveys are a valuable tool for assessing the potential tidal resource and suitability of an area for TST deployment (as will be shown in Chapter 4), as well as providing an insight into wake recovery, the following chapter will show that these surveys do not fully capture the detailed flow structures downstream of oceanic features due to aeration of the water column and the lack of spatial resolution between survey tracks. In addition, the navigational constraints of maintaining a fixed vessel position, coupled with the difficulties of capturing turbulence using ADCP devices (sampling frequency is not sufficient) meant that these flow structures could not be captured fully. To accurately quantify these wake characteristics would require a grid of seabed-mounted ADCPs running in a northsouth direction along the centreline of Horse Rock. As discussed in the following chapter, however, seabed-mounted ADCPs (given their beam angles) require a minimum spacing of approximately 80 m to avoid interference from adjacent units. This would be sufficient for studies of far wake development and decay (with the assumption that the wake follows the centreline of the obstruction and does not migrate from it, which is not the case within Ramsey Sound due to the complicated bathymetry) but too coarse to examine the flow structures in the near wake region. Laboratory experiments were therefore deemed necessary to support and extend the findings of previous field (including those pertaining to Chapter 3), laboratory and numerical studies on wake development downstream of a submerged structure.

## 2.2 Methodology

# 2.2.1 Flume description

The laboratory experiments were undertaken in the Hydro-Environmental Research Centre (HRC) of Cardiff University in a horizontal slope-adjustable flume with glass sidewalls and bed, 10 m long, 1.2 m wide, and 0.3 m deep, as shown in Figure 10. A head tank, which provided a constant flow rate, was located at the upstream end of the flume. A 50 mm thick hexagonal honeycomb flow straightener with 6 mm openings was positioned immediately downstream of the head tank and extended the full width of the 1.2 m wide flume to reduce velocity fluctuations and produce smooth, uniform flow. A weir at the downstream end of the flume controlled the flow depth. A storage tank comprising 9 x 1 m<sup>3</sup> capacity tank sections was located downstream of the weir. The gradient of the bed was adjusted by a lever, which was set at approximately 0.001 (1 in 1000). Examination of the bed revealed that the glass pane situated at approximately 8000 mm downstream of the inlet was slightly raised (in the order of 7.5 – 8.5 mm) compared with the one upstream. This resulted in a small increase in water levels in the vicinity of this step.



Figure 10 – Schematic diagram of the flume used for the laboratory experiments

# 2.2.2 Discharge and flow depth measurement

The relative submergence level is continually changing as the tide ebbs and floods; thereby making its influence on the wake a difficult parameter to isolate. By setting a constant flow rate during the laboratory experiments ensured that the effect of relative submergence on the wake extent and structure could be examined. Values of H/h less than unity indicate a surface piercing condition, while values of H greater than unity indicate a submerged condition. The minimum (0.96) and maximum (1.24) relative submergence level used during the laboratory experiments represent the approximate minimum and maximum relative submergence levels of Horse Rock.

The flow within the flume was driven by a pump, which was controlled by a flow meter. A flow gauge, which was connected to an impeller within the pipe conveying the flow back to the inlet beneath the flume, was used to measure the discharge rate. A water level gauge with an accuracy of 0.1 mm was mounted on the railings of the flume and was used to measure the water surface elevation relative to the bed level at 500 mm increments between 1000 mm and 9000 mm along the length of the flume, measured from the inlet. Measurements were not recorded within 200 mm of the outlet in the longitudinal (x) direction as this area was shown to be affected by the raised glass panel. Elsewhere, the variations in the bed elevations were within 0.5 mm of the mean bed level due to the positioning of the railings.

Uniform flow conditions occur when the flow depth remains unchanged over the channel length, with the energy line, water surface and channel bed all being parallel (Singh, 2009). Uniform flow conditions could not be achieved during the

experimentation because of the uneven base of the flume. Quasi-uniform flow conditions were therefore used, and were established using a similar approach to Xavier (2009), namely:

- 1. Select the lowest flow rate (~  $10 \, \text{l} \, \text{s}^{-1}$ );
- 2. Increase the elevation of the weir incrementally to the maximum flow capacity of the flume ( $z = \sim 240$  mm) without adjusting the discharge and measure the water surface elevation along the length of the flume at each increment using a Vernier point gauge;
- 3. Reset the weir to its lowest elevation, increase the flow rate and repeat the above;
- 4. Plot the longitudinal flow depth gradient against each weir elevation to select a weir height that has a flow depth gradient close to zero, i.e. a uniform flow depth for the required discharges.

As previously mentioned, it was not possible to achieve uniform flow conditions, however, a discharge of  $13.3 \, 1 \, s^{-1} \, (0.01 \, m^3 \, s^{-1})$  provided a zero gradient of flow along the flume and as such, this discharge was chosen for the laboratory experiments. This flow rate was kept constant for both submergence levels.

# 2.2.3 Conical island

The conical island was constructed from a turned stainless steel section (Figure 11). The base diameter and height of the conical island were originally 650 mm and 115 mm respectively; a 1:200 scale based on the approximate dimensions of Horse Rock, which has a base width and height of approximately 100 m and 23 m respectively. According to Lasher (2001), the blockage ratio (*D/B*), where *D* represents the base diameter of the conical island and *B* is the channel width, should generally be < 0.1 to avoid the effect of the side walls. To prevent sidewall effects given the width of the flume, the base diameter of the conical island was restricted to 162.5 mm (1:800). This equated to a side slope of 55°. These conical island dimensions resulted in a blockage ratio of 0.14 at the base to 0.005 at the apex, which was considered acceptable. Having a geometrically distorted scale is relatively common in physical models (Peakall *et al.* 1996; Sellin *et al.* 2001; Willson *et al.* 2007) in order to reduce scale-effect artefacts (Novak *et al.* 2010; Uijttewaal, 2014). To work within the limits of both the laboratory and flume conditions, it was necessary to have a horizontally exaggerated the scale, i.e. 1:800 in the horizontal and 1:200 in the vertical.



Figure 11 – Conical island with dimensions height 115 mm and bed width 162.5 mm

# 2.2.4 Scaling effects

The difference that occurs when extrapolating the results from a model that is not a direct replication of the prototype is termed a 'scale effect' (Balachandran, 2011). This effect occurs because the model assumes that the dominant force alone controls the fluid motion, however, other forces that are not so important in the prototype may become dominant in the model, which prevents complete similarity (Balachandran, 2011). Scale effects can also arise from difficulties in replicating surface roughness, for example. Although the extrapolated results of a model may differ to the prototype due to scale effects, models can still provide important information that is difficult to acquire at prototype scale.

### 2.2.5 Acoustic Doppler velocimetry

Laboratory-based velocity and turbulence measurements can be made using a number of techniques, including ADV, Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) (Garcia *et al.* 2005). Given the geometry and size of the flume, as well as instrument availability at the time, a 10 MHz Vectrino II profiler acoustic Doppler ADV (termed 'ADV profiler' hereafter) manufactured by Nortek was employed to collect accurate velocity and turbulence measurements. The ADV profiler differs to the more conventional Vectrino ADV as the sampling volume is much larger in the former (as shown in Figure 13 and 14). The ADV profiler makes velocity measurements down a 35 mm range over a 6 mm diameter sampling volume, while the Vectrino I provides point velocity measurements, again over a 6 mm diameter sampling volume. Although the spatial and temporal resolution of ADV measurements is lower than LDA techniques, they display a similar accuracy (Lohrmann *et al.* 1994).

The probe, which is composed of titanium and consists of four receive transducers and one transmit transducer, was joined to the main housing via a cable through the probe end bell (Nortek, 2011b). A mount was fabricated to ensure the probe remained fixed in position. A ruler was attached to the mount to allow the distance from the bed to the face of the transmit receiver to be known. Likewise, a ruler was present on the mount that could be moved across the flume to ensure the exact location of the probe within the flume was known.

The ADV profiler is similar to an ADCP in that it uses the Doppler Effect to measure current velocity (Nortek, 2011b). The velocity data from the ADV is transformed into a Cartesian coordinate system (XYZ), representing the longitudinal (streamwise), lateral (cross-stream) and vertical dimensions in the respective x, y and z planes. The coordinate system of the flume was non-dimensionalised (unless otherwise stated) by dividing by the diameter of the conical island at its half-height ( $D_{50}$ ). For instance, a distance of 100 mm downstream of the conical island represented a longitudinal,  $x/D_{50}$  value of 1.23. Similarly, a distance of 30 mm from the bed represented a vertical,  $z/D_{50}$  value of 0.37. A schematic of the XYZ coordinates is given in Figure 12. Table 5 provides a summary of the ADV profiler configuration and specifications.

The ADV profiler transmits short pairs of sound pulses and measures the change in pitch or frequency of the returned sound based on the Doppler Effect (Nortek, 2011b). Nortek claim that the Vectrino profiler differs from standard Doppler profilers as it is

a bistatic sonar, i.e. it uses separate transmit and receive beams (Nortek, 2011b). The sound pulse is transmitted through a central transducer and received via four passive transducers angled at  $30^{\circ}$  towards the centre (Craig *et al.* 2011), as shown in Figure 13. The angle of these passive transducers produces an intersection point 50 mm below the central transducer (Nortek, 2011b). This results in a 40 - 70-80 mm profiling region away from the central transducer (Craig *et al.* 2011). The ADV continuously transmits ensembles of pulses at 10 MHz, with the sampling rate (up to 100 Hz) being determined by the number of pings per ensemble (Craig *et al.* 2011). The three velocity components within the same sampling volume are acquired by the four receivers (Nortek, 2011b). A  $30^{\circ}$  slant angle means that all three beam pairs measure velocity that is  $15^{\circ}$  away from the transmit beam (Nortek, 2011b). The ADV probe was connected to a PC, which comprised the Vectrino-II Data Acquisition System software, for data collection.



Figure 12 – Nortek ADV profiler. The red taped arm points in the positive *x*-direction.



Figure 13 – ADV profiler velocity range



Figure 14 – ADV profiler operating principle (Nortek, 2011b)



Figure 15 – ADV profiler coordinate system (Nortek, 2011b)
Configuration			
Doppler		Bottom Check	
Sampling rate (Hz)	100	Gain reduction (dB)	50
Velocity range (m s <sup>-1</sup> )	0.5	Sample rate (Hz)	10
Range to first cell (mm)	40	Minimum depth	20
-		(mm)	
Cell size (mm)	1	Maximum depth	150
		(mm)	
Range to last cell (mm)	75	Cell size (mm)	1
Number of cells	35	Number of cells	130
Calibrated range (mm)	40 - 75		

 Table 5 – ADV profiler configuration and specifications (Nortek, 2011b)

Prior to data collection, it was necessary to correctly configure the ADV profiler to ensure the velocity measurements were accurate and representative. The maximum sampling rate of the ADV profiler was used (100 Hz, equating to 100 samples per second) during the measurements. According to the ADV profiler software manual (Nortek, 2011a), 'individual velocity samples are collected at a rate related to the ping interval (related to the velocity range) and averaged over the sampling rate period to produce a final velocity estimate'. A velocity range (which is the maximum measurable velocity for a given ping interval) of 0.5 m s<sup>-1</sup> was used. Nortek (2011a) state that this 'velocity range, combined with the ping algorithm determines the appropriate ping timing parameters to achieve the desired velocity', while ensuring the Doppler uncertainty (or noise) is reduced to an acceptable level. According to Nortek (2011a) and advice from a scientist at Nortek (P Rusello, September 2013, personal communication), the maximum ping algorithm is best suited to relatively low flow conditions and as such, was selected for the experimentation.

The profiling range during the experiments was set at 40 - 75 mm, however, scrutiny of the data quality during data collection revealed that the acoustic signal within the

last 9 mm of the profile, i.e. 66 - 75 mm from the probe, had attenuated such that the signal-to-noise ratio (*SNR*) and correlation (*COR*) values were below the recommended threshold, i.e. < 15 dB and < 70% respectively (P Rusello, September 2013, personal communication). The *SNR* is a measure of the strength of the received acoustic pulse. Seeding the water column increases the *SNR*. The higher the *SNR* values the more reliable the velocity measurements. Throughout the ADV measurements the average *COR* was generally within 75 – 100%. Bottom check was used to determine the distance from the centre transducer to the bottom at a given sampling interval (10 Hz in this case). Bottom check was enabled during data collection to ensure distances to the bed were being collected.

#### 2.2.6 Velocity statistic measurements

Prior to the installation of the conical island, a series of sampling time tests were conducted in the vicinity of the island location for 110 mm: the flow depth corresponding to the submerged test (see Table 6). These tests were conducted to ensure that the sampling period was sufficient to capture meaningful time-averaged velocity statistics. Time series samples are shown in Figure 16a and 16b corresponding to the cumulative time-averaged longitudinal velocity ( $\bar{u}$ ) and cumulative fluctuations in the longitudinal velocity component for the time-averaged value (u') respectively based on a 360 s sampling period at an elevation of 30 mm from the bed. It can be seen that the difference in the cumulative velocity between a sampling period of 100 s and 360 s is less than 0.4%. The cumulative velocity fluctuation with increasing time should tend to zero. By 110 s the cumulative velocity fluctuation is less than 0.5% from zero. Therefore, a sampling time of 150 s was chosen and deemed to be conservative to capture the velocity statistics in the island wake.



Figure 16 – Cumulative time-averaged plots of the longitudinal velocity component  $(\bar{u})$  (A) and turbulent fluctuations in the time-averaged longitudinal velocity component (u') (B) taken at the conical island apex (3500 mm downstream of inlet, or  $x/D_{50} = 0$ ). The z value represents the distance of the central transducer from the bed.

The flow parameters for the surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions are presented in Table 7. These represented the minimum and maximum relative submergence, H/h, that is observed in the field at a 1:200 scale. Based on tide tables of Ramsey Sound, the highest tide is around +5.5 m CD during springs, which equates to a depth of water above the crest of the pinnacle (at approximately +0.9 m CD) of 4.6 m. The lowest tide is around +0.3 m CD, which means that the crest of the pinnacle is surface-piercing with a height of around 0.6 m above the water surface respectively. In this respect, the water depth during the highest and lowest tides are approximately 28.1 m (23 m + 4.6 m) and 22 m (23 m - 0.6 m) respectively, which scales down to a flow depth of approximately 142 mm and 110 mm respectively (see Table 6). Table 7 highlights the previous studies and parameters that are pertinent to this research.

		I.					
Flow condition	Tailgate weir setting (mm)	Water depth (mm)	Relative submergence	Discharge (l s <sup>-1</sup> )	Cross- sectional mean velocity (m s <sup>-1</sup> )	Diameter Reynolds number	Depth Reynolds number
Surface- piercing	81	110	0.96	13.3	0.10	7100	7310
Submerged	113	142	1.24	13.3	0.10	5220	8114

 Table 6 – Summary of experimental conditions. Island height 115 mm.

Table 7 –	<b>Summarv</b>	of 1	previous	experiments	pertinent	to this study
		~			F	

Author(s)	Object	H/h	$Re_d$
Lloyd and Stansby (1997b)	Cone	1.01 - 1.37	5750 - 14416
Sadeque <i>et al.</i> (2009)	Cylinder	0.73 - 4.0	21000
Lacey and Rennie (2012)	Cube	2.0, 2.5, 3.0	92000 - 140000
Shamloo <i>et al</i> . (2001)	Hemisphere	0.62 - 4.27	6557 - 57377
Current study	Cone	0.96, 1.24	7100, 5220

### 2.2.7 Data acquisition

Seeding material was in the form of neutrally buoyant silicate powder with a 10  $\mu$ m mean diameter (density of 1.1 g/cm<sup>3</sup>) and was added the flow when the *SNR* dropped below 20 dB.

A series of probe configurations were adopted to examine the wake structure in the vicinity of the conical island. The initial measurements were undertaking with the probe orientated in a downward-looking position (see Figure 17).

The first set of measurements were sampled for the surface-piercing, H/h = 0.96, condition (Figure 17a). Two probe elevations were used at this submergence level in order to capture the flow structure for the entire mid-bottom part of the water column, namely 87 mm and 62 mm from the bed (measured from the central transducer). These elevations were selected in order to collect measurements for the greatest volume of water. With the probe located 87 mm from the bed, the top and bottom of the measured profile occurred 47 mm and 12 mm from the bed. With the probe positioned 62 mm from the bed, the top of the measured profile occurred 22 mm from the bed. This probe elevation resulted in a profile range of 22 mm given the presence of the bed and as such, the last 13 mm of the profile was disregarded. Both elevations allowed for a 10 mm overlap of both profiles and thus prevented data gaps within the water column. A 40 mm blanking region existed where no measurements could be made. It was therefore not possible to examine the velocities in this portion of the water column.

The second set of experiments were carried out for the submerged, H/h = 1.24, condition (see Figure 17b). The increased flow depth allowed three downwardorientated probe profiles to be measured at elevations of z = 120 mm, z = 90 mm and z = 60 mm. With the probe located 120 mm from the bed, the top and bottom of the measured profile occurred 80 mm and 45 mm from the bed. With the probe located 90 mm from the bed, the top and bottom of the measured profile occurred 50 mm and 15 mm from the bed. With the probe located 60 mm from the bed, the top of the measured profile occurred 20 mm from the bed. As before, this probe elevation resulted in a profile range of 20 mm given the presence of the bed and as such, the last 15 mm of the profile was disregarded. Figure 17 provides a schematic of the downward-orientated probe positions for H/h = 0.96 and H/h = 1.24 respectively.



Figure 17 – Downward-looking ADV profiler configuration for two velocity measurements for H/h = 0.96 (A) and H/h = 1.24 (B). Profiles are measured from the face of the ADV's central transducer (as shown in Figure 13).

The second probe configuration required the ADV to be orientated on its side to face the sidewall (as shown in Figure 18) in order to examine the velocities higher in the water column. Since the probe head had to be fully submerged during data collection it was still not possible to collect velocity measurements in top 35 - 40 mm of the water column. Three sideways probe elevations were employed; 72 mm, 62 mm and 52 mm from the central transducer to the bed for the surface-piercing condition (H/h = 0.96), and 110 mm, 100 mm and 90 mm from the central transducer to the bed for the submerged condition (H/h = 1.24). Since the probe was orientated sideways, the spatial resolution of these measurements in the water column was not as high (i.e. increments of 10 mm as opposed to 1 mm for the downward-orientated configuration) as the ADV was now profiling laterally across the flume. The probe head was initially oriented towards the farthest sidewall, however, the communication cable attached to the probe head prevented measurements to be taken close to the nearest sidewall. The probe head was therefore rotated 180° in the same axial plane to ensure velocity measurements could be made close to the nearest sidewall.

A copy of the measurement grids used for the laboratory experiments is provided in Appendix B. A much denser grid (25 mm spacing) in both the lateral (y) and longitudinal (x) directions was used in the vicinity of the conical island in order to capture the detailed wake structure. As distance from the conical island increased, the spacing of the measurements, both longitudinally and laterally, also increased. The symmetrical nature of the conical island plus its central position within the flume meant that measurements for half of the flume (laterally) were made. A mirror image of the measurements was subsequently made during post-processing in order to present data for the entire width of the flume.



Figure 18 – Sideways-orientated ADV profiler configuration

# 2.2.8 Post-processing

Given the large datasets that were created during data collection (each sampling point generated 15,000 measurements for each flow component, u, v,  $w_1$ ,  $w_2$ ), it was necessary to use a relatively powerful post-processing tool to filter any poor quality data. Therefore, all ADV data was post-processed (filtering, re-structuring, and calculation of time-average velocities and turbulence statistics) using the Matlab software due to its data handling capability. Furthermore, given the relative infancy of the ADV profiler, no standard post-processing software currently exists.

The initial stage involved the removal of data according to the *SNR* and *COR* thresholds. A Matlab filtering script was developed by Nortek to screen the ADV

profiler data (P Rusello, September 2013, personal communication). The script was examined to ensure its appropriateness for this study and a batch processing script was created (see Appendix A) to interrogate each individual data file and remove the data that did not meet the following criteria: *SNR* < 15 dB and *COR* < 70%. The bad quality data were replaced by NaNs. The filtering script also applies an outlier filter, which assumes a Gaussian distribution, calculates the centre via the median or mean, and removes data outside the defined threshold (3.5 in this case). For example, data greater and/or less than the mean + threshold \* std(signal) are removed (P Rusello, September 2013, personal communication). The standard deviation is calculated using a more robust definition than estimating it from the data so outliers do not have too much influence. All files were copied and the filtered filenames saved with "\_Screened" so as to retain the original unfiltered files. The Matlab script used to filter the velocity data is included in Appendix A.

To accurately quantify the turbulent wake created by the conical island, Matlab (vR2012a) was used for the data processing. The processing steps included:

- i. Time average the velocity data over the 150 s sampling period;
- ii. Turbulent kinetic energy (k) and Reynolds shear stresses (-u'w'; -u'v') calculated for each sample point;
- iii. Data flipped about the centreline of the flume (y-plane);
- iv. Data re-structured into the following matrices (measurements grids are provided in Appendix B):

- Depth-averaged Each data point in the *z*-plane was depth-averaged to
   create a single depth-averaged value at each *x*, *y* grid point.
- xy-plane Data arranged into xy-planes containing a single timeaveraged velocity ( $\bar{u}, \bar{v}, \bar{w}$ ) and turbulent statistic for grid point in the xy-plane (i.e. plan view).
- xz-plane Data arranged into xz-planes containing a single timeaveraged velocity ( $\bar{u}, \bar{v}, \bar{w}$ ) and turbulent statistic for each grid point in the xz-plane (i.e. parallel to the sidewall).
- yz-plane Data arranged into yz-planes containing a single timeaveraged velocity ( $\bar{u}, \bar{v}, \bar{w}$ ) and turbulent statistic for each grid point in the yz-plane (i.e. perpendicular to the sidewall).

Time-averaged and turbulence statistics were calculated at each measurement location using a second Matlab script ('Laboratory data re-structuring script') given in Appendix A. These statistics included time-averaged velocities ( $\bar{u}$ ,  $\bar{v}$ ,  $\bar{w}$ ), turbulent kinetic energy (k) per unit mass as given in Eq. [5], and Reynolds shear stresses (–  $\overline{u'w'}$ ;  $-\overline{u'v'}$ ).

The time-averaged velocities and k were subsequently exported either to spreadsheets (MS-Excel) for further analysis or to the Tecplot (v10.0-6-012) flow visualization software.

The longitudinal (*x*), lateral (*y*) and vertical (*z*) distances in the flume were normalised (unless otherwise stated) by the diameter of the conical island at its half-height ( $D_{50}$ ).

For instance, a distance of 100 mm downstream of the conical island represents an  $x/D_{50}$  value of 1.23. Similarly, a distance of 50 mm from the bed represents a  $z/D_{50}$  value of 0.62.

#### 2.3 Results

Although these laboratory experiments are based on idealised conditions, i.e. a flat bed and a quasi-uniform flow, they provide a useful insight into the longitudinal extent of the far wake, which is difficult to quantify in the field given the spatially-varying freestream velocity (U), varying bathymetry and near wake flow structures immediately downstream of the island. Furthermore, tidal velocities and water levels are constantly changing in the field, which makes it difficult to quantify the effect of the submergence of Horse Rock on both the near wake flow characteristics and wake recovery.

# 2.3.1 Near wake region

The purpose of examining the near wake zone was to understand the flow features that are likely to be occurring immediately upstream and downstream of Horse Rock. For ease of comparison between both submergence levels, the longitudinal velocities ( $\bar{u}$ ) will be used to assess wake velocities.

Longitudinal velocity profiles ( $\bar{u}$ ) in the plane of symmetry (along the centreline of the flume) have been produced for a variety of downstream distances of the island ( $x/D_{50}$ ) and are presented in Figure 19a and 19b for the surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions respectively. Upstream of the island (-1.9 $D_{50}$ ), the

approach flow decelerates until a relatively intense flow reversal occurs on the leeward side of the island within the recirculation zone ( $x/D_{50} = 1.2$ ) (this is presented later in more detail in Figure 30b). The flow reversal associated with the recirculation zone is observed in the velocity profiles at  $x/D_{50} = 1.2$  and 1.8 but not at  $x/D_{50} = 2.5$ , suggesting that the reattachment point, i.e. where the velocity becomes positive, occurs somewhere between  $x/D_{50} = 1.8$  and 2.5 for both submergence levels. However, these profiles show that the recirculation zone extends further downstream for the submerged condition compared with the surface-piercing condition. The velocity magnitude of the recirculation zone is slightly higher for the submerged condition. At approximately  $x/D_{50} = 2.5$ , a velocity peak occurs at  $z/D_{50} = 0.25$  and  $z/D_{50} = 0.17$  for H/h = 0.96 and H/h = 1.24 respectively, as the flow accelerates in the vicinity of the reattachment point. Beyond the closed recirculation zone ( $x/D_{50} > 2.5$ ), where the longitudinal velocity is positive, the profiles display a more characteristic log-law profile.

In the vicinity of the apex of the island  $(z/D_{50} = \sim 1.2)$  for the submerged condition (H/h = 1.24) a shear layer exists, particularly at  $x/D_{50} = 1.2$ , 1.8 and 2.5, where the higher  $\bar{u}$  velocities within the upper layer above the apex of the island interact with the undisturbed velocities. Given the blanking zone of the ADV, this region could not be measured for the surface-piercing condition (H/h = 0.96).



Figure 19 – Longitudinal velocity profiles  $(\bar{u})$  (along the centreline of the flume) for the surface-piercing (H/h = 0.96) (A) and submerged (H/h = 1.24) (B) conditions. Dashed lines represent the water surface. Negative values denote flow reversals.

Vertical velocity profiles ( $\overline{w}$ ) are presented in Figure 20a and 20b for the surfacepiercing (H/h = 0.96) and submerged (H/h = 1.24) conditions respectively. Positive and negative values refer to upwelling and downwelling respectively. It is apparent that at both submergence levels, the profiles return to a characteristic log-law profile with increasing distance downstream of the island ( $x/D_{50} = -1.9$ ; 7.4 – 55) as the influence of the obstruction is reduced. This suggests that the near-wake zone, particularly in the vicinity of the recirculation zone and slightly beyond (i.e.  $x/D_{50} =$ 0.9 - 2.5) experiences intense upwelling, particularly for the surface-piercing condition, peaking 0.035 m s<sup>-1</sup> and 0.018 m s<sup>-1</sup>, which peaks at an elevation of  $z/D_{50} =$ 0.4 and 0.5 for the surface-piercing and submerged conditions, respectively.

Immediately downstream of the island for the submerged condition (Figure 19b), water within the surface layer is forced downwards as it overtops the apex of the island. This is seen more clearly in Figure 20b. The highest negative velocity occurs between  $x/D_{50} = 1.8$  and 2.5. During both conditions, there is some upward movement of water particles in the immediate lee of the island, which generally decays with distance downstream.



Figure 20 – Vertical velocity profiles ( $\overline{w}$ ) (along the centreline of the flume) for the surface-piercing (H/h = 0.96) (A) and submerged (H/h = 1.24) (B) conditions. Dashed and dotted lines represent water surface and apex of island respectively. Positive and negative values denote upwelling and downwelling respectively.

Figure 21 displays the longitudinal velocities ( $\bar{u}$ ) at  $z/D_{50} = 0.12$  (10 mm from the bed), 0.37 (30 mm from the bed), 0.6 (47 mm from the bed) and 0.9 (72 mm from the bed)

for the surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions. The streamlines are resultant of the  $\bar{u}$  and  $\bar{v}$  velocity components. The *x*-axis represents distance downstream of the inlet while the *y*-axis represents the distance from the RH sidewall looking in the downstream direction. The island apex is at  $x = 3500 \text{ mm} (x/D_{50} = 0)$  and  $y = 600 \text{ mm} (y/D_{50} = 0)$ .

At  $z/D_{50} = 0.12$ , the flow decelerates on the upstream face of the conical island prior to flow separation for both submergence levels (Figure 21a and 21b). At the separation point, flow separates from the island earlier and stronger for the surface-piercing condition. Local flow acceleration is observed at the sides and immediately downstream of the island outside the wake. Downstream of the conical island, the flow converges at the reattachment point at approximately  $x = 140 \text{ mm} (x/D_{50} = 1.7)$  and x $= 160 \text{ mm} (x/D_{50} = 2.0)$  for the surface-piercing and submerged conditions respectively. This suggests that the recirculation region, defined as the region of flow reversal up to the reattachment point, is marginally longer for the submerged condition and is approximately twice the island's diameter at this elevation.

Higher in the water column ( $z/D_{50} = 0.37$ ), the approach velocities for both conditions are greater (see Figure 21c and 21d). Again, the recirculation region is marginally longer for the submerged condition and there are two distinct counter-rotating cells present at this elevation. The longitudinal and lateral extent of the recirculation zone is greater at this elevation.

At  $z/D_{50} = 0.6$ , the longitudinal extent of the recirculation zone continues to grow and again is greater for the submerged condition (length = 170 mm, or 2*D*<sub>50</sub>) compared to

the surface-piercing condition (length = 150 mm, or  $1.9D_{50}$ ). The two counter-rotating vortices remain for both conditions, however, the longitudinal extent of these vortices is greater for the submerged condition. Conversely, the lateral extent of these vortices is greater during the surface-piercing condition. At  $z/D_{50} = 0.9$ , although the extent of the wake has reduced in the lateral (y) direction, there is still evidence of the counter-rotating vortices for both conditions. At this elevation, the longitudinal extent of the recirculation zone continues to grow for the surface-piercing condition but is slightly reduced for the submerged condition (see Figure 22).



Figure 21 – Longitudinal velocities ( $\bar{u}$ ) and resultant ( $\bar{u}$ ,  $\bar{v}$ ) streamlines in near-wake region in the *xy*-plane at  $z/D_{50} = 0.12$  (10 mm from the bed – A, B), 0.37 (30 mm from the bed – C, D), 0.6 (47 mm from the bed – E, F) and 0.9 (72 mm from the bed – G, H) for surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions

Figure 22 shows the length ( $R_l$ ) and width ( $R_w$ ) of the recirculation zone in both the longitudinal (x) and lateral (y) directions respectively as a function of elevation from the bed for both conditions. The recirculation length and width is defined here as the longitudinal (x) and lateral (y) distance (normalised by the diameter of the island at its half-height,  $D_{50}$ ) at which negative velocities occur. The recirculation width has been measured immediately downstream of the island (x = 100 mm,  $x/D_{50} = 1.2$ ). It is clear that the recirculation zone in the longitudinal (x) direction and associated streamlines are longer and stronger for the submerged condition compared with the surface-piercing condition. Furthermore, the width of the recirculation zone ( $R_w$ ) at  $x/D_{50} = 1.2$ 



Figure 22 – Recirculation length ( $R_l$ ) and width ( $R_w$ ) of island wake at different elevations for surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions

Figure 23 displays the vertical velocities ( $\overline{w}$ ) for the same elevations as shown above in Figure 21 for both conditions. Near to the bed ( $z/D_{50} = 0.12$ ), there is a zone immediately downstream of the separation point where there is a strong downward movement of flow for both conditions; this area is marginally larger for the submerged condition. An area of upward flow is also present within the recirculation zone for the surface piercing condition between  $x/D_{50} = 1.1$  to 2.2. A weaker area of upward flow occurs at a similar location for the submerged condition. At  $z/D_{50} = 0.37$ , the area of downward flow increases on either side of the island and commences earlier. It is accompanied by a stronger upward (positive) movement of flow in the recirculation zone. Both areas are more intense and expansive, both in longitudinal and lateral extent for both conditions, however, the change in vertical velocities is more noticeable for the surface-piercing condition. This can clearly be seen in the vertical velocity profile data provided in Figure 20. At  $z/D_{50} = 0.6$ , negative  $\overline{w}$  is reduced at the sides of the object for the submerged condition but remains relatively constant for the surfacepiercing condition. The upward flow in the recirculation zone extends further downstream at this elevation during the surface-piercing condition. At  $z/D_{50} = 0.9$ , the longitudinal extent of the downward flow at the sides of the island increases for both conditions, while the area of upward flow within the recirculation zone reduces, particularly in the lateral (y) direction. Interestingly, although the surface area of the island at this elevation is reduced, there is stronger upward flow immediately upstream of the island (between  $x/D_{50} = -1.2$  to -0.2).



Figure 23 – Vertical velocities ( $\overline{w}$ ) and resultant ( $\overline{u}$ ,  $\overline{v}$ ) streamlines in near-wake region in the *xy*-plane at  $z/D_{50} = 0.12$  (10 mm from the bed – A, B), 0.37 (30 mm from the bed – C, D), 0.6 (47 mm from the bed – E, F) and 0.9 (72 mm from the bed – G, H) for surfacepiercing (H/h = 0.96) and submerged (H/h = 1.24) conditions

Figure 24a displays the longitudinal velocities ( $\bar{u}$ ) at  $z/D_{50} = 1.4$  (110 mm from the bed) for the submerged (H/h = 1.24) condition only (the velocity measurement did not extend to this elevation for the surface-piercing condition given the constraints of the ADV). The longitudinal and lateral extent of the recirculation zone is reduced at this elevation given the reduced surface area of the island.

Figure 24b displays the vertical velocities ( $\overline{w}$ ) at and 1.4 (110 mm from the bed) again for the submerged (H/h = 1.24) condition only. At the apex of the island there is strong upwelling surrounding this area, peaking at 0.02 m s<sup>-1</sup>. However, between approximately  $x/D_{50} = 1.4$  and 3.5), the surface water layer plunges downwards as it passes over the island's apex, peaking at -0.02 m s<sup>-1</sup>. Since this surface water layer is not present during the surface-piercing condition, this downward flow is unlikely to occur.



Figure 24 – Longitudinal ( $\bar{u}$ ) (A) and vertical ( $\bar{w}$ ) (B) velocities with resultant ( $\bar{u}$ ,  $\bar{v}$ ) streamlines in near-wake region in the *xy*-plane at  $z/D_{50} = 1.4$  (110 mm from the bed for submerged (H/h = 1.24) condition (island height is 115 mm)

The spatial distribution of turbulent kinetic energy (*k*) at elevation  $z/D_{50} = 0.6$  is shown in Figure 25. High *k* values occur slightly further downstream for the surface-piercing condition. Furthermore, *k* values are higher in the near-wake zone for the surfacepiercing condition compared with the submerged condition. It is also apparent that the extent of high *k* values is greater, both longitudinally and laterally for the surface piercing condition. The location of the most intense turbulence coincides with the maximum upward velocity where there are high velocity gradients in the *x* and *z* directions (Figure 23). Higher in the water column at elevation  $z/D_{50} = 1.1$  and 1.4 for the submerged condition (see Figure 28), *k* values are reduced both laterally and longitudinally.

Corresponding contour plots of the Reynolds shear stress components (-u'v') and (-u'w') are shown in Figure 26 and 27 respectively at elevation  $z/D_{50} = 0.6$ . It is apparent that the Reynolds stress, -u'v', dominates in the wake of the island. As with the turbulent kinetic energy (k) values, -u'v' values increase with distance from the bed for both conditions. The strength of -u'v' increases by a factor of three from the elevation  $z/D_{50} = 0.12$  to  $z/D_{50} = 0.6$ . Furthermore, the values of -u'v' are higher during the surface-piercing condition, suggesting that the velocity shear is greater corresponding to the shear layer across the channel width. These stresses also extend further downstream during this condition. Again, there is a trend of increasing -u'w' values with distance from the bed. Likewise, -u'w' values are greater, both in magnitude and spatial extent, for the surface-piercing condition, signifying a greater velocity shear over the flow depth. As previously mentioned, no velocity measurements were able to be taken at the object layer/water surface layer interface

and if this had been possible, then one would have expected higher  $\overline{-u'w'}$  in this vicinity indicative of vertical shear layer over the flow depth.



Figure 25 – Turbulent kinetic energy (k) and resultant ( $\bar{u}, \bar{v}$ ) streamlines in near-wake region in the *xy*-plane at  $z/D_{50} = 0.6$  for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions



Figure 26 – Reynolds shear stresses  $(-\overline{u'v'})$  and resultant  $(\bar{u}, \bar{v})$  streamlines in near-wake region in the *xy*-plane at  $z/D_{50} = 0.6$  for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions



Figure 27 – Reynolds shear stresses  $(-\overline{u'w'})$  and resultant  $(\overline{u}, \overline{v})$  streamlines in nearwake region in the *xy*-plane at  $z/D_{50} = 0.6$  for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions



Figure 28 – Turbulent kinetic energy (k) and resultant ( $\bar{u}, \bar{v}$ ) streamlines in near-wake region in the *xy*-plane at  $z/D_{50} = 1.1$  (90 mm from the bed – A) and 1.4 (110 mm from the bed – B) for submerged (H/h = 1.24) condition



Figure 29 – Reynolds shear stresses  $(-\overline{u'w'})$  and resultant  $(\overline{u}, \overline{v})$  streamlines in nearwake region in the *xy*-plane at  $z/D_{50} = 1.1$  (90 mm from the bed – A) and 1.4 (110 mm from the bed – B) for submerged (H/h = 1.24) condition

To better understand the flow structures through the water column in the vicinity of the island, longitudinal sections of the velocity contours and streamlines along the centreline of the flume are presented in Figure 30a and 30b for the surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions respectively, while the distribution of turbulent kinetic energy (k) is given in Figure 31. Lines have been drawn in the water column to indicate the elevations in the water column used in Figure 21 and 24. The streamlines are based on the Tecplot software interpretation algorithm, which uses a two-step second-order Runge-Kutta method (Tecplot, 2009).

The deceleration of the flow as it approaches the object can be seen, resulting in an upward movement of water particles as the flow is impeded by the obstruction. Strong upward velocities occur immediately downstream of the island for both the surface-piercing and submerged conditions as the recirculating flow is impeded by the obstruction and forced upwards. The longitudinal extent of the recirculation zone is greater for the submerged condition compared with the surface-piercing condition as has been shown previously (see Figure 21).

Although no velocity measurements could be acquired within the top 30 - 40 mm layer of the water column, it is likely that the water surface flow layer above the apex of the cone is moving at a higher velocity compared to the island layer and hence forms the shear layer that is suggested in Figure 30b. Rather than flowing in a downward direction after passing over the island's apex, the flow encounters the upward current within the recirculation zone. This is a flow feature that is unique to the submerged condition (Figure 30b). A clockwise-rotating vortical structure with a radius of  $0.3D_{50}$ in the longitudinal direction is created at  $x/D_{50} = 1.2$  with the foci at an elevation of 95 mm from the bed. This vortex forms as the upward flow immediately downstream of the island encounters the current flowing over the apex of the obstruction. This has been shown qualitatively by Shamloo *et al.* (2001) and Martinuzzi (2008) in Figure 8 and 7 respectively.

Turbulent kinetic energy (*k*) is stronger for the surface-piercing condition, particularly at  $z/D_{50} = 0.6$ . This is consistent with that shown in Figure 25. For both conditions, *k* values are greatest immediately downstream of the island at an approximate longitudinal distance of  $x/D_{50} = 2.4$ .



Figure 30 – Longitudinal velocities  $(\bar{u})$  and resultant  $(\bar{u}, \bar{w})$  streamlines in near-wake region in the *xz*-plane (looking through the sidewall) along the flume centreline  $(y/D_{50} = 0)$  for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions. Solid lines represent the *xy*-planes given in Figure 21 and Figure 24. Dash-dot lines represent the water surface.



Figure 31 – Turbulent kinetic energy (k) and resultant ( $\bar{u}$ ,  $\bar{w}$ ) streamlines in near-wake region in the *xz*-plane (looking through the sidewall) along the flume centreline ( $y/D_{50} = 0$ ) for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions. Solid lines represent the *xy*-planes given in Figure 21 and Figure 24. Dash-dot lines represent the water surface.

Cross-sections of the longitudinal velocities ( $\bar{u}$ ) looking in the upstream flow direction at  $x/D_{50} = 1.2$  (100 mm downstream of the island apex) are presented in Figure 32. Evidence of two counter-rotating vortices in the recirculation zone observed previously in Figure 21 can be observed. The vortices occur closer to the bed for the submerged condition, however, this may be an anomaly of the visualisation software. The larger cells have a radius in the order of  $0.3D_{50}$ .

As distance downstream of the island increases to  $x/D_{50} = 1.8$  (146 mm downstream of the island apex), the wake velocities for both conditions increases as the influence of the obstruction is reduced (see Figure 33). Although the two counter-rotating vortices that exist at  $1.2D_{50}$  for the surface-piercing condition do not exist here, the vortices at the approximate half-height of the island are still present for the submerged condition. There is still strong upward flow in the lee of the island with downward flow at its sides for both conditions.

Further downstream from the island at  $x/D_{50} = 2.5$  (200 mm downstream of the island apex), the influence of the obstacle diminishes and the vortices present closer to the island have diminished (see Figure 34). This suggests that the level of turbulence decreases with downstream distance. This will be examined in greater depth in the following section.



Figure 32 – Longitudinal velocities  $(\bar{u})$  and resultant  $(\bar{v}, \bar{w})$  streamlines in near-wake region in the *yz*-plane (flow is directed out of the page) at  $x/D_{50} = 1.2$  (100 mm downstream of the island) for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions. Solid lines represent the *xy*-planes given in Figure 21 and Figure 24. Dash-dot lines represent the water surface.


Figure 33 – Longitudinal velocities  $(\bar{u})$  and resultant  $(\bar{v}, \bar{w})$  streamlines in near-wake region in the *yz*-plane (flow is directed out of the page) at  $x/D_{50} = 1.8$  (146 mm downstream of the island) for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions. Solid lines represent the *xy*-planes given in Figure 21 and Figure 24. Dash-dot lines represent the water surface.



Figure 34 – Longitudinal velocities  $(\bar{u})$  and resultant  $(\bar{v}, \bar{w})$  streamlines in near-wake region in the *yz*-plane (flow is directed out of the page) at  $x/D_{50} = 2.5$  (200 mm downstream of the island) for surface-piercing (H/h = 0.96 - A) and submerged (H/h = 1.24 - B) conditions. Solid lines represent the *xy*-planes given in Figure 21 and Figure 24. Dash-dot lines represent the water surface.

#### 2.3.2 Wake recovery

A reference velocity ( $U_{ref}$ ) was used to examine wake recovery. The velocity at a reference point 100 mm upstream of the island and a lateral distance of 400 mm from the flume centreline was used. This point was a sufficient distance from both the sidewall and island to ensure both frictional effects and local acceleration had minimal effect (the velocity profiles are shown in Figure 35). This reference velocity, which was derived with the island installed, differed for a) both submergence levels, and b) elevations in the water column.



Figure 35 – Reference velocity ( $U_{ref}$ ) for the surface-piercing (H/h = 0.96) and submerged (H/h = 1.24) conditions. Dashed and dotted lines represent water surfaces for the surface-piercing and submerged conditions respectively.

Time- and depth-averaged wake velocities ( $\overline{U}$ ) with increasing distance downstream along the flume centreline are presented in Appendix C. These data have been depthaveraged over the following elevations:  $z/D_{50} = 0.12$  (10 mm from the bed), 0.25 (20 mm from the bed), 0.37 (30 mm from the bed), 0.49 (40 mm from the bed), 0.62 (50 mm from the bed) and 0.74 (60 mm from the bed). The error bars display the standard deviation of the data, i.e. the variance in the data from the average velocities at the elevations given above. The recovery rate is based on the average reference velocity  $(U_{ref})$  over the elevations given above. The average variance in the data during the submerged (H/h = 0.96) and surface-piercing (H/h = 1.24) is  $\pm 0.01$  m s<sup>-1</sup>. This plot provides an indication of longitudinal wake recovery and how this recovery is affected by relative submergence. Although full recovery (i.e. back to the reference velocity) does not occur within the length of the flume for either condition, recovery back to 90% of the average reference velocity occurs for the submerged (H/h = 1.24) condition at approximately  $x/D_{50} = 55$ . At the same longitudinal location (i.e.  $x/D_{50} = 55$ ), velocities only recover back to 80% of the average reference velocity for the surface-piercing (H/h = 0.96) condition within the length of the flume. Test section length limitations were also observed by Myers and Bahaj (2007) and Maganga *et al.* (2010).

Lateral velocity profiles provide an indication of both the lateral displacement from the island centreline and flow recovery downstream of the island. The wake is constrained between the sidewalls of the flume and is therefore unable to expand. This is comparable to Ramsey Sound, as the wake of Horse Rock is laterally constrained between Ramsey Island and the mainland.

Figure 36a and 36b display the time- and depth-averaged lateral wake velocities ( $\overline{U}$ ) as a function of lateral distance ( $y/D_{50}$ ) from the centre of the island for the surfacepiercing (H/h = 0.96) and submerged (H/h = 1.24) conditions respectively. These data have again been depth-averaged over the same elevations as those given in Appendix C.

The recovery rate back to approximately 90% of the average reference velocity does not occur within the length of the flume for the submerged (H/h = 0.96) condition. During the surface-piercing (H/h = 1.24) condition, the depth-averaged wake velocities recover back to 90% of the average reference velocity at approximately  $x/D_{50} = 31$ , which suggests that wake recovery occurs sooner for the submerged condition. Furthermore, the width of the lateral profiles in the lateral (y) direction indicates that the wake is more expansive for the submerged condition. The wake velocities ( $\overline{U}$ ) are greater away from the velocity deficit region (~  $y/D_{50} = 0.9$ ) at 1.8 $D_{50}$ due to the flow acceleration around the sides of the island, particularly for the surfacepiercing condition.



Figure 36 – Time- and depth-averaged longitudinal wake velocities  $(\overline{U})$  in the lateral (y) direction for different longitudinal distances  $(x/D_{50})$  downstream of the island for the surface-piercing (H/h = 0.96) (A) and submerged (H/h = 1.24) (B) conditions. Solid and dotted boxes indicate diameter of island at its half-height and base respectively.

#### 2.4 Discussion

This study reveals some important wake characteristics, both with regard to the spatial distribution of mean and turbulent flow structures in the near wake region and wake recovery in the far wake region of a conical island, and how these features are affected by relative submergence.

The plots presented in Section 2.3.1 display similar patterns to the classic flow patterns in the vicinity of an obstruction as shown in Figure 4. Given the relatively high Reynolds numbers associated with these flow conditions, it is likely that form drag dominates over friction. The upstream and downstream faces of the island comprise high pressure and low pressure zones. As the flow approaches the obstruction there is a pressure increase on its front surface as the fluid is impeded and decelerates. At the separation point, the flow diverges from the centreline as the flow is redirected around the island, which is consistent with the experimental studies performed by Lacey and Rennie (2012) for flow around a cube. An upward movement of flow was observed at the upstream face of the obstacle  $(x/D_{50} = -1.9)$ , as the flow encounters the obstacle and is forced upwards, which is consistent with the findings of Shamloo *et al.* (2001). Acceleration occurs as flow travels past an obstacle with the formation of horizontal shear layers either side of the island marking the boundary of flow acceleration and the low flow region in the near wake, as observed by Lloyd and Stansby (1997a) for surface flows. Lloyd and Stansby (1997a) also noted that the interaction of these shear layers produce large-scale vortices in the far wake region. Energy dissipation in the turbulent wake zone immediately downstream of the obstruction creates a low pressure zone with significant form drag. Although form drag dominates, frictional

forces (as noted by Tomczak, 1988) retard the flow as it passes the sides of the island. A recirculation zone with complex turbulent structures exists downstream of the island and is dominated by flow reversals and vortices. These turbulent structures dictate the form of the wake, which can be vortex shedding, unsteady or steady (no recirculation) (Lloyd and Stansby, 1997a).

The velocity profiles clearly show a recirculation zone immediately downstream of the island. This recirculation zone did not extend beyond  $x/D_{50} = 2.1$  for either submergence level and was longer for the submerged condition (Figure 22). This is comparable to the findings of Sadeque *et al.* (2008) and Sadeque *et al.* (2009). They observed that the recirculation zone was greater in both its longitudinal and lateral extent when the submergence level was minimal compared to when the object was surface-piercing. However, this disagrees with the findings of Lacey and Rennie (2012) who noted a trend of increasing recirculation length with decreasing submergence. This disparity could be due to the deeper levels of submergence used by Lacey and Rennie (2012) (H/h = 2, 2.5 and 3), as well as different velocities and discharges between studies. As would be expected, the velocity profiles recover to their upstream form (i.e. at  $x/D_{50} = -1.9$ ) at a given distance downstream, which was also observed by Sadeque *et al.* (2009) at approximately x/D = 7 for cylindrical objects.

The extent of the recirculation zone in both the longitudinal (x) and lateral (y) directions was greater as distance from the bed increased. Bed-frictional forces dominate within the lower portion of the water column and as such, the velocities here are lower, which results in less momentum and a reduced recirculation zone extent.

As distance from the bed increases so too do the approach velocities, which results in a greater recirculation extent. In addition, the lateral velocity profiles suggest that the wake is also more laterally constrained (less expansive) for the surface-piercing condition compared with the submerged condition. This suggests that lateral wake extent is a function of the submergence level. From the bed to an elevation of  $z/D_{50} =$ 0.6, the recirculation length and width increased with increasing distance from the bed, then they both reduced for the submerged condition. For the surface-piercing condition, the recirculation length increased from the bed to  $z/D_{50} = 0.9$ , while the recirculation width showed a similar trend as the submerged condition, increasing from the bed to  $z/D_{50} = 0.6$ . This is due to the shape of the island, which results in a reduction in the blockage with increasing distance from the bed.

Profiles of the vertical velocity component ( $\overline{w}$ ) along the plane of symmetry show that away from the island ( $x/D_{50} = > 13.5$ ) vertical velocities are close to zero. Upwelling, however for both conditions, occurs immediately upstream of the obstruction ( $x/D_{50} =$ -1.9) as the flow is forced upwards. Within the recirculation zone, upward velocity along the centreline dominates for both submergence levels because the recirculating flow within the low pressure zone immediately downstream of the obstruction is forced upwards as it encounters the island. This is comparable to findings of Lacey and Rennie (2012) for a bed-mounted cube albeit at a greater submergence level (H/h= 2). The magnitudes of the upward velocities, particularly within the recirculation zone, are greater during the surface-piercing condition as they are likely to be dampened by the surface flow layer during the submerged condition. However, at the edges of the object (particularly closer to the bed:  $z/D_{50} = 0.37$ ), the flow is a combination of upward and downward flow, which could be evidence of the horseshoe vortex system (Figure 23), as suggested by Shamloo *et al.* (2001).

Changes in both the extent and spatial distribution of the vertical velocities are apparent with different submergence levels. Both the upward and downward velocities are more intense and expansive during the surface-piercing condition. Lacey and Rennie (2012) suggested that the differences observed in the vertical velocities downstream of the object are likely to be due to differences in the shape and size of the obstacles during different studies.

Vortices exist at specific elevations in the water column in the wake of the island. Although there are strong flow reversals downstream of the island for the surfacepiercing condition, vortices are not present at  $z/D_{50} = 0.37$  (30 mm from the bed). However, at the same elevation for the submerged condition, two counter-rotating vortices are present, which resemble the arch-type vortices observed in previous studies (Shamloo *et al.* 2001; Lacey and Rennie, 2012). Close to the island's half-height ( $z/D_{50} = 0.6$ ), two counter-rotating vortices exist for both submergence levels. The extent of the vortices was greater in the longitudinal (x) direction for the submerged condition, however, the lateral extent was greater for the surface-piercing condition. Lacey and Rennie (2012) suggest that this increased lateral extent is likely to be due to a reduction in the free surface as the submergence level decreases, which compresses the flow and the associated shedding structures leading to lateral vortex stretching. Shamloo *et al.* (2001) noted that when the hemisphere became submerged, there is a separation of flow from the top of the hemisphere combined with that separated from the sides to produce a pair of arch vortices. The symmetric nature of the vortices for both the surface-piercing and submerged conditions suggests that the type of vortex structure observed here is not a function of relative submergence since the submergence level investigated is not great enough to see these changes. At deeper submergence levels, these flow structures are likely to change. The symmetrical nature of these vortices suggests that they are arch vortices (as shown by Kawamura *et al.* 1984). Shamloo *et al.* (2001) noted that for submerged flows (H/h > 1) flow separation occurring at the top and sides of the object produce an arch vortex. The results presented here suggest that the flow features at these submergence levels are more consistent with the findings of Pattenden *et al.* (2005) and Frederich *et al.* (2008), i.e. a horseshoe vortex at the base of the obstacle and arch vortices shed from the obstacle sides.

Shamloo *et al.* (2001) also found that for surface-piercing flows (H/h < 1), the downwash over the apex of the obstruction is not present and the wake becomes 2-D with the appearance of the Kármán vortex street and the disappearance of the arch vortices. This is contrary to the findings of this study whereby two symmetrical arch-type vortices exist for the surface-piercing condition (H/h = 0.96). However, as the submergence level increased to H/h = 1.24 (submerged condition), overtopping of flow over the apex occurs creating a vertical shear layer and a clockwise-rotating vortical structure in the *xz*-plane (Figure 30). Although this object geometry differs from the surface-mounted pyramids studied by Martinuzzi (2008), a similar vortex structure of clockwise rotation in the *xz*-plane was observed downstream of the tip as the flow passing over the apex of the obstruction interacts with the upward movement of flow immediately downstream, which is forced upwards due to the presence of the island. This downward movement of water immediately downstream of the island was

also observed by Shamloo *et al.* (2001) at a similar submergence level, however, they noted that this downward movement manifested itself through the entire water column rather than within the upper surface flow layer. Conversely, Lacey and Rennie (2012) observed comparable vertical velocity structures to this study at a similar submergence level (H/h = 1.3): upward flow within the island layer of a bed-mounted cube with downward flow at the island apex at a similar longitudinal distance downstream. This suggests that the shear layer separating the island flow layer and surface flow layer also exists for their study, albeit with a dissimilar object geometry. Martinuzzi (2008) also observed this upper shear layer with downward flow downstream of the apex of a bed-mounted pyramid.

The velocities used to inform the analyses in this chapter have been averaged over the 150 s sampling period using conventional time-averaged analysis and as such, it is difficult to capture and identify unsteady hydraulic features such as the von Kármán vortex street if they exist given their periodic nature. Although instantaneous velocity measurements (*u*) could give a clearer indication of the presence of a von Kármán vortex street, it was beyond the scope of this study to perform the necessary analysis. However, Martinuzzi (2008) did not observe vortical structures downstream of a bedmounted pyramid obstacle when the time-averaged values were used.

Although surface flow features were not examined as part of this study, Lloyd and Stansby (1997b) observed vortex shedding in the wake at the water surface when the water level was at or just above the island apex (H/h = 1). This flow feature was also observed during this study for the submerged condition (H/h = 1.24) with flow in the upper layer (i.e. above the apex of the island) travelling at a faster rate than that

immediately downstream of the island. However, they noted that a minor increase in water level (H/h = 1.1) resulted in the vortex shedding to shift downstream since the island is less effective at sheltering the near wake region at this submergence level. This has been observed herein (albeit lower in the water column as opposed to the surface water layer) with the two counter-rotating vortices at the island half-height extending slightly further downstream for the submerged condition. This unsteady wake is created by the horizontal shear layers (created between the accelerated flow and the low velocity region immediately downstream of the island) and the unseparated flow further away from the apex (Lloyd and Stansby, 1997b). As the water level increases further, the low-velocity zone narrows since the greater depth prevents the separated fluid from mixing over the entire water column; resulting in vortex shedding with a lower intensity. Lloyd and Stansby (1997b) noted that vortex shedding at the surface stopped at around H/h = 1.18. This was because the flow over the island's apex sheltered the near wake region and prevented the generation of vortices, which were created by the interaction of the horizontal shear layers and the sides of the island; similar to that observed by Martinuzzi (2008) for bed-mounted pyramids (Figure 7) and Shamloo et al. (2001) for hemispheres (Figure 8c).

Total turbulent kinetic energy (*k*) values were greater away from the bed; an observation also made by Sadeque *et al.* (2009). The location of the most intense turbulence coincided with the greatest upward velocity values. This turbulent area is also the location of the reattachment point marking the boundary between the positive and negative longitudinal ( $\bar{u}$ ) velocities, which indicates the location of the boundary layer: the area that experiences the greatest change in velocity and therefore the location of intense velocity shear and turbulence. Sadeque *et al.* (2009) also noted that

intense turbulence occurred in the upward flow at the edge of the recirculation zone. Higher values of k were also observed in the near-wake zone for the surface-piercing condition compared with the submerged condition. This is in agreement with the findings of Lacey and Rennie (2012) who noted that values of k generally decrease as submergence increases downstream of a bed-mounted cube. Lacey and Rennie (2012) also noted that high k values in the wake were also observed by Tritico and Hotchkiss (2005) and Lacey and Roy (2007); suggesting the presence of shear layers along the sides of the obstruction, as has been reported by Lloyd and Stansby (1997a; 1997b). It was observed that the location of high k values shifted further downstream for the surface-piercing condition, i.e. as submergence level decreased.

It is apparent that the Reynolds stress,  $-\overline{u'v'}$ , dominates in the wake of the island, corresponding to the existence of a horizontal shear layer. This is contrary to Lacey and Rennie (2012) who noted that  $-\overline{u'w'}$  dominated and was the principal shear stress. The magnitude and spatial extent of both stresses,  $-\overline{u'v'}$  and  $-\overline{u'w'}$ , increase with decreasing submergence level due to the increased blockage extent. Furthermore, the magnitude of both stresses from the bed increase but the spatial (lateral) extent is reduced as the blockage ratio decreases (at the island's apex). Lacey and Rennie (2012) also noted increases in  $-\overline{u'w'}$  from near the bed to the island's apex and a subsequent reduction in the lateral extent. They observed this trend for each submergence level the upward propagation and growth of shedding coherent flow structures is limited; compressing these structures in the horizontal plane and laterally stretching the vortices.

The greatest velocity deficit occurs immediately downstream of the obstruction with recovery occurring as downstream distance increases. This is consistent with previous laboratory experiments (Bahaj et al. 2007b) and numerical modelling (Malki et al. 2011) related to TSTs. Both Bahaj et al. (2007b) and Malki et al. (2011) found that wake recovery is a function of inlet velocity with quicker recovery occurring at lower velocities. The current study has shown that wake recovery was shown to be a function of relative submergence with recovery occurring sooner for the submerged condition. Recovery back to 90% of the reference velocity occurs at approximately  $x/D_{50} = 55$  for the submerged condition but does not recover for the surface-piercing condition within the length of the flume. This suggests that greater island submergence results in a quicker recovery. The measured velocities associated with the submerged condition were slightly lower than for the surface-piercing condition within the island flow layer, which could explain this faster recovery rate, however, it would be expected that the presence of the water surface flow layer and the smaller sheltering effect of the submerged condition would aid in the velocity recovery. A submerged TST was studied experimentally by Bahaj et al. (2007b) and numerically by Malki et al. (2011). They showed that lower velocities resulted in faster recovery. This demonstrates that the same wake recovery trends occur.

#### 2.5 Chapter summary

This chapter has presented the results of a controlled laboratory investigation of the far and near wake downstream of a conical island. These experiments comprised two submergence levels (surface-piercing, H/h = 0.96 and submerged, H/h = 1.24) to isolate the influence of submergence on the characteristics of both the far and near

wake zones. The principal objectives of this laboratory investigation were twofold: 1) to examine the effect of relative submergence on near wake flow characteristics, and 2) to examine the effect of submergence level on wake recovery, downstream of an island.

This chapter has demonstrated the importance of experimental studies to supplement field-based wake measurements where the resolution precludes an examination of the detailed flow structures. As will be shown in the following chapter, separating and examining the effects of submergence in the field is difficult because the hydrodynamic parameters (velocity, discharge, water level) cannot be controlled. This chapter has provided a valuable insight into the hydraulics of flow around a surfacepiercing and submerged bed-mounted structure to improve the understanding of the flow characteristics in both the shallow turbulent near wake zone and the more uniform far wake region downstream of an obstruction, and the effect of relative submergence. Natural oceanic islands encompass aspects such as a complicated bathymetry, which results in high levels of turbulence and shear that laboratory and numerical investigations can only partially define. The following chapter therefore examines the wake created by a natural pinnacle located in an energetic tidal strait.

# **3 WAKE CHARACTERISTICS OF A NATURAL PINNACLE**

## 3.1 Introduction

The primary motivation for conducting this research is the general lack of field-based wake studies of natural submerged pinnacles. The cost and difficulties of collecting field data of flow structures in the vicinity of submerged pinnacles in macrotidal areas has pushed much of the research to laboratory and numerical modelling studies. Measurements of tidal flows near and around a natural submerged feature are therefore rare and as such, it was considered important to quantify the wake characteristics of a submerged structure in a macrotidal strait, using Ramsey Sound (which will soon host Wales' first TST demonstration device) as a field site.

This chapter outlines the methods (Section 3.3) adopted for the field study campaign. The results of the wake study are subsequently presented and discussed in Section 3.4 and 3.5 respectively.

## 3.2 Case location: Ramsey Sound

## 3.2.1 Geographical and hydrodynamic setting

Connected to the Irish Sea, Ramsey Sound (Figure 37) 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 Chart Datum (CD) (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,  $D_{50}$ ) 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.

The area experiences a strong, semi-diurnal tidal regime with a range of approximately 1.5 - 5 m from mean neap to mean spring, and includes zones of high turbulence (Togneri and Masters, 2012a; Togneri and Masters, 2012b). Charted tidal streams indicate current speeds of up to 6 knots (~ 3 m s<sup>-1</sup>). Although the general tidal dynamics in Ramsey Sound has been known for decades, very few studies have characterised the hydrodynamics of this area, which is of particular importance given its tidal stream energy potential. One of the aims of this thesis is to therefore address this general lack of knowledge and understanding of the local hydrodynamics within macrotidal straits using Ramsey Sound as a field site.



Figure 37 – Location map of Ramsey Sound, Pembrokeshire (UK). Bathymetric contours show seabed elevation. ADCP survey transects are represented by black lines and red dots represent vertical shear profile locations.

## 3.2.2 Tidal stream energy extraction in Ramsey Sound

In 2011, Tidal Energy Ltd. (TEL), a UK-based commercial energy company, was granted permission to trial a DeltaStream TST (O'Rourke *et al.* 2010) in Ramsey Sound, estimated to have an extractable power-output of approximately 75 GW-h year<sup>-1</sup> (Fairley *et al.* 2011). The proposed deployment site is situated in a water depth of approximately -30 m CD. This location was chosen as it is sheltered from the prevailing south-westerly wave and wind conditions by Ramsey Island, water depths are adequate, it is in close proximity to the mainland with a suitable grid connection, the tidal currents are in excess of 3 m s<sup>-1</sup> during peak spring tide conditions, vessel traffic is limited to shallow-draughted vessels with no trawling or commercial shipping passing through the Sound, and there are good port facilities and marine engineering capabilities nearby (Pembroke Dock) (Tidal Energy Limited, n.d.).

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 over complicating the design it was decided to install a single turbine on one of the apexes thereby reducing the generation capacity to 400 kW of electricity, which will still greatly contribute to the energy demands of the communities of St David's. The tip of DeltaStream's turbine will be approximately 11.9 m from the water surface at the lowest tide level, so not to restrict boating activity (Tidal Energy Limited, 2009). The prototype device is currently being constructed at Pembroke Dock, Wales, with the intention of installing the device in mid-September 2014 as part of a one year demonstration project in Ramsey Sound to test its integrity and power-output capabilities in this macrotidal

strait. If successful, the device will be scaled up to full commercial scale and suitable locations identified for a turbine array. Much of the research used to inform this thesis has been used to aid site selection.

## 3.3 Methodology

#### 3.3.1 Survey equipment and design

To measure the tidal velocity data in the vicinity of Horse Rock, a four-beam 600 kHz broadband Workhorse Sentinel ADCP unit, manufactured by Teledyne RD Instruments, was gunwhale-mounted on Cardiff University's Research Vessel *Guiding Light* (Figure 38). The ADCP operates by transmitting bursts of sound (called pings) at a fixed interval and frequency into the water column. Pings are reflected from suspended particles in the water and the echoes produced from these reflections are received by the ADCP. The particles move at the same velocity as the water current, therefore the echoes produce a Doppler shift or a change in the frequency between the transmitted sound and the sound reflected back to the ADCP.

The ADCP calculates water speed, current direction and the depth of return within the water column by a combination of the Doppler shift and the timing of the returned echoes. To calculate the current velocities the ADCP assumes the currents at each depth bin are homogeneous between each beam. Three-dimensional (3-D) current velocity vectors (u, v, w) are calculated by trigonometric relations between the beams, representing the longitudinal (north-south, x-direction), lateral (east-west, y-direction), and vertical (z-direction) velocity components respectively. In a four-beam configuration, one pair of beams acquires one horizontal velocity component and the

vertical velocity component, while the second pair of beams obtains a second perpendicular horizontal component and a second vertical velocity component (Teledyne, 2011a). There are therefore two horizontal velocity component and two vertical velocity component estimates. The error velocity is calculated by the variance in the two vertical velocity estimates (Teledyne, 2011a). The ADCP also produces a longer-pulsed ping for bottom-tracking, which is used to track the seafloor for downward-looking, vessel-mounted applications. This is used to determine both the overall depth of the water column and the relative speed and direction of the ADCP as it moves along a transect.



Figure 38 - Cardiff University's Research Vessel Guiding Light

Prior to the introduction of ADCPs, the measurement of current velocities in estuaries and coastal waters was performed by a combination of float tracking to examine the surface circulatory patterns and current meters deployed within the water column at specific elevations from the bed to determine the horizontal (u, v) velocity components (Wewetzer *et al.* 1999). ADCPs offer an advantage over these conventional methods given their ability to measure the quasi 3-D velocity structure of moving bodies of water throughout the water column. The system can operate in a number of configurations: vessel-mounted (downward or sideways looking), moored / seabed-mounted (upward looking), or downward/sideways use in harbours, etc. The former method was used for this study. Tidal currents in narrow straits can vary in space and this variability cannot be realistically captured with seabed-mounted techniques unless a dense grid of multiple units is deployed. Vessel-mounted ADCPs are a valuable tool for characterising tidal energy sites, especially in areas that are exposed to strong currents where the deployment and retrieval of seabed-mounted ADCPs can be challenging.

A downward-looking vessel-mounted ADCP requires a stable seafloor (no bed movements during data collection). Bottom-tracking is used to measure speed-overground and velocities determined through bottom-tracking are used to correct the velocities measured relative to the boat (apparent velocity) to actual values. A moving bed results in an inability to correctly measure vessel velocity and direction, and therefore current velocity. Side-scan sonar data for Ramsey Sound show a bottom characterised by swept bedrock.

Aboard the *Guiding Light*, the ADCP transducers were placed 1.4 m below the water surface to ensure clearance from the vessel's hull; water column measurements presented here begin at a depth of 2.75 m below the water surface. The longitudinal (*u*) lateral, (*v*) and vertical (*w*) velocity components were recorded at a sampling rate

of 1 Hz (one ping per second); the maximum sampling rate of the ADCP unit. 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 $\pm$ 15° with
accuracy $\pm 0.5^{\circ}$ , precision $\pm 0.5^{\circ}$ , and resolution $\pm 0.01^{\circ}$ , which results in a velocity
accuracy of 0.003 m s <sup>-1</sup> (Teledyne, 2011b). The integrated system for recording
position, heading, and attitude was configured in close proximity to the ADCP
transducers. Table 8 summarises the specifications and setup configuration used
throughout the ADCP survey.

20110)	
Configuration	
Acoustic frequency	600 kHz
Sampling frequency	1 Hz
Vertical cell size	1 m
Transducer depth	1.4 m
Blanking distance	0.25 m
Specification	
Typical range @ 1 m vertical	42 – 56 m
resolution	
Vertical accuracy	0.3% of the water velocity relative to ADCP $\pm 0.003$ m
	S <sup>-1</sup>
Vertical resolution	$0.001 \text{ m s}^{-1}$
Velocity range	$\pm 5 \text{ m s}^{-1}$ (default); $\pm 20 \text{ m s}^{-1}$ (max)
Tilt sensor	Range $\pm 15^{\circ}$ , accuracy $\pm 0.5^{\circ}$ , resolution $0.01^{\circ}$
Compass	Accuracy $\pm 2^{\circ}$ ; Precision $\pm 0.5^{\circ}$ ; Resolution 0.01°,
	Maximum tilt ±15°

Table 8 – RDI Workhorse Sentinel ADCP configuration and specifications (Teledyne,2011b)

Prior to survey execution, it was necessary to calibrate the ADCP's internal flux-gate compass to correct for any distortions caused by the magnetic signature of the internal battery. The compass was calibrated on the survey vessel due to the difficulties in transporting the ADCP ashore. Both calibration and data collection were performed

using RDI's WinRiver II software. Magnetic declination, the angle between compass north and true north, was determined prior to data collection to counteract the effects of magnetic variance at the survey site. A value of -3.42° was used (Magnetic-Declination, 2012). The magnetic variation value is only important when GPS is used as a velocity reference since both the water velocity and boat velocity are measured in the same coordinate system (Teledyne, 2001c).

Surveying across the central portion of Ramsey Sound (Figure 37) was conducted over two consecutive days in June 2012, just prior to a peak spring tidal cycle. Flood-tide velocities were recorded in one day along 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); ebb-tide velocities were recorded the following day along a different set of three transects (T4 - T6) just south of Horse Rock (but again downstream with respect to flow on the ebb tide, and so sited south of the feature). No 'upstream' transects were made because the principal aim of this study was to examine the wake created by Horse Rock. Aside from the navigational hazard of collecting velocity data upstream of this feature, collecting upstream measurements would result in a large time lag (circa one hour) from the start to the end of a circuit of six transects. This reduction in temporal resolution would halve the number of passes downstream of Horse Rock from approximately two circuits per hour to one circuit per hour; potentially masking important wake characteristics. Downstream distance from Horse Rock varied from 100 m (T3 and T4), 250 m (T2 and T5), and 400 m (T1 and T6). The transects covered a significant area of the Sound encompassing the deeper northsouth trending trench as well as the shallower outer margins. Each set of transects was surveyed in a continuous, five-hour circuit from one hour after slack water (Slack+1)

to one hour before the next slack water (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 (Easton *et al.* 2011; Fairley *et al.* 2013).

Two self-recording current meters (SRCMs) (Figure 39) were deployed during the entire survey deployment to examine the strength and duration of the apparent recirculation zone at the eastern margin of the Sound. Each current meter was mounted on the boat mooring at a depth of 5 m and 3 m. The mooring was located in St Justinian mooring area, off the lifeboat slipway (as indicated in Figure 40).

The current meters function on a one second cycle, during which impeller counts are taken and a single compass heading reading is made. From this, longitudinal (*u*) and lateral (*v*) velocity vectors are calculated, which are subsequently summed over the averaging period to produce time-averaged velocity data ( $\bar{u}$ ,  $\bar{v}$ ). A sampling period of 10 s and an averaging period (multiples of sample period) of 3 were specified, which resulted in 30 s data output to ensure the resultant velocity data accounts for the mean magnitude and direction and as such, removes the small-scale disruptions to the mean flow caused by factors such as wind and waves. Table 9 provides a summary of the instrument configuration and specifications.



Figure 39 – Self-Recording Current Meter



Figure 40 – Location of SRCM within Ramsey Sound

Configuration	
Sampling frequency	1 Hz
Sampling period	10 s
Averaging period	3 (equating to data output every 30 s)
Water depth	5 m and 3 m
Specification	
Velocity range	$0.03 - 5 \text{ m s}^{-1}$
Velocity accuracy	$\pm 1.5\%$ of reading above 0.15 m s <sup>-1</sup>
	$\pm 0.004 \text{ m s}^{-1} \text{ below } 0.15 \text{ m s}^{-1}$
Direction range	0-360°
Direction accuracy	$\pm 2.5^{\circ}$
Direction resolution	0.5°

 Table 9 – Valeport current meter configuration and specifications

## 3.3.2 Data post-processing

The next stage involved the removal of errant velocity values using the WinRiver II software. Figure 41 shows the processing dialog box and the values used to screen the data. The following data screening options (as detailed by Teledyne, 2011c) were checked:

- *Mark Below Bottom "Bad"* 'marks data below the ADCP-detected bottom'
- *Mark Below Sidelobe "Bad"* 'marks data below the sidelobes'
- *Use 3 Beam Solution For BT* 'allows 3-beam solutions if one beam is below the correlation threshold set by the BC (Correlation Magnitude Minimum) command'
- *Use 3 Beam Solution For WT* 'allows 3-beam solutions if one beam is below the correlation threshold set by the WC (Low Correlation Threshold) command'
- Use Weighted Mean Depth 'allows WinRiver II to calculate the depth'.

Following guidance from a Field Service Supervisor at Teledyne RD Instruments (K Grangier, April 2013, personal communication) a value of 1.0 was subsequently specified for the following thresholds (Teledyne, 2011c):

- *Bottom-track Error Velocity* 'to determine good bottom-track velocity data. If the ADCP's error velocity value exceeds this threshold, it flags data as bad for a given depth cell'.
- *Water Track Error Velocity* 'to set a threshold value to flag water-current data as good or bad. If the ADCP's error velocity value exceeds this threshold, it flags data as bad for a given depth cell.'
- Bottom-track Up Velocity 'to determine good bottom-track velocity data. If the ADCP's upward velocity exceeds this threshold, it flags data as bad for a given depth cell'.
- *Water Track Up Velocity* 'to set a threshold value used to flag water-current data as good or bad. If the ADCP's upward velocity value exceeds this threshold, it flags data as bad for a given depth cell'.
- *Fish Intensity* 'to screen water-track data for false targets (usually fish)'. A value of 30 was input as recommended by Teledyne RD Instruments (K Grangier, April 2013, personal communication).

<ul> <li>Properties</li> <li>Commands</li> <li>DS / GPS / EH</li> <li>Discharge</li> <li>Edge Estimates</li> <li>Offsets</li> <li>Processing</li> <li>Recording</li> </ul>	Speed Of Sound Use ADCP Value		Crossectional Area Perpendicular to Mean Flow Perpendicular to Proj. Angle Parallel to Average Course	
	<ul> <li>Calculate For Each Ping</li> <li>Use Salinity [ppt] :</li> <li>Fixed</li> <li>Use Value [m/s] :</li> </ul>	e Salinity [ppt] : 0 xed e Value [m/s] : 1500	Data Screening Mark Below Bottom "Bad" Mark Below Sidelobe "Bad" Use 3 Beam Solution For BT Use 3 Beam Solution For WT Screen Depth Use Weighted Mean Depth Screen Depth Using BT Vel	
	Projection Angle (F2-Current) Projection Angle [deg]:	0.00		
	Near-Zone Distance [m]: Calculate For Each Ping Use Fixed Values: Int. Scale [dB/cts]: Absorption [dB/m]:	2.100 Threshol BT Error WT Erro 0.430 BT Up Ve 0.139 WT Up V	Thresholds BT Error Vel. [m/s] WT Error Vel. [m/s] BT Up Vel. [m/s] WT Up Vel. [m/s]	1.000 1.000 1.000 1.000 30
				Cancel

Figure 41 - WinRiver II's processing dialog box

Selected parameters (date, time, latitude/longitude, average beam depth, distance along transect, the three instantaneous velocity components (u, v, w), magnitude and direction) for each track line were subsequently exported to ASCII and imported into Microsoft Excel. The velocity and seabed data collected by the ADCP was subsequently reduced to Chart Datum (CD), the same vertical datum as the bathymetric data.

Over the duration of the survey, a RBR TWR 1050p Peizo-resistive pressure transducer was installed at low water in the sheltered area to the immediate west of the lifeboat slipway, in the north-eastern portion of Ramsey Sound to collect water pressure data every 10 minutes. Hourly atmospheric pressure data at Mean Sea Level was also acquired from the Met Office for the Milford Haven weather station to convert water pressure collected by the pressure transducer to water elevation. The data was initially exported from the data collection software, Ruskin. Water depth was calculated using the following formula: (water pressure – atmospheric pressure (dBar)) / density \* 0.980665). Density (1.0281) was extracted from the Ruskin software. The pressure transducer elevation was subsequently converted from Ordnance Datum (OD) to CD (CD is 2.9 m below OD at Ramsey Sound). Water depth was finally converted to water elevation (CD) by multiplying by the pressure transducer elevation. The water surface elevation data was used to reduce the ADCP data to CD rather than a depth below the water surface. Seabed depths were also reduced to CD for consistency.

Instantaneous velocity measurements (u, v, w) for each transect were spatially averaged with a sliding 5 m window  $(\bar{u}, \bar{v}, \bar{w})$ , equating to an averaging interval of approximately 5 – 10 s; a filter size significantly smaller than the width of the strait, to dampen signal noise. This is consistent with the averaging approach adopted by Neill and Elliott (2004a). Increasing the averaging period will reduce the standard deviation at the expense of the horizontal resolution, which is not appropriate for submerged pinnacle wake studies. 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 (Yoshikawa *et al.* 2007) because the instrument is sampling over the same portion of the water column. However, moving platform applications require a much shorter averaging period. This post-processing step reduces the standard deviation ( $\sigma$ ) of the velocity data from  $\pm$  0.07 m s<sup>-1</sup> to  $\pm$  0.04 m s<sup>-1</sup>. Therefore, a velocity of 2 m s<sup>-1</sup> represents an error of  $\pm$  2%. The vertical resolution of the data (1 m) remained unchanged to allow the vertical shear in the velocity profile and the extractable power to be determined with a meaningful resolution. Dialogue with a Field Service Supervisor at Teledyne RD Instruments (K Grangier, July 2012, personal communication) confirmed that these averaging intervals were appropriate for this study.

The SRCM meters required very little post-processing. The SRCM data was imported into Microsoft Excel and the depth of each current meter (5 m and 3 m water depth) was reduced to CD to allow for direct comparison with the ADCP data. The numerical computing environment Matlab by Mathworks was employed to linearly interpolate between tidal elevations, which were acquired every 10 minutes, as opposed to 30 s for the SRCMs, using the script shown in Appendix A.

Prior to arranging the datasets into useable formats, a number of software packages were investigated in order to determine the most suitable for data analysis. It was decided that the Eonfusion 4D analysis software would be employed for analysing the velocity data given its flexibility and powerful analytical features. The spreadsheets containing the ADCP data were modified using various 'IF' and 'VLOOKUP' statements so that they could be imported into CSV, a file format recognised by Eonfusion.

To accurately quantify the wake of Horse Rock, contour plots were created. This process comprised a number of discrete steps within Eonfusion. The first step involved the creation of a series of CSV files containing the horizontally averaged velocity data. This process is illustrated in Figure 42. The individual survey tracks (T1 - T3 for the

flood data and T4 - T6 for the ebb data) were input into the dataflow and subsequently merged to create one flood and one ebb dataset. Erroneous latitude and longitude values were present for the first few seconds of some transects and as such, these data were removed through a 'No Data' operator. Although some minor deviations off the desired track occurred, it has been assumed that the survey tracks were completed at a constant latitude. An operator was therefore created to calculate the average latitude per transect. An operator was subsequently added to define the averaging interval for the distance along the transect (5 m).

The averaged velocity data for each phase of the tide (i.e. peak flood / ebb) was subsequently added to the next dataflow, which was set up to create contour plots in plan view to examine the spatial variability of the flow across the Sound at user-defined elevations in the water column (Figure 42). This was performed by setting the elevation in the water column over which to plot the data before interpolating the data over both the 5 m averaged data in the lateral direction and over the three transects in the longitudinal (*x*) direction. The magnitude and geometric direction of the tidal velocities (resultant of the  $\bar{u}$ ,  $\bar{v}$  velocity components) were calculated by:

$$Magnitude = \sqrt{\bar{u}^2 + \bar{v}^2}$$
 [8]

Direction = 90 - tan<sup>-1</sup> 
$$\left(\frac{|\bar{v}|}{|\bar{u}|}\right) \times 180/\pi$$
 [9]



Figure 42 – Create averaged velocity dataflow



Figure 43 – Plan view dataflow

## 3.3.3 Velocity analyses

According to Malki *et al.* (2011), the reduction in the longitudinal velocity downstream of a TST is a measure of flow recovery. Quantifying wake recovery is useful for determining the appropriate longitudinal distance between TSTs in a farm

in order to ensure device-generated turbulence has decreased to an acceptable level before encountering the downstream TST. The longitudinal wake recovery can be defined by the non-dimensional 'velocity deficit' (Myers and Bahaj, 2010):

$$U_{def} = 1 - \frac{\overline{u}}{U}$$
[10]

where  $\bar{u}$  is the mean longitudinal velocity and U is the undisturbed free-stream, or 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 (2004a, p. 232) who noted that '... the large scatter of data is also due to the difficulties in specifying an appropriate value for U'. 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.
One approach for determining the free-stream velocity would be to estimate the volumetric flow rate ( $Q_{vol}$ ) and volumetric averaged velocity ( $\bar{u}_{vol}$ ) upstream of Horse Rock based on the assumption that the flow travelling past each cross-section (upstream and downstream of Horse Rock) has to maintain continuity. To test this, a cross-section was created 200 m upstream of the pinnacle using the Global Mapper software. A line (with the same length as transect T3 for each phase of the tide – one hour after slack through to one hour before slack) was drawn in the lateral direction over the 2 m horizontal resolution bathymetry data. This was then discretised by averaging the seabed data every 10 m. The cross-sectional area was subsequently calculated using the tidal elevation for each tidal phase. The volumetric flow rate  $(Q_{vol})$ was subsequently calculated for each phase of the tide at transect T3 (flood) and T4 (ebb) by means of multiplying the mean longitudinal ( $\bar{u}$ ) velocities by a flow area of 5  $m^2$  (the horizontal, 5 m, and vertical, 1 m, resolution of the data). These values were subsequently summed to give  $Q_{vol}$ . This value was finally divided by the crosssectional area of the transect 200 m upstream of Horse Rock to give the volumetric averaged velocity  $(\bar{u}_{vol})$  for each phase of the tide. The  $\bar{u}_{vol}$  value was assumed to represent the free-stream velocity or the velocity unaffected by this pinnacle and therefore replaces U in Eq. [10]. This approach assumes that the  $\bar{u}_{vol}$  value represents the approach velocity upstream of Horse Rock, which in this case is not true given the variability of the flow within the Sound.

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). This reference velocity was taken at the half-height of Horse Rock at same location along T3 (flood) and T4 (ebb) to the east of Horse Rock. This reference velocity (which varied for each phase of the tide) was subsequently used to normalise the timeaveraged longitudinal velocities. Wake recovery is therefore defined here as the relationship between the mean longitudinal velocity and the reference velocity ( $\bar{u}/U_{ref}$ ). 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 time-averaged normalised longitudinal velocities ( $\bar{u}/U_{ref}$ ) at the half-height of Horse Rock (~ -10 m CD) were used as they allow a more direct comparison of the wake extent, both longitudinally and laterally, at different tidal phases. Southerly flow during the ebb tide was denoted by a negative value, however, for the purposes of the wake analysis, the absolute values ( $|\bar{u}|$ ) have been used, with the exception of the flow reversals immediately downstream of Horse Rock, which display negative values ( $\bar{u}/U_{ref} < 0$ ).

#### 3.4 Results

### 3.4.1 Wake analysis

This section examines the development of the wake created by Horse Rock and its dissipation downstream over different phases of the tidal cycle. The longitudinal (u) velocities have been used as these represent the dominant flow direction.

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 ( $\approx$  +0.9 m CD). This elevation was chosen as it represents the half-height of Horse Rock, which represents an average rock diameter ( $D_{50}$ ) of approximately 50 m. Table 10 provides a summary of the relative submergence (H/h) of Horse Rock at various phases of the tide, as well as the reference velocities ( $U_{ref}$ ) and associated diameter Reynolds number ( $Re_d$ ) as given in Eq. [2].

Flood									
	Water depth over Horse Rock (m)	Water depth (H) (m)	Relative submergence ( <i>H</i> / <i>h</i> )	Reference velocity $(U_{ref})$ (m s <sup>-1</sup> )	Diameter Reynolds number ( <i>Re</i> <sub>d</sub> )				
Slack+1	2.7	25.6	1.11	2.2	9.65 x 10 <sup>7</sup>				
Slack+2	3.3	26.2	1.14	2.8	1.23 x 10 <sup>8</sup>				
Slack+3	3.6	26.5	1.15	3.0	$1.32 \ge 10^8$				
Slack+4	3.3	26.2	1.14	2.1	9.21 x 10 <sup>7</sup>				
Slack+5	2.9	25.8	1.12	1.5	6.58 x 10 <sup>7</sup>				
Ebb									
Slack+1	1.0	23.9	1.04	0.9	3.95 x 10 <sup>7</sup>				
Slack+2	0.5	23.4	1.02	1.1	4.82 x 10 <sup>7</sup>				
Slack+3	0.3	23.2	1.01	1.1	4.82 x 10 <sup>7</sup>				
Slack+4	0.5	23.4	1.02	0.8	3.51 x 10 <sup>7</sup>				
Slack+5	1.1	24.0	1.04	0.4	1.75 x 10 <sup>7</sup>				

Table 10 – Summary of relative submergence levels of Horse Rock (H/h) at various tidal phases, the reference velocity  $(U_{ref})$  and associated diameter Reynolds number  $(Re_d)$ 

The normalised time-averaged longitudinal velocities ( $\bar{u}/U_{ref}$ ) as a function of the longitudinal downstream distance (normalised by the diameter of the obstruction at its half-height –  $x/D_{50}$ ) from Horse Rock are presented in Figure 44 for a range of  $U_{ref}$  velocities; representing different phases of the flood (A) and ebb (B) tides respectively. Again, an elevation of -10m CD was used as this represents the half-height of Horse Rock and therefore the average diameter of the pinnacle ( $D_{50} \approx 50$  m) for a direct comparison with the downstream distance ( $x/D_{50}$ ). This is consistent with the methodology adopted by Lloyd and Stansby (1997a). These data translate to a distance of 10.9 m below the crest of Horse Rock.

These plots show that for each phase of the tide, the greatest velocity deficit is found immediately downstream of the pinnacle. The initial recovery rate during the flood tide is high (between  $x/D_{50} = 2 - 4$ ), however, as downstream distance increases, wake recovery is reduced and begins to plateau. At  $x/D_{50} = 8$ , the velocities have recovered to approximately 65% for the reference velocity ( $U_{ref}$ ) of 2.2 m s<sup>-1</sup>. During the ebb phase of the tide (Figure 44b) the wake recovery rate is faster given the lower velocities associated with this phase of the tide, with two of the profiles recovering back to 90% of the reference velocity ( $U_{ref}$ ) by  $x/D_{50} = 8$ . Recovery tends to be slower as the reference velocity increases.



Figure 44 – Normalised time-averaged longitudinal wake velocities  $(\bar{u}/U_{ref})$  in the longitudinal  $(x/D_{50})$  direction along wake centreline at the pinnacle half-height for different flood (A) and ebb (B) reference velocities  $(U_{ref})$ 

Another wake characteristic that is important in the planning and placement of multiple turbines within an array is its lateral displacement: the lateral distance of the

wake from the flow axis of a turbine, or in this case, from the centreline of Horse Rock. To assess the lateral wake migration, a north-south orientated line was drawn through the centre of Horse Rock. The lateral 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 longitudinal (downstream of this pinnacle) and lateral 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.

Lateral profiles are presented in Figure 45 - 49 for a range of distances downstream of Horse Rock, and at different phases of the flood and ebb tides. Positive lateral 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 ( $U_{ref}$ ).

Figure 45 displays the lateral extent of the wake one hour after slack water for the flood (A) and ebb (B) phases of the tide. During the flood phase the wake is relatively symmetrical at  $x/D_{50} = 2$ , 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  $x/D_{50} = 8$ , the lateral displacement is approximately by  $y/D_{50} = 0.4$  from the centreline. During the same phase of the ebb tide, the wake is again relatively symmetrical at  $x/D_{50} = 2$  but starts to migrate to the west as flow is deflected by the shallower water depth to the east.

Two hours after slack water (Figure 46),  $y/D_{50}$  increases to 0.8 at  $x/D_{50} = 8$  during the flood tide (A), while during the same phase of the ebb tide,  $y/D_{50}$  increases to -1.2 at

 $x/D_{50} = 6$ . Based on these plots, it would be expected that as the mean longitudinal velocity ( $\bar{u}$ ) increases, the lateral displacement would also, however, the lateral profiles during the lower velocity phases of the tide, i.e. four (Figure 48) and five (Figure 49) hours after slack water, display relatively large lateral 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 lateral displacement. This is dissimilar to the longitudinal extent, which is predominantly controlled by the mean longitudinal ( $\bar{u}$ ) velocity.



Figure 45 – Normalised time-averaged longitudinal velocities  $(\bar{u}/U_{ref})$  one hour after slack water in the lateral  $(y/D_{5\theta})$  direction for different longitudinal distances  $(x/D_{5\theta})$  downstream of Horse Rock at the pinnacle half-height during the flood (A) and ebb (B)



Figure 46 – Normalised time-averaged longitudinal velocities  $(\bar{u}/U_{ref})$  two hours after slack water in the lateral  $(y/D_{50})$  direction for different longitudinal distances  $(x/D_{50})$  downstream of Horse Rock at the pinnacle half-height during the flood (A) and ebb (B)



Figure 47 – Normalised time-averaged longitudinal velocities  $(\bar{u}/U_{ref})$  three hours after slack water in the lateral  $(y/D_{50})$  direction for different longitudinal distances  $(x/D_{50})$  downstream of Horse Rock at the pinnacle half-height during the flood (A) and ebb (B)



Figure 48 – Normalised time-averaged longitudinal velocities  $(\bar{u}/U_{ref})$  four hours after slack water in the lateral  $(y/D_{50})$  direction for different longitudinal distances  $(x/D_{50})$  downstream of Horse Rock at the pinnacle half-height during the flood (A) and ebb (B)



Figure 49 – Normalised time-averaged longitudinal velocities  $(\bar{u}/U_{ref})$  five hours after slack water in the lateral  $(y/D_{50})$  direction for different longitudinal distances  $(x/D_{50})$  downstream of Horse Rock at the pinnacle half-height during the flood (A) and ebb (B)

The far wake is the most significant region for spacing between TST devices, however, it is still important to understand the flow characteristics of the near wake region (Bahaj and Myers, 2013). Mean longitudinal velocity profiles along the wake centreline are presented in Figure 50 and 51 for the flood (A) and ebb (B) phases of the tide at  $x/D_{50} = 2$  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  $(x/D_{50} = 2)$  during the flood tide. Flow reversals occur immediately downstream of Horse Rock  $(x/D_{50} = 2)$  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 m s<sup>-1</sup>, 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  $(\bar{u})$  velocity. As the downstream distance increases  $(x/D_{50} = 8)$ , 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  $x/D_{50} = 2$  does not extend this far downstream.

During the ebb tide the profiles at  $x/D_{50} = 2$  are more uniform than those during the equivalent flood tide, although recirculation still occurs at all phases of the tide. The strength of this recirculation is, however, greatly reduced given the lower velocities associated with the ebb tide. At the lowest velocity phases of the tide (Slack+1 and Slack+5) there is little negativity in the flow; reinforcing the fact that recirculation strength is linked to the streamwise velocity. Again, as downstream distance increases

the ebb profiles become more uniform with no negative values. This suggests that profile uniformity is a function of velocity magnitude, as the reference velocity decreases, profile uniformity increases. The increased uniformity with downstream distance indicated that the flow becomes "cleaner" and less turbulent.



Figure 50 - Time-averaged longitudinal velocity profiles  $(\bar{u})$  in m s<sup>-1</sup> at  $x/D_{50} = 2$  (i.e. 2 diameters downstream of Horse Rock) along wake centreline for each flood (A) and ebb (B) tidal phase



Figure 51 - Time-averaged longitudinal velocity profiles  $(\bar{u})$  in m s<sup>-1</sup> at x/D<sub>50</sub> = 8 (i.e. 8 diameters downstream of Horse Rock) along wake centreline for each flood (A) and ebb (B) tidal phase

Vertical ( $\overline{w}$ ) velocity profiles along the wake centreline are presented in Figure 52 and 53 for the flood (A) and ebb (B) phases of the tide at  $x/D_{50} = 2$  and 8 respectively.

Comparison of the flood and ebb phases of the tide clearly shows significantly reduced vertical velocities during the ebb as a result of the lower velocities. At  $x/D_{50} = 2$ , there is a dominance of upwelling downstream of Horse Rock, particularly three, four and five hours after slack water, while downwelling dominates one hour after slack water. However, the profiles at this location are very non-uniform. For example, the vertical velocity profile around peak flood (three hours after slack water) displays upwelling in the upper portion of the water column (peaking a 0.8 m s<sup>-1</sup>) before downwelling is initiated at -3.3 m CD, followed again by upwelling. This pattern is consistent with the longitudinal ( $\bar{a}$ ) velocities given in Figure 50 at this phase of the tide reinforcing the likelihood that an eddy at this location existed. Although the profiles are more uniform at  $x/D_{50} = 8$  during the flood, positive and negative velocities still existed. At  $x/D_{50} = 8$ , downwelling occurs at the wake centreline for three phases of the flood tide (one, three and four hours after slack water) while upwelling occurs two and five hours after slack water. This demonstrates that the velocity structure downstream of Horse Rock is complicated.



Figure 52 - Time-averaged vertical velocity profiles  $(\overline{w})$  in m s<sup>-1</sup> at  $x/D_{50} = 2$  (i.e. 2 diameters downstream of Horse Rock) along wake centreline for each flood (A) and ebb (B) tidal phase



Figure 53 – Time-averaged vertical velocity profiles ( $\overline{w}$ ) in m s<sup>-1</sup> at  $x/D_{50} = 8$  (i.e. 8 diameters downstream of Horse Rock) along wake centreline for each flood (A) and ebb (B) tidal phase

### 3.4.2 Re-circulatory flow

Anecdotal evidence suggests that localised re-circulatory flow is common within zones of Ramsey Sound. However, until now little has been recorded about the duration and strength of these flow reversals. Flow reversals occur at the outer margins of the Sound during the majority of the tidal cycle and are resultant from the interaction of flow with the coastline configuration of the Sound. During the flood tide, the flow on the western and eastern sides of the Sound is deflected by approximately 180° off the north-eastern tip of Ramsey Island and Point Saint John (headland at the northeastern portion of Ramsey Sound – see Figure 40), respectively before flowing in a southerly direction. On the western side of the Sound, this flow is impeded by The Bitches reef and is deflected to the east before returning to the principal northwardflowing body of water. On the eastern side, the southward-flowing water is deflected by the mainland promontory; driving the flow to the west to return to the principal northward flow. These recirculation zones have a counter-clockwise and clockwise rotation on the western and eastern margins of the Sound respectively. These flow patterns have been confirmed by a 2-D TELEMAC oceanographic model (Figure 54) created at Bangor University (Hashemi et al. 2012), which has been refined at Ramsey Sound and covers the same time period as the ADCP data. Although this model is depth-averaged and requires calibrating to measured data, comparison of the outputs shows good correlation with the ADCP data. This model also shows that both flood (A) and ebb (B) velocities accelerate as they are constrained through the relatively narrow gap (~ 450 m) between The Bitches and the mainland. This hydrodynamic regime is comparable to a tidal streaming site as suggested by Couch and Bryden (2006).



Figure 54 – 2-D depth-averaged TELEMAC oceanographic model of Ramsey Sound during peak flood (A) and ebb (B) (Hashemi *et al.* 2012). Each grid square is 1 km<sup>2</sup>. Filled colour contours and vectors represent the u, v velocity components.

Furthermore, two self-recording current meters (SRCMs) were positioned in the sheltered region on the eastern margin of the Sound (off the lifeboat slipway as shown in Figure 40) to both ground-truth the ADCP measurements and confirm the strength and duration of the eastern recirculation zone. These current meters collected continuous point velocity measurements (resultant of the u, v velocity components) at a depth of 3 m and 5 m below the water surface. The current meters were attached to the vessel mooring and therefore rose and fell with the tide to ensure the same elevation in the water column was sampled. Table 11 provides a summary of the velocities associated with the SRCMs during the flood tide on 1<sup>st</sup> June 2012; the same day as the ADCP measurements. At slack water, the 5m SRCM is directed towards  $336^{\circ}$ , i.e. with the principal northerly flowing water, however, as the tide strengthens the flow begins to rotate and the flow reversal is initiated. The SRCM begins to rotate around 0.25 hours (15 minutes) after slack water with directions of 52° for the 5 m SRCM and 22° for the 3 m SRCM. An increase of velocities within the main channel results in an increase of velocities within the recirculation zone. However, the maximum velocities within this recirculation zone do not coincide with the peak velocities within the main channel (ADCP data at -5 m CD), which occur around two hours after slack water. Instead, they peak at 0.4 m s<sup>-1</sup> (3.0 m s<sup>-1</sup> within the main channel), which is approximately 1.25 hours before. The direction of the flow within this recirculation zone at its peak (0.75 hours after slack water) is around  $160^{\circ}$ , i.e. SSE direction. Scrutiny of the directions from both flow meters suggests that the flow rotates back to approximate due north 4.75 hours after slack water. This corresponds to a peak velocity of  $1.6 \text{ m s}^{-1}$  within the main channel. There is therefore a critical velocity of around 1.6 m s<sup>-1</sup> within the main channel that initiates this eastern recirculation zone. Although the velocity data from the SRCMs have only been plotted

for the flood tide, inspection of the data shows that flow reversals occur within this portion of the Sound during the ebb tide; which is consistent with the ADCP data.

	5 m SI	RCM	3 m SR	Peak ADCP	
lehiT	Speed (m s <sup>-1</sup> )	Direction	Speed (m s <sup>-1</sup> )	Direction	velocities in
nhase		(°N)		(°N)	main
phase					channel at -5
					m CD (ms <sup>-1</sup> )
Slack	0.2	336	-	-	1.6
Slack+0.25	0.2	52	0.1	22	2.6
Slack+0.5	0.2	101	0.2	95	2.6
Slack+0.75	0.4	159	0.4	157	3.0
Slack+1	0.2	189	0.2	188	3.0
Slack+1.25	0.1	207	0.1	211	3.3
Slack+1.5	0.1	227	0.1	215	3.7
Slack+1.75	0.1	238	0.1	200	3.3
Slack+2	0.1	197	0.2	183	4.0
Slack+2.25	0.1	227	0.1	222	3.5
Slack+2.5	0.1	165	0.1	157	3.8
Slack+2.75	0.1	208	0.1	173	3.9
Slack+3	0.1	205	0.1	176	3.0
Slack+3.5	0.1	240	0.1	243	3.3
Slack+3.75	0.1	216	0.1	186	2.5
Slack+4	0.1	153	0.1	137	2.7
Slack+4.25	0.2	180	0.2	191	2.6
Slack+4.5	0.2	213	0.2	218	1.9
Slack+4.75	0.1	226	0.1	239	1.6
Slack+5	0.1	254	0.1	252	1.6
Slack+5.25	0.1	315	0.1	286	-
Slack+5.5	0.1	317	0.1	280	-
Slack+5.75	0.1	309	0.1	271	-
Slack	0.1	284	0.1	265	-

#### Table 11 – SRCM velocities

### 3.5 Discussion

In an idealised system, such as a numerical model or laboratory experiments that comprise a flat bottom, the free-stream (U) velocity is relatively straightforward to determine. However, when a complicated bathymetry and coastline are introduced, 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 (K 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 thesis. 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 "freestream" velocity.

Despite this, the wake created by Horse Rock has been examined using a reference velocity ( $U_{ref}$ ) to determine both its longitudinal (x) and lateral (y) extent. Velocity magnitude (in the longitudinal, x, direction) largely dictates the wake extent in the longitudinal plane ( $x/D_{50}$ ), 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 longitudinal (x-direction) velocities, i.e. as the approach velocities (or reference velocities 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. 2011) 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 (Bahaj et al. 2007b). 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 longitudinal, x, lateral, y, 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 costeffective 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 (2013) 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 (Thomson et al. 2010) 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 (Myers and Bahaj, 2012). 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 ( $\bar{u}$ ) tended towards the reference velocity ( $U_{ref}$ ), which is consistent with the findings of previous experimental (Bahaj *et al.* 2007b; Gunawan *et al.* 2012; Myers and Bahaj, 2012; Bahaj and Myers, 2013) and numerical (Mason-Jones, 2010; Malki *et al.* 2011) 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 (2008) 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 (2004a) 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.* (2008) 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 (Giles *et al.* 2011). In order to reduce wake length, the most optimal turbine diameter to flow depth ratio is 0.25 (Giles *et al.* 2011). 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 (Giles *et al.* 2011).

There are currently only a few deployment initiatives underway to investigate TST performance (Fraenkel, 2007b; Gilson, 2010; Paish *et al.* 2010). 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 shear as well as turbulence to be captured. The only comprehensive wake study of a fully commercial TST was undertaken in Strangford Lough downstream of Marine Current Turbine's SeaGen device (Boake, 2011). The influence of bathymetry and coastline configuration is also captured through field-based measurements, which is challenging through

experimental (Johansson and George, 2006; Bahaj *et al.* 2007b; Giles *et al.* 2011; Myers and Bahaj, 2012) and numerical (Malki *et al.* 2011) 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 (Johansson and George, 2006).

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. (2005) 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 (2004a) 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 (Bahaj *et al.* 2007b). 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 northwardflowing 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.* (2011) 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 bidirectional 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 (Bahaj *et al.* 2007b). 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 (Giles *et al.* 2011). Myers and Bahaj (2012) provide a number of variables (Figure 55) that could affect the structure of the wake downstream of a TST, which, unlike natural pinnacles such as Horse Rock, extract energy from the system. 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 (Myers and Bahaj, 2012). 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.



Figure 55 – Variables affecting the flow field around TSTs (Myers and Bahaj, 2012)

#### **3.6** Chapter summary

This chapter 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, and is the topic of the subsequent chapter.

# 4 CONSTRAINTS ON TIDAL STREAM TURBINE DEPLOYMENT IN MACROTIDAL STRAITS

## 4.1 Introduction

The aim of this chapter is to identify the parameters (both hydrodynamic and physical) that constrain TST deployment sites and therefore assessed the viability of deploying TSTs in macrotidal straits using Ramsey Sound as a test site. The complicated hydrodynamics of this tidal system have already been examined in Chapter 3. Given that TEL are installing a demonstration TST device in the northern portion of Ramsey Sound in 2014, it is important to investigate the viability of such schemes, taking due consideration of physical (bed slope, water depth) and hydrodynamic (velocity magnitude, vertical shear, vertical velocities, tidal asymmetry, directionality) parameters. All of these parameters affect the available power in the system and therefore the cost effectiveness of generating power, which is of great importance to tidal energy developers.

This chapter outlines the methods employed before the characterisation of an macrotidal energy site (using Ramsey Sound as a case study) is subsequently given in Section 4.3 taking account of a number of hydrodynamic and physical parameters and constraints, including velocity magnitude, vertical shear, vertical velocities, tidal asymmetry, directionality, water depth, and bed slope. The results of a novel tool are also presented, which examines the effect of three parameters on TST viability, namely the longitudinal velocity over the vertical depth of a 15 m TST swept area  $(\overline{u_p})$ , water depth and bed slope.

#### 4.2 Methodology

Section 3.3 outlines the survey approach and data post-processing techniques used to inform this chapter, in which an additional analytical approach is taken. Once the timeaveraged velocity data for both the flood and ebb had been input into the Eonfusion software, the data was clipped to the 15 m TST swept area (i.e. 4.5 m and 19.5 m from the seabed, equating to a distance of 12 m from the seabed to the centre of the nacelle). This configuration was chosen as it represented the same dimensions as the DeltaStream TST designed by TEL, which is to be installed in Ramsey Sound in 2014. Given the flexibility of this software, any turbine diameter / nacelle height can be specified to examine the hydrodynamics and suitability of other TST designs. The next stage involved vertically-averaging the longitudinal velocities ( $\bar{u}$ ) over the 15 m TST diameter ( $\overline{u_{\nu}}$ ). Averaging velocity data across the swept width of a turbine is common practise. This is supported by Bryden et al. (1998, p. 703) who noted that 'it is reasonable to assume that the current speed should be averaged over the swept area of the turbine'. This vertically-averaged depth was subsequently interpolated across the flood (T1 - T3) and ebb (T4 - T6) survey tracks using an Inverse Distance Weighted (IDW) operator to create a raster of the time-averaged longitudinal velocities ( $\bar{u}$ ). The longitudinal velocity component  $(\bar{u})$  was used for these velocity data as this is the dominant flow direction (axial flow) within the Sound that a TST will be subjected to. Furthermore, examination of the longitudinal  $(\bar{u})$  and lateral  $(\bar{v})$  velocity components revealed that the lateral  $(\bar{v})$  velocity component (especially within the central portion of the Sound that experiences the greatest velocities) was approximately 5 - 10% of the longitudinal  $(\bar{u})$  velocity component. Power flux (Hardisty, 2009) was subsequently calculated by:

$$P = 0.5\rho A v^3 \tag{[11]}$$

where  $\rho$  is water density (1025 kg/m<sup>3</sup> in this case), *A* is the cross-sectional area of the turbine, and *v* is the velocity. This equation shows that power is the cube of velocity and therefore small fluctuations in velocity can lead to large changes in power-output.

The cross-sectional area is usually based on the area occupied by the turbine, however, for simplicity the area for these calculations is based on an area of 75 m<sup>2</sup> (5 m in the lateral (*y*) plane and 15 m in the vertical (*z*) plane). Furthermore, velocity in this case is based on the dominant longitudinal time-averaged velocity component ( $\bar{u}$ ). Since tidal velocities within the Sound are not uni-directional, the absolute longitudinal velocities ( $|\bar{u}|$ ) have been calculated to remove any negative numbers associated with flow reversals. The averaged longitudinal ( $\bar{u}$ ) velocity was subsequently converted to power flux using Eq. [11] to show the proportion of the Sound that would be suitable for a TST of this scale. Again, the thresholds can be altered dependant on the TST design. The next stage was to combine the 2 m bathymetry data and the slope raster for use in the suitability tool.

The suitability tool was based on three parameters and associated thresholds following discussions with an engineer at TEL (P Bromley, April 2013, personal communication), specifically a minimum water depth of 30 m and a maximum bed slope of 5°. The minimum velocity for economic viability is, however, difficult to determine without testing the device. Physically meaningful estimates of power depend on two general conditions: the swath of a cross-section that the swept area of
a given TST, and the minimum velocity at which power production is deemed economically viable. Couch and Bryden (2006) noted that sites existing device developers are initially interested in exploiting tend to have peak spring tidal velocities of > 3 m s<sup>-1</sup>. Furthermore, according to the UK's Carbon Trust summary report on tidal stream resources (Black and Veatch, 2005), sites with maximum velocity below 2.5 m s<sup>-1</sup> during mean spring tides may not be capable of generating enough power to warrant development. A recent report by the UK's South West Regional Development Agency (PMSS, 2010) suggests a slightly lower threshold of 2 m s<sup>-1</sup>. The minimum velocity ultimately depends on TST design to extract energy more efficiently and with reduced start-up torques. With technological advances tending toward more efficient power generation at lower velocities, tidal sites are likely to become more rather than less viable for resource development as velocity becomes a less important limiting factor. However, considering that first generation tidal energy devices require relatively high flow speeds (Harding and Bryden, 2012) and energy extraction at lower velocities is not considered to be economical with first generation devices (Sustainable Energy Ireland, 2008), the power flux calculations presented here use a minimum velocity threshold of 2 m s<sup>-1</sup>, which is consistent with PMSS (2010) and RenewableUK (2011). The principal stages of creating this dataflow are outlined in Figure 56.

The dataflow used to create the contour plots described above was subsequently copied and modified to create two further dataflows. The first calculated the depth-averaged velocities through the entire water column ( $\overline{u_d}$ ). This dataflow was created to examine the effect of depth-averaging data in macrotidal straits. The depth-averaged raster ( $\overline{u_d}$ ) was subsequently subtracted from the data averaged over the vertical

diameter of the 15 m TST swept area  $(\overline{u_v})$  to create a raster showing the effects of depth-averaging over the entire water column on the resultant power flux.

In addition to the plan view plots, cross-sectional plots in the lateral plane were also created to examine the spatial variability of the flow both across the Sound and with depth, as shown in Figure 57. Again, the horizontally averaged data (T1 – T3 for the flood and T4 – T6 for the ebb) were input into the dataflow. The data were subsequently grouped by transect so a cross-section could be plotted for each transect. An operator was then added to interpolate over the 5 m horizontally averaged data along these transects and vertically over the 1 m data to create a surface in the *x*-plane. Power flux was subsequently calculated using Eq. [11].

The next step involved the generation of a slope raster from the 2 m bathymetry data that could be used within the suitability tool. This process is outlined in Figure 58. Slope angle was calculated using the following equation (Burrough and McDonell, 1998):

$$Slope = \tan^{-1}\left(\sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}\right) \times 180/\pi$$
 [12]

where dz / dx is the rate of change in x direction and dz / dy is the rate of change in the y direction. A search radius of 3 m x 3 m was used to create the slope raster. To convert radian to degrees, the resultant value is multiplied by  $180/\pi$ .



Figure 56 – Plan view of suitability tool dataflow



Figure 57 – Cross-sectional dataflow



Figure 58 – Slope raster dataflow

Only velocity data recorded at the peaks of the flood and ebb tides are presented here, when flow through the strait was fastest as this gives the maximum power available in the system over the tidal cycle and corresponds to the worst-case scenario in terms of structural loading. This study offers an insight into Ramsey Sound's internal tidal flow structures and demonstrates the importance of characterising potential tidal energy sites taking due account of physical (bed slope and water depth) and hydrodynamic (longitudinal velocity ( $\bar{u}$ ), vertical velocity ( $\bar{w}$ ), direction, vertical shear, etc.) factors from a TST suitability perspective.

#### 4.3 Results

#### 4.3.1 Tidal asymmetry

This chapter is principally concerned with (unless stated otherwise) the average velocity over the vertical diameter of a 15 m TST swept area ( $\overline{u_v}$ ), with a centre of the nacelle positioned 12 m above the seabed during the peak of the flood/ebb tides, rather than at a particular elevation in water column.

Figure 59a-c shows the average longitudinal velocity component ( $\bar{u}$ ) measured along the cross-sectional transects T1 – T3 (shown in Figure 37) during the peak of the flood tide. The high spatial variability in the tidal velocities, particularly in the lateral direction is evident, with the greatest velocity located on the eastern side of the deep channel and in the shallower region to the east of Horse Rock. The wake created by this natural feature is also discernible (particularly at Transect T3), albeit to a lesser extent as distance downstream increases.

Figure 59d shows the time-averaged longitudinal velocities  $(\bar{u})$  over the vertical diameter of the 15 m swept area  $(\bar{u}_{v})$  during the peak of the flood tide, when water pushes into the Sound from the south. The non-uniform variability in the tidal flow is evident as it separates around Horse Rock. The wake created by this pinnacle is clearly visible and its influence on the currents at transect T1 (~ 400 m downstream) is still

apparent. Flow reversals (described in Section 3.4.2) are evident near the margins of the Sound as the main current is influenced by the local bathymetry.



Figure 59 – Cross-sectional plots of average longitudinal ( $\bar{u}$ ) velocities downstream of Horse Rock for transects T1 (A), T2 (B) and T3 (C) at peak flood (positive and negative values denote northward and southward flow respectively; solid black line shows 15 m diameter TST swept area while dotted line represents seabed profile); and (D) depthaveraged ( $\overline{u_{\nu}}$ ) contour plot over 15 m TST swept area at peak flood.

Figure 60a-c show the time-averaged longitudinal velocities ( $\bar{u}$ ) along cross-sectional transects T4 – T6 during the peak of the ebb tide. The lower ebb velocities result in a reduced spatial variability in tidal velocities as well as a less noticeable wake of Horse Rock. Figure 60d shows the depth-averaged velocity ( $\bar{u}_v$ ) over the 15 m TST swept area. During the ebb, when water drains through the Sound from the north, the highest velocities occur in the corridor of the strait defined by the deep channel. Again, a velocity deficit zone exists in the lee of Horse Rock and persists for hundreds of meters

downstream. Although the velocities associated with this phase of the tide are lower, a flow reversal on the western margin of the Sound occurs as the currents are deflected to the north by The Bitches reef. Maximum flood velocities over the 15 m TST swept area are 3.8 m s<sup>-1</sup> compared with 1.9 m s<sup>-1</sup> during the equivalent ebb phase of the tide, an increase of 100%. This is consistent with previous observations of flood-dominated tidal asymmetry around the Pembrokeshire promontory (Fairley *et al.* 2013).



Figure 60 – Cross-sectional plots of average longitudinal ( $\bar{u}$ ) velocities downstream of Horse Rock for transects T1 (A), T2 (B) and T3 (C) at peak ebb (positive and negative values denote northward and southward flow respectively; solid black line shows 15 m diameter TST swept area while dotted line represents seabed profile); and (D) depth-averaged ( $\bar{u}_{\nu}$ ) contour plot over 15 m TST swept area at peak flood.

## 4.3.2 Vertical velocity data

The tidal velocity data examined in Section 4.3.1 related to the time-averaged longitudinal ( $\bar{u}$ ) velocity component. This section, however, scrutinises the time-averaged vertical ( $\bar{w}_v$ ) velocity component in order to investigate the magnitude of the positive (upwelling) and negative (downwelling) velocities over the 15 m diameter TST swept area. Very few studies have examined vertical velocities in tidal data, however, velocities approaching a TST at an angle to the axial, or longitudinal (x) plane, are undesirable as they will affect turbine performance and increase the structural loading. Placing a TST in areas of high vertical velocity should therefore be minimised, or ideally avoided, in order to maximise the device design life.

Although termed 'vertical', the flow is likely to be travelling somewhere between horizontal and vertical, however, the following plots provide an insight into areas that experience greater degrees of vertical velocities, which is undesirable for a TST as they subject the turbine to unnecessary loadings. Figure 61a-c shows the vertical ( $\overline{w}$ ) velocity component measured along the cross-sectional transects T1 – T3 (shown in Figure 37) during the peak of the flood tide. Away from Horse Rock, the degree of upwelling within the deep channel (particularly at transect T3) is relatively high, peaking at 0.4 m s<sup>-1</sup>. These cross-sections demonstrate the influence of the bathymetry (coupled with the high tidal velocities during this phase of the tide) on tidal velocities, which cause large deviations from the longitudinal (*x*) direction. Figure 61d shows vertical velocity fields based on the depth-averaged velocity ( $\overline{w_v}$ ) over the 15 m TST swept area during the peak of the flood tide. Again, over the 15 m TST swept area there are relatively large variations in the vertical velocity component across the Sound with the greatest vertical velocities occurring in the vicinity of Horse Rock and within the deep channel to the west.



Figure 61 – Cross-sectional plots of vertical ( $\overline{w}$ ) tidal velocities downstream of Horse Rock for transects T1 (A), T2 (B) and T3 (C) at peak flood (positive and negative values denote upwelling and downwelling respectively; solid black line shows 15 m diameter TST swept area while dotted line represents seabed profile); and (D) depth-averaged contour plot of vertical ( $\overline{w_v}$ ) velocities over 15 m TST swept area at peak flood.

Figure 62a-c shows the vertical ( $\overline{w}$ ) velocity component of flow measured along the cross-sectional transects T1 – T3 (shown in Figure 37) during the peak of the ebb tide. The flood-dominated tidal asymmetry is clearly evident; resulting in lower vertical velocities both through the water column and across the Sound. Likewise, the averaged vertical velocities ( $\overline{w_v}$ ) across the 15 m TST swept area Figure 62d are lower when compared with the same phase of the ebb tide, peaking at approximately -0.13 m s<sup>-1</sup> to the south-west of Horse Rock as the flow is forced down into the deep channel.



Figure 62 – Cross-sectional plots of vertical ( $\overline{w}$ ) tidal velocities downstream of Horse Rock for transects T1 (A), T2 (B) and T3 (C) at peak ebb (positive and negative values denote upwelling and downwelling respectively; solid black line shows 15 m diameter TST swept area while dotted line represents seabed profile); and (D) depth-averaged contour plot of vertical ( $\overline{w_v}$ ) velocities over 15 m TST swept area at peak ebb.

These data demonstrate that the magnitude of the vertical velocity component is largely dictated by the longitudinal  $(\bar{u})$  velocity component, i.e. the greater the velocity in this north-south (x) direction, the greater vertical velocity. Although the bathymetry in the vicinity of the Sound where ebb tidal data exists is still very irregular, the lower velocities associated with this phase of the tide results in reduced vertical velocities at the expense of available power. There is therefore a compromise that needs to be met in these macrotidal systems between sufficient longitudinal  $(\bar{u})$  velocities for power

generation and tolerable vertical velocities. Ideally, the seabed should be wide and flat enough to limit undesirable vertical velocities / vertical shearing. Velocities resultant of the  $\bar{u}$  and  $\bar{v}$  velocity components that approach a TST at an angle other than the dominant longitudinal (*x*) direction, are another factor to consider when designing a device. This is discussed in more detail in Section 4.3.6.

### 4.3.3 Velocity profiles

Velocity profiles of the longitudinal ( $\bar{u}$ ) velocities at three longitudinal locations across the Sound are presented in Figure 63. Negative values represent southerly flow. Again, these data have been spatially averaged with a sliding 5 m window in the horizontal direction to reduce the standard deviation of the data. To prevent the peaks from being averaged, the 1 m vertical resolution has been retained. Three longitudinal locations, displaying differing hydrodynamic conditions, have been selected: to the west of the deep channel (T3 'A' & T4 'A' in Figure 37), within the deep channel (T3 'B' & T4 'B' in Figure 37) and downstream of Horse Rock (T3 'C' & T4 'C' in Figure 37). These locations were examined at the peak of both the flood and ebb tides.

The velocities to the west of the deep channel (Location 'A') during the peak of the flood (T3) and ebb (T4) tides are relatively low and uniform through the water column, peaking at 0.5 m s<sup>-1</sup> and 0.2 m s<sup>-1</sup> respectively. Low flow conditions are experienced at this location during the peak of both the flood and ebb tides given their close proximity to the centre of counter-clockwise (flood) and clockwise (ebb) recirculatory zones at the outer margins of the Sound. The presence of "The Bitches" reef deflects the northward flooding currents to the east, which results in a velocity

deficit zone to the north and a zone of accelerated flow as the currents are constrained through passage between this reef and the mainland. During the ebb, the southward currents are able to flow across a wider area, however, as the currents encounter this reef they are deflected northwards resulting in a recirculation zone.

The velocities increase towards the deep channel (Location 'B'), peaking at 3.2 m s<sup>-1</sup> at this location during the flood tide (T3). There is a maximum velocity difference of 1.6 m s<sup>-1</sup> over the 15 m TST swept area. During the ebb, the profile displays a more unfirm shape with velocities peaking at -1.7 m s<sup>-1</sup>. Downstream of Horse Rock (Location 'C') the turbulent nature of the flow results in a fluctuation in the longitudinal ( $\bar{u}$ ) velocities from 3.9 m s<sup>-1</sup> near the surface to 1.4 m s<sup>-1</sup> near the seabed.



Figure 63 – Longitudinal velocity profiles  $(\bar{u})$  for T3 (flood) and T4 (ebb) – Location A (west of deep channel); Location B (within deep channel); and Location C (in the vicinity of Horse Rock)

### 4.3.4 Velocity shear profiles

Velocity shear  $(d\bar{u} / dz)$  across the 15m TST swept area is the first derivative of the velocity profiles shown in Figure 63. Shear profiles of the longitudinal  $(\bar{u})$  velocity component, extracted from transects T3 (flood) and T4 (ebb), deliver another view of the non-uniform flow structures during peak tidal flow (Figure 64). The same three longitudinal locations used for the velocity profiles have been used for the shear profiles.

The shear to the west of the deep channel (Location 'A') during the peak of the flood (T3) and ebb (T4) tides is relatively low given the reduced velocities. As the velocities increase towards the deep channel (Location 'B'), the shear during the flood tide (T3) varies through the water column with a peak of  $0.9 \text{ s}^{-1}$  close to the seabed. During the ebb tide (T4) the lower velocities result in a reduced vertical shear. Downstream of Horse Rock (Location 'C') the turbulent nature of the flow results in a maximum shear of  $0.99 \text{ s}^{-1}$  and  $0.27 \text{ s}^{-1}$  across the 15 m diameter during the flood (T3) and ebb (T4) tides respectively.



Figure 64 – Vertical shear profiles (based on the longitudinal ( $\bar{u}$ ) velocity component) for T3 (flood) and T4 (ebb) – Location A (west of deep channel); Location B (within deep channel); and Location C (in the vicinity of Horse Rock)

Maximum shear  $(d\bar{u} / dz)$  across a 15 m diameter as a function of average longitudinal  $(\bar{u}_{v})$  velocity across the 15 m diameter during peak flood and ebb flow is shown in Figure 65a. Since seabed depths greater than -25 m CD allow sufficient freeboard (~ 6 m) between a turbine with a 15 m diameter and the water surface during spring tide lows, these calculations are bounded between 5 – 20 m above the seabed (placing the centre of the TST approximately 12 m above the seabed). At low velocities (< 0.5 m s<sup>-1</sup>) the shear is also low (~ 0.2 s<sup>-1</sup>), with maximum shear occurring at mean flow

velocities exceeding 2 m s<sup>-1</sup>. Figure 65b demonstrates that the magnitude of the variance in shear increases with increasing tidal velocity, particularly at the peak of the flood tide. As would be expected, the variance in vertical shear is directly related to the velocity with increased velocities resulting in a greater variance in the shear.



Figure 65 – Maximum vertical shear as a function of  $(\overline{u_v})$  during peak flood and ebb (A); and (B) variance in maximum shear as a function of  $(\overline{u_v})$  during peak flood and ebb

## 4.3.5 Power estimation

Flow velocity can be used to estimate power flux, using Eq. [11]. The longitudinal velocity can be the point velocity  $(\bar{u})$ , depth-averaged across the entire water column  $(\overline{u_d})$  or in this case, vertically averaged across the TST swept area  $(\overline{u_n})$ . Figure 66a-c shows available power based on Eq. [11] using the longitudinal  $(\bar{u})$  velocities along the cross-sectional transects T1 - T3 (shown in Figure 37) during the peak of the flood tide, while Figure 67a-c shows the equivalent power for the ebb tide (transects T4 -T6). The zone of maximum energy differs on each tidal peak. During maximum flood conditions, available power is focussed to the east of the deep channel invert and to the east of Horse Rock, while at peak ebb, the energy peaks to the western side of the channel invert. Figure 66d shows the available power (calculated from the depthaveraged velocity over the 15 m swept area of the TST  $(\overline{u_v})$  during the peak of the flood tide, which reaches 27.4 kW m<sup>2</sup>. Figure 66e and Figure 67e display the effect of depth-averaging the longitudinal velocities over the entire water column ( $\overline{u_d}$ ) on power availability during the peak of the flood and ebb tides, respectively. There is a general underestimation of the available power during the peak of the flood tide, however, power in the vicinity of Horse Rock is overestimated by approximately 2 kW m<sup>2</sup>. As would be expected, there is little difference in the velocities when depthaveraging the data over the 15 m TST swept area  $(\overline{u_v})$  compared to over the entire water column  $(\overline{u_d})$  in the shallower outer margins of the Sound given the similar flow depths and lower velocities. In the deeper regions, however, there is a greater difference between swept area  $(\overline{u_v})$  and water column  $(\overline{u_d})$  depth-averaged velocity. During the flood tide (particularly at transects T2 and T3) the velocities accelerate as they pass Horse Rock, resulting in increased velocities to the immediate east and west.

Furthermore, within the area of accelerated flow to the west of Horse Rock, the velocities are generally greater within the 15 m swept area compared with higher in the water column. This therefore results in an underestimation in the velocity and power availability when depth-averaging over the entire water column. Any depth-averaging in regions with a large variation in velocities with depth will therefore prevent the detailed hydrodynamics and true power availability from being captured. Table 12 shows the available power based on both the depth-averaged velocities over the 15 m TST swept area ( $\overline{u_v}$ ) and over the entire water column ( $\overline{u_d}$ ). This comparison suggests that depth-averaging velocity over the entire water column ( $\overline{u_d}$ ) tends to generally underestimate the velocities and available power in macrotidal straits. It is therefore recommended to calculate power only over the swept area of a TST.



Figure 66 – Cross-sectional plots of power (based on the longitudinal ( $\bar{u}$ ) velocity component) at peak flood for transects T1 (A), T2 (B) and T3 (C) (solid black line represents 15 m diameter TST swept area while dotted line represents seabed profile); (D) depth-averaged contour plot of power over 15 m TST swept area at peak flood based on ( $\overline{u_v}$ ); and (E) the difference in available power when depth-averaging ( $\overline{u_d}$ ) tidal velocities over the entire water column ( $\overline{u_d}$ ). Positive and negative values denote an overestimation and underestimation of power respectively.



Figure 67 – Cross-sectional plots of power (based on the longitudinal  $(\bar{u})$  velocity component) at peak ebb for transects T1 (A), T2 (B) and T3 (C) (solid black line represents 15 m diameter TST swept area); (D) depth-averaged contour plot of power over 15 m TST swept area; and (E) the difference in available power when depth-averaging tidal velocities over the entire water column  $(\overline{u_d})$ . Positive and negative values denote an overestimation and underestimation of power respectively.

	Depth-averaged velocities over vertical diameter of a 15 m TST swept area $(\overline{u_{\nu}})$ m s <sup>-1</sup>	Depth-averaged velocities over entire water column $(\overline{u_d})$ m s <sup>-1</sup>	% Difference
Flood tide	3.8	3.5	8.6
Ebb tide	1.9	1.8	5.6
	Power (kW m <sup>-2</sup> )	Power (kW m <sup>-2</sup> )	
Flood tide	27.4	22.2	23.4
Ebb tide	3.5	3.1	12.9

Table 12 –	Effects	of	depth	-averag	ging	tidal	data*
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<sup>\*</sup> Based on area of the Sound that experiences maximum  $\bar{u}$  velocity

Temporal variability in the tidal velocity also controls power availability over daily, monthly (spring-neap cycle) and yearly timescales. Figure 68 displays the temporal variability of available power during a typical semi-diurnal tidal cycle. Power has been estimated for the area of the Sound that experiences the greatest  $\overline{u_v}$  velocities. Power availability across the turbine's swept area fluctuates over both the flood and ebb limbs, peaking at 4840 kW and 620 kW respectively. The flood-dominated tidal asymmetry is clear, with maximum power at the peak of the ebb tide which is 680% lower than that of the equivalent phase of the flood tide.



Figure 68 – Power availability within 15 m TST swept area over flood and ebb tidal limbs

Based on the above values, the average daily power available across the swept area of a 15 m diameter TST within this portion of Ramsey Sound is 6080 kWh/day; equating to approximately 13000 households per day. This value is based on an average annual household electricity consumption in the UK (in 2012) of 4000 kWhyr<sup>-1</sup> per household (Department of Energy and Climate Change, 2013), which equates to 0.46 kW usage per household and assumes that the TST is only operational for 20 hours of the day (i.e. no power is generated during slack water), which is a conservative estimate.

### 4.3.6 Directionality

So far, the average longitudinal  $(\bar{u})$  tidal velocity component has been examined as this is the dominant flow direction that a TST in this area would be subjected to. Although this is the principal flow direction within Ramsey Sound, it is important to understand the degree to which the velocities deviate from this dominant north-south direction, especially at the outer margins of the Sound, which has been shown to experience a recirculation in the flow during the majority of the tidal cycle.

This section is therefore concerned with the direction resulting from both the longitudinal  $(\bar{u})$  and lateral  $(\bar{v})$  tidal velocity components in order to quantify the misalignment angle, i.e. the angle from the longitudinal  $(\bar{u})$  velocity component over the 15 m TST swept area during the peak of both the flood and ebb phases of the tide. While this section focuses on the misalignment angle, Section 3.4.2 has examined the recirculation zones at the outer margins of the Sound. During the flood tide, the directional values vary from 0° (northerly direction) to 180° (southerly direction), however, the data have been limited to represent angles that deviate from the dominant longitudinal velocity component  $(\bar{u})$  for flow travelling in a northerly direction. Any currents travelling in a southerly direction, i.e. within the recirculation cells at the outer margins of the Sound have not been accounted for given the shallow flow depths and low velocities. Any vector with a negative direction  $(-1^{\circ} \text{ to } -90^{\circ})$  represents the angle at which the flow deviates from  $0^{\circ}$  (due north) to the west, while a positive angle ( $1^{\circ}$ to 90°) denotes the angle at which the velocities have deviated from north  $(0^{\circ})$  to the east. During the ebb tide, the data has again been restricted to velocities with a southerly direction and the deviation from the principal southerly direction (180°). Values of between 270° and 180° represent a velocity with a westerly direction, while between 180° and 90° the velocities have an easterly flow component. Only flow with a direction between  $-90^{\circ}$  (due west) and  $90^{\circ}$  (due east) during the flood tide and  $90^{\circ}$ to 270° during the ebb tide has been displayed, which corresponds to the portion of the Sound away from the outer margins, which is subjected to both low tidal velocities and a re-circulatory flow.

Figure 69 presents the velocity magnitude (resultant of the  $\bar{u}$ ,  $\bar{v}$  tidal velocity components) as a function of the incident flow angle during the peak of both the flood (A) and ebb (B) tides. Both datasets have been averaged over the vertical diameter of the 15 m TST swept area. Also shown on this plot are lines representing the economically viable velocity (2 m s<sup>-1</sup>), the principal flow axis (0°), and a 20° TST tolerance. Harding and Bryden (2012) use a range of 20° either side of the principal flow axis (0°) as a threshold. It is expected that angles greater than this are likely to compromise both the power-output and structural integrity of a turbine.

It is clear that during the peak of the flood tide, the velocities within the central portion of Ramsey Sound (with the exception of those immediately downstream of Horse Rock, namely transect T3) generally fall within this 20° tolerance for velocities greater than 2 m s<sup>-1</sup>. Below this velocity there is a greater directional spread from the principal flow axis, indicating that there is a greater variation in flow direction with lower tidal velocities. This suggests that as the velocity increases, the flow tends to align with the principal flow axis. However, bathymetry and coastline configuration are again highly influential on both the flow magnitude and direction. Away from the central portion of the Sound, the velocities are acted upon by various promontories, reefs and shelving areas, which deflect and retard the flow, resulting in a flow direction greater than 20°, particularly towards the outer edges of the Sound. During the ebb tide, the lower velocities over the 15 m TST swept area are clear with velocities barely reaching 2 m s<sup>-1</sup> during the peak. The velocities tend, however, to be concentrated within the 20° tolerance region. Furthermore, velocities with an angle greater than  $20^{\circ}$  tend to flow in a general south-westerly direction (between  $200^{\circ}$  to  $270^{\circ}$ ) as they are defected by the shallower shelving region to the east. Comparison with lower velocity phases of the tide (here, one hour after slack water – Figure 70) suggests that lower velocities, particularly during the ebb, result in a greater directional spread.



Figure 69 – Plots of average velocity magnitude (resultant of  $\bar{u}, \bar{v}$  velocity components) over the 15 m TST swept area as a function of the average incident flow angle during peak flood (A) and ebb (B)



Figure 70 – Plots of average velocity magnitude (resultant of  $\bar{u}, \bar{\nu}$  velocity components) over the 15 m TST swept area as a function of the average incident flow angle, one hour after slack water during flood (A) and ebb (B)

# 4.3.7 Physical constraints of TST deployment

A tool has been developed as part of this study using the Eonfusion software to identify suitable TST sites based on  $\overline{u_{\nu}}$ , the bed slope and water depth. Various scenarios (Table 13) have been modelled to investigate the effect of different design configurations. Each scenario uses a 15 m TST swept area with the centre of the nacelle positioned 12 m above the seabed. Scenario 1 is based on the design criteria of TEL's DeltraStream demonstration device, which can tolerate a minimum water depth of 30 m and a maximum bed slope of 5°. Although the minimum velocity for economic viability is difficult to determine without testing the device, a velocity of 2 m s<sup>-1</sup> has been used (Sustainable Energy Ireland, 2008). Figure 71 shows suitable areas for TST deployment based on Scenario 1. The vertically-averaged longitudinal velocities over the 15 m TST swept area  $(\overline{u_{\nu}})$  have been converted to power using Eq. [11]. Only 2% of this portion of the Sound meet these requirements during the peak of the flood tide and again, given the lower velocities associated with the peak of the ebb tide, no areas are viable. Furthermore, suitable areas are extremely limited in extent and therefore depending on the TST design (i.e. TST arrays) could prove impractical.

Scenario	Description	Minimum longitudinal, $\overline{u_{\nu}}$ , velocity (m s <sup>-1</sup> )	Minimum water depth (m)	Maximum bed slope (°)	Suitable TST sites during peak flood / ebb (%)
1	TEL's TST criteria	2	30	5	2 / 0
2	Monopile design criteria (no bed slope threshold)	2	30	-	8 / 0
3	Lower water depth	2	20	5	10 / 0
4	Lower water depth (no bed slope threshold)	2	20	-	29 / 0
5	Lower economic viability	1.5	30	5	3 / 1
6	As Scenario '5' but no bed slope threshold	1.5	30	-	10 / 8
7	As Scenario '5' but lower water depth	1.5	20	5	12 / 2
8	As Scenario '5' but lower water depth and no bed slope threshold	1.5	20	-	34 / 12

# Table 13 – TST suitability scenarios



Figure 71 – Scenario 1: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $(\overline{u_v})$  of 2 m s<sup>-1</sup>, a minimum water depth of 30 m and a maximum bed slope of 5°

Scenario 2 is applicable to a monopile design where bed slope is less important. Figure 72 displays suitable areas for TST deployment based on  $\overline{u_{\nu}} > 2 \text{ m s}^{-1}$  and a water depth greater than 30 m. This time only 8% of the Sound where measurements exist meets these criteria during the flood with no suitable areas during the ebb.



Figure 72 – Scenario 2: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $(\overline{u_v})$  of 2 m s<sup>-1</sup> and a minimum water depth of 30 m

Scenario 3 relaxes the water depth threshold to 20 m, however, based on the current TST design only leaves a freeboard of 0.5 m from the tip of the turbine to the water surface (not accounting for lower water levels due to atmospheric or wave influences). Figure 73 shows that 10% of the Sound (where data exists) is now viable during the flood with no areas suitable during the ebb.



Figure 73 – Scenario 3: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $\overline{u_v}$  of 2 m s<sup>-1</sup>, a minimum water depth of 20 m and a maximum bed slope of 5°

Scenario 4 uses the same velocity and water depth thresholds as Scenario 3, however, the bed slope threshold has been omitted. Comparison with Scenario 3 (Figure 73) shows that there is much greater area of this portion of the Sound during the flood tide (29%) that is suitable for deployment.



Figure 74 – Scenario 4: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $(\overline{u_v})$  of 2 m s<sup>-1</sup> and a minimum water depth of 20 m

Scenario 5 (Figure 75) examines the effect of reducing the economically viable velocity to  $1.5 \text{ m s}^{-1}$  with a minimum depth of 30 m and a maximum bed slope of 5°. Even at this lower velocity, the area suitable for energy extraction is limited to 3% of the measured area during the flood tide. Bed slope therefore has a major influence on deployment viability. Due to the lower velocities associated with the ebb tide, there is now sufficient power available during this phase of the tide albeit restricted to 1% of the portion of the Sound where measurements exist.



Figure 75 – Scenario 5: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $\overline{u_v}$  of 1.5 m s<sup>-1</sup>, a minimum water depth of 30 m and a maximum bed slope of 5°

Scenario 6 (Figure 76) uses the same thresholds as Scenario 5 but discounts bed slope.

Approximately 8% and 10% of the measured area now meet these criteria during the

peak of the flood and ebb tide respectively.



Figure 76 – Scenario 6: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $\overline{u_v}$  of 1.5 m s<sup>-1</sup> and a minimum water depth of 30 m

Scenario 7 (Figure 77) examines the effect of reducing the minimum water depth to 20 m with a 5° bed slope and  $\overline{u_{\nu}}$  of 1.5 m s<sup>-1</sup>. Although the lateral extent during the flood tide is greater, a patchy area of suitability exists.



Figure 77 – Scenario 7: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $\overline{u_v}$  of 1.5 m s<sup>-1</sup>, a minimum water depth of 20 m and a maximum bed slope of 5°

Finally, Scenario 8 (Figure 78) discounts the bed slope threshold. Approximately 34% and 12% of the measured area meet these criteria during the flood and ebb respectively, suggesting that this configuration provides the greatest power potential.



Figure 78 – Scenario 8: Contour plot of power for suitable TST areas at peak flood and ebb based on a minimum  $\overline{u_v}$  of 1.5 m s<sup>-1</sup> and a minimum water depth of 20 m

Figure 79 shows the percentage of suitable TST locations as a function of bed slope angle based on the various a minimum  $\overline{u_v}$  and depth values given above. It can be seen that for all scenarios as the tolerable bed slope angle increases, the percentage of suitable areas increases as the tolerable bed slope angle is relaxed. It is also evident that the area of availability increases quite significantly when the minimum allowable depth is reduced from 30 m to 20 m at a minimum velocity of 1.5 m s<sup>-1</sup> during the peak of both the flood and ebb tides.



Figure 79 – Percentage of suitable TST areas under a variety of physical and hydrodynamic scenarios as a function of tolerable bed slope during peak flood and ebb

This suitability tool has demonstrated the significance of bed slope, and therefore device base width, which is generally overlooked during site selection. Out of each test, Scenario 8 offers the greatest developable area for energy extraction. A minimum water depth of 20 m has been applied to this scenario, however, a 15 m diameter TST set 4.5 m off the seabed will have insufficient clearance for vessels. A smaller turbine may seem an attractive alternative, however, a sensitivity test using a 10 m diameter turbine with the bottom of the swept area set at the same distance above the seabed as the 15 m diameter turbine (4.5 m) shows the same percentage area of suitability as a 15 m diameter turbine. This scenario also discounts bed slope and therefore only devices with a small footprint would be appropriate in the majority of areas. Furthermore, a lower  $\overline{u_v}$  velocity (1.5 m s<sup>-1</sup>) has been used. It is unlikely that this
velocity would be sufficient given the limitation of present technology and the current economic value of making use of tidal streams to generate power.

#### 4.4 Discussion

#### 4.4.1 Tidal asymmetry

Tidal asymmetry, which is the variation in current speed between the flood and ebb phases of the tidal cycle, is an important parameter to consider when designing a TST device. This parameter is not routinely considered when selecting suitable TST sites but one that has an important role in quantifying the resource.

The 2-D hydrodynamic TELEMAC model (Hashemi *et al.* 2012) suggests that the variability between the flood and ebb tides could be due in part to the narrowing of Ramsey Sound between The Bitches and the mainland, as suggested by Fairley *et al.* (2011), which accelerates the flow as it is laterally constrained through the narrow channel between The Bitches and the mainland. Ramsey Sound is therefore a good example of a tidal streaming site, as identified by Couch and Bryden (2006), where the narrow channel between The Bitches reef and the mainland causes a local flow acceleration with increasing velocities to the north and south of The Bitches during the flood and ebb tide respectively. Furthermore, the configuration of the coastline to the north of Ramsey Sound, particularly the promontory of St David's Head, focuses the ebbing flow to the west of Ramsey Sound.

Tidal asymmetry is not limited to Ramsey Sound with many coastal areas experiencing this phenomenon (Brown and Davies, 2010; Iglesias and Carballo, 2011; Goddijn-

Murphy *et al.* 2013; Neill *et al.* 2014). Neill *et al.* (2014) examined this parameter in Orkney, Scotland through a high-resolution 3-D ROMS tidal model. Many turbine designs, including TEL's TST, are two-way generating devices, i.e. the turbines are able to harness both the flood and ebb tidal velocities. In Ramsey Sound, maximum power available during the flood tide is approximately 680% higher than the equivalent phase of the ebb tide.

Designing a TST with a yaw system that allows the turbine to face the principal tidal current does have its advantages, i.e. where the flood and ebb tidal velocities are of a similar strength. However, many coastal areas (as identified by Neill *et al.* 2014) are either flood-dominated or ebb-dominated, which raises the question of the need for such a yaw system if, during the peak of the weaker tidal regime, there is insufficient power available for economic viability. This research has shown that the northern portion of Ramsey Sound has a flood-dominated tidal asymmetry; with minimal power available during the peak of the ebb tide. When accounting for the power coefficient ( $C_p$ ) the extractable power is less, which greatly reduces the economic viability. As the available power is proportional to the cube of the velocity, even small asymmetries in velocity lead to substantial asymmetries in power-output, which is consistent with previous observations of tidal asymmetry (Neill *et al.* 2014).

Although the majority of the data presented in this chapter reflects the peak of the flood and ebb tides, the magnitudes of the velocities are lower at other phases of the tidal cycle. This daily fluctuation in energy results in a further reduction in suitable locations for TSTs, which suggests that this portion of the fast-flowing strait is not a viable energy extraction area for large arrays of TSTs, particularly seabed-mounted,

with current technology. As well as the daily semi-diurnal fluctuations, the resource varies over a variety of timescales: seasonal, lunar and turbulent (Neill *et al.* 2014). Since the data presented in this chapter represent spring tidal conditions, there will be a reduction in the available energy as the tidal range reduces towards neap conditions.

#### 4.4.2 Directionality

In addition to the velocity variations over a semi-diurnal tidal cycle (tidal asymmetry), another aspect of tidal energy capture that is considered important from a turbine performance, capacity factor and structural loading perspective is the directionality, or the misalignment angle from the principal flow axis throughout the tidal cycle (Harding and Bryden, 2012). Unlike wind energy conversion, tidal currents tend to have lower directionality with flow often reversing by 180° in direction between the flood and ebb tides (Bahaj and Myers, 2013). Many TST designs rely on near uni-directional flows and are therefore relatively unresponsive to small deviations in directionality (Harding and Bryden, 2012). Deviations from the axial plane can compromise the performance of horizontal-axis TSTs (Bahaj *et al.* 2007a). Furthermore, Goddijn-Murphy *et al.* (2013) noted that large deviations from the principal flow axis could result in an inefficient use of the resource. This is reinforced by Easton *et al.* (2010) who noted that these flow features could significantly affect a TST's operational efficiency.

Understanding the degree of misalignment from the principal flow axis (which is primarily a function of the local bathymetric / coastline configuration) over the turbine swept area allows tidal energy developers to design devices that can accommodate

such misalignments in order to maximise power-output while minimising the structural loading. The magnitude and direction of tidal velocities are site-specific and highly influenced by the local bathymetry and coastline shape, particularly in areas subject to an irregular seabed / coastline comprising various headlands and promontories, such as in Ramsey Sound. It is therefore important for tidal energy developers to fully understand the local hydrodynamics of a prospective tidal energy site prior to the installation of a TST or an array of TSTs. Quantifying an acceptable misalignment angle is difficult, however, Harding and Bryden (2012) use a range of  $20^{\circ}$  either side of the principal flow axis ( $0^{\circ}$ ) as a threshold. It is expected that angles greater than this are likely to compromise both the power-output and structural integrity of a turbine. The effect of directionality is of course dependent on a variety of factors, including the type of tidal energy device being installed. Although the majority of tidal flows are bi-directional with the flood and ebb being 180° to each other  $(\pm 10^\circ)$ , Legrand (2009) notes that some tidal flows are not, and it is therefore important to establish the optimum orientation of a TST if the device is unable to extract energy from all directions.

It has been proposed that scrutinizing the flood and ebb tide separately provides a more complete characterization of this misalignment (Legrand, 2009). Furthermore, it was suggested by Gooch *et al.* (2009) that the flood and ebb phases of the tide should be considered independently, however, the majority of TST devices, particularly first generation horizontal axis devices, are unable to react to considerable directional changes other than those associated with the principal flood and ebb directions. Therefore, site-specific resource characterisation is important in order to quantify deviations from the principal flow axis, which could be integrated into the TST device design.

Work is currently being undertaken within the Cardiff Marine Energy Research Group (CMERG) at Cardiff University to examine the impact of misalignment between a TST and its surrounding free stream velocity using the data presented in this thesis as the inlet boundary to an ANSYS CFX Computational Fluid Dynamics (CFD) model. Examining the effects of misalignment between the flow and axial direction of the turbine on performance characteristics facilitates enhancements to condition monitoring control, thereby reducing the requirement of external instrumentation, which can be both costly and challenging to install and maintain in these highly dynamic environments.

Since the primary objective of this study was to examine the wake characteristics downstream of Horse Rock, the nature of the surveys (i.e. the flood and ebb tidal velocity data were collected downstream of Horse Rock and therefore not in the same spatial location) precludes a direct comparison of both the flood and ebb tidal phases. Despite this, it is still possible to compare both the asymmetry (see Section 4.3.1) and directionality (see Section 4.3.6) of both tidal phases to highlight favourable and unfavourable TST locations. While it is beyond the scope of this thesis to incorporate directionality into the suitability tool, having an understanding of the magnitude of these misalignments from the principal longitudinal ( $\bar{u}$ ) direction is important as it allows developers to account for this in their designs.

## 4.4.3 Vertical velocities

Vertical velocities are not often considered by tidal energy developers, however, they can exert undesirable loadings on a turbine, particularly if placed downstream of a significant bathymetric feature, such as Horse Rock. This can compromise the structural integrity of a device while reducing its power-output. In the northern part of Ramsey Sound, the flood-dominated asymmetry produces greater vertical velocities than the ebb tide. Knowing a site's hydrodynamic and bathymetric characteristic is therefore of vital importance to preserve the design life of a device.

Preferably, the flow approaching the turbine is uniform with very little vertical or horizontal shear across the swept area and uni-directional, flowing in the longitudinal (*x*) direction with low levels of turbulence. However, in reality the velocities are likely to deviate from this plane by the turbulent nature of the sites in which these devices will be installed. The bathymetry is a major factor controlling both the magnitude and direction of the flow. The highly changeable bathymetry within Ramsey Sound results in a high spatial variability in the tidal velocities, including the vertical ( $\overline{w}$ ) velocity component. Therefore, in order to reduce this variability and ensure the flow is relatively uniform both in the vertical and lateral directions, devices should be installed in areas comprising a relatively flat seabed. The slope of the seabed is therefore important, not solely within the footprint of a device but also upstream of the device as this bathymetry will largely dictate the flow direction. As noted by Dewey *et al.* (2005, p. 1911), an abrupt rise in the seabed "... can introduce numerous disturbances into the flow, including turbulent wakes, internal waves, and eddies". These hydraulic structures are undesirable and potentially detrimental to a TST as they introduce lateral and vertical velocities.

## 4.4.4 Vertical shear

Vertical shear is another major consideration for tidal energy developers as large differences in current speeds with depth (especially in the vicinity of the turbines themselves) can create pressure differences across the turbine as it rotates, which can lead to significant stresses and potential failure of a TST.

Given the complicated bathymetry of this tidal strait, the shear magnitude is spatially variable across the Sound with the greatest shear occurring in the vicinity of Horse Rock: an area of increased turbulence. Zones of high-velocity, low-shear flow (optimal conditions for a TST) may neighbour zones of high-velocity flow dominated by high vertical shear (deleterious conditions for a TST). These desirable and undesirable flow conditions may be as little as 20 m apart in the lateral direction, a distance barely larger than the swept area of a single turbine. Tidal energy developers should therefore have a sound understanding of this shear, particularly across the swept area of a TST since high vertical shear can exert large, asymmetrical loadings on a submerged structure such as a TST. There does not, however, appear to be a clear relationship between velocity magnitude and velocity shear, i.e. an increasing or decreasing velocity does not result in an increase in the level of shear. This suggests that shear is not controlled purely by the velocity magnitude; there must be another factor (such as turbulence) that influences the degree of shear through the water column.

It is therefore important to fully understand the upstream and downstream (if the turbine is bi-directional) bathymetric configuration of an area proposed for marine energy extraction to prevent installing a device in close proximity to these unfavourable features. If deploying a device / array of devices downstream of a sharp rise / fall in the seabed is unavoidable then it is advisable to install a series of moored ADCPs for a minimum period of 31 days (coupled with simultaneous vessel-mounted surveys for validation purposes) to understand the hydrodynamics and expected structural loadings on a TST.

## 4.4.5 Depth-averaging

Although depth-averaging tidal data over the entire water column is common practise within oceanographic models, it can disguise important flow characteristics in these fast-flowing environments, resulting in a general underestimation and a subsequent inaccurate estimation of the available power in the system. Waldman *et al.* (2014) noted that where turbines (or indeed naturally-occurring features) are present, the flow is not uniform with depth and does not conform to a standard log-law vertical shear profile. This has been demonstrated through the field measurements (Figure 64) used to inform this thesis, particularly downstream of Horse Rock. A 2-D, depth-averaged model may therefore be inaccurate in predicting the effects of energy extraction on sediment and benthic habitats, at least in the near field.

Velocities within the Sound vary with depth and the degree of variation fluctuates across the channel. This highlights the problems associated with depth-averaging tidal velocities over the entire water column (such as the outputs of a depth-averaged numerical model), which is seen to generally underestimate the velocities and therefore the energy available in the system compared to averaging over the TST swept area (here, 15 m diameter). Clearly, where ratio of water depth to the turbine diameter is close to unity or a similar order of magnitude as this swept area (i.e. 15 m) there is little difference in the velocities when depth-averaging, however, as the ratio increases, the vertical variability in the velocities (particularly during the flood tide) will not be captured when the data are depth-averaged over the entire water column. Depth-averaging tidal velocities in areas comprising highly variable velocity profiles have the tendency to average out the peaks. This is likely to result in an inaccurate estimation of the available energy in the system. Numerical models of tidal hydrodynamics (Neill and Elliott, 2004a; Easton et al. 2010; Easton et al. 2011; Hashemi et al. 2012; Serhadlıoğlu et al. 2013) are commonly depth-averaged. Hashemi et al. (2012) have developed a 2-D hydrodynamic TELEMAC model of the Irish Sea, which has been refined at Ramsey Sound. Measured data suggest that the modelled, depth-averaged tidal velocities in the area of the Sound that experiences maximum velocities are underestimated by approximately 40% during both peak flood and ebb conditions. Three-dimensional models, based on a non-hydrostatic pressure assumption, are therefore required in macrotidal regions in order to resolve the complicated hydrodynamics that exist.

As noted by Easton *et al.* (2011), depth-averaging velocity data in fast-flowing tidal areas masks important flow variations between flood and ebb regimes. Direct measurement allows for a more representative assessment of tidal energy sites (Fairley *et al.* 2013), both in terms of regions of flow accessible to a given turbine design, and

with regard to characteristics of the flow, such as strong shear zones in the water column, that may adversely affect the turbine apparatus itself.

## 4.4.6 Physical constraints of TST deployment

Power decreases with downstream distance from Horse Rock, and the maximum power is localised on either side of the pinnacle as the flow accelerates around this feature. This thesis has indicated that insufficient power is available near the outer margins of the Sound. Furthermore, although there appear to be power hotspots in the high velocity region that separates around Horse Rock, the steep bed slope presents a new complicating factor for TST placement, especially for gravity-based systems (Fairley et al. 2011). Seabeds are rarely flat and conditions vary significantly around the coast. An irregular or undulating seabed is more suited to piled foundations because bed preparation is very difficult for gravity structures (Sustainable Energy Ireland, 2008). Arrays that mount multiple turbines on a single structure (as opposed to the one tower, typical of wind turbines, for example) require reasonably low gradient beds. A number of TSTs are gravity-mounted and can only tolerate relatively low bed slopes. TEL's DeltaStream device can tolerate a maximum bed slope of 5° (P Bromley, December 2013, personal communication), which results in a base width of 20 m having a vertical drop of 2 m across the structure, while a 5 m base width equates to a 0.5 m drop. Lower bed slopes are desirable since the base has to remain stable. The maximum tolerable bed slope is dependent on the device mounting / anchoring arrangement but could be increased for a piled device. For the purposes of this study, a gravity-based device or small array of turbines sharing a common structure was used. Assuming no blasting or excavation of the Ramsey Sound channel bottom, local bed

slope in several locations within the channel render high-energy zones functionally inaccessible.

Water depth is another limiting factor. The majority of TSTs are deployed in water depths exceeding 30 m (Pacheco *et al.* 2014) since many devices extend approximately 20 m from the seabed to the tip of the turbine. A minimum 5 m clearance is normally recommended for recreational activities (small boats, swimmers, etc.), as well as to minimise turbulence and wave loading effects on the TSTs and damage from floating materials on the assumption that an exclusion zone be created restricting vessels with a draught greater than 2 m (Legrand, 2009). This generally results in a minimum water depth of 25 - 30 m with the inclusion of a 5 - 10 m freeboard. The bathymetry data (Figure 37) shows that there are large areas that meet this criterion, however, these are generally confined to the deep channel. Bryden et al. (1998) noted that where there is no exclusion of shipping, the top tip of the turbine has to be at the lowest astronomical tide (LAT) with additional safety factors to account for the lowest negative storm surge (-1.5 m), the trough of a 5 m wave (-2.5 m) and shipping and waves (-5 m). Therefore, based on this guidance and using TEL's DeltaStream device configuration, a 15 m diameter rotor with the hub set 12 m from the seabed requires a minimum water depth of 33.5 m. However, vessel activity within Ramsey Sound is restricted to local fishing and coastal vessels, which have a draught rarely extending 5 m below the water surface. Bryden et al. (1998) also noted that the bottom tip of the turbine must not be within 25% of the water depth from the seabed. This portion of the water column is subject to large vertical velocity shears due to bed friction.

To take maximum advantage of the tidal stream resource both in the UK and on a global scale, it will be necessary to design devices that can operate in water depths less than 30 m, subject to navigational and other physical constraints. This was realised by Pacheco *et al.* (2014) who noted that deploying devices in shallower water has the added benefit of being in closer proximity to the electrical grid and associated infrastructure.

Given the importance of bed slope in determining suitable TST locations, a high resolution (2 m in the horizontal plane) bathymetric grid has been used. This detailed bathymetry accounts for small-scale irregularities in the seabed, which are masked by either coarser bathymetric grids and / or low mesh resolution; an inherent limitation of far-field oceanographic models. These models generally employ an unstructured mesh with a relatively coarse grid away from the area of interest with increasing resolution as distance to the site decreases. However, grid sizes are often still too large at the area of interest to capture the local bathymetric irregularities, which, as shown previously, can have a significant influence on the flow. Haverson et al. (2014) developed a 2-D depth-averaged TELEMAC model of the Pembrokeshire coast, refined at Ramsey Sound with a mesh resolution of approximately 35 m. Aside from the fact that the model is depth-averaged, which has been shown to generally underestimate the velocities in these macrotidal straits, thereby masking the detailed flow structures, a bathymetric resolution of 30 m has been mapped onto the 35 m mesh. This relatively coarse grid is likely to ignore the small-scale bathymetric features, such as Horse Rock, which are highly influential on the local flow field. Much higher resolution bathymetric data of the area exists (~ 2 m resolution) and has been used to inform this thesis. Embedding this grid into this TELEMAC model

(coupled with a finer mesh) would improve the accuracy and confidence in the modelled outputs (particularly if further validation is undertaken). Sensitivity tests using smaller mesh sizes and ideally higher resolution bathymetric grids should be a prerequisite for these types of models to determine their accuracy. These models are therefore appropriate for larger-scale far-field modelling of sediment dynamics, for example, but become problematic when attempting to resolve medium- to near-field (i.e. CFD) modelling issues, such as TST array impacts on the local flow field using an extra sink in the momentum equations.

Furthermore, using these far-field models as a tool to identify viable TST sites based on bed slope tolerances may not be practicable as the coarser grids can smooth and even ignore important bathymetric features that may otherwise (i.e. if a higher resolution bathymetric grid was used) prevent a site from being developed. Until computer technology advances such that finer grids can be utilised to resolve these small-scale features, it is prudent to use these finer grids outside a numerical model, such as within GIS-based software, to ensure seabed gradients can be accurately defined at proposed TST sites.

#### 4.5 Chapter summary

This chapter has examined the hydrodynamics associated with a narrow, fast-flowing macrotidal strait and has evaluated the viability deploying TSTs in these dynamic coastal areas, using Ramsey Sound as a field site. These sites are often dominated by a complicated bathymetry and coastal configuration, which have a significant influence on the tidal flow, both in terms of vertical and horizontal directionality and

shear. Velocity is an important consideration when identifying potential areas for the exploitation of the kinetic energy from tidal sites, particularly in a flood- or ebbdominated area. However, water depth and bed slope are equally as important, but their significance ultimately depends on the TST design.

# 5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

#### 5.1 Conclusions

Tidal stream energy offers a predictable and clean renewable energy source in response to growing energy demands, diminishing fossil fuels and global climate change. The work presented in the former chapters of this thesis examines the effect of coastal features, specifically a prominent pinnacle, on tidal currents in narrow, macrotidal straits by drawing on a number of oceanographic, hydrographic and engineering elements, and evaluates the suitability of these dynamic tidal channels for TST deployment.

Ramsey Sound has been the focus of this study because it will soon host the first demonstration tidal stream energy project in Wales. However, the hydrodynamic and hydrographic characteristics of this dynamic strait were previously poorly understood. This information is crucial for the accurate estimation of the tidal energy potential in the area as well as the potential constraints that could preclude development. Given this gap, field and laboratory measurements were undertaken to investigate the effect of bathymetry and coastline configuration on the local hydrodynamics in these dynamic areas.

The findings presented here may be of particular relevance to developers and regulators as they demonstrate the complexity of these dynamic tidal straits and describe the various hydrodynamic and physical aspects considered important when selecting suitable TST deployment sites. Furthermore, the data collected as part of this study may be useful to oceanographic modellers for calibration purposes as well as providing a general understanding of the complicated nature of these energetic straits.

Based on the three objectives articulated in Chapter 1, the principal conclusions that can be drawn from this research are outlined below:

**Objective 1:** To examine the influence of submerged objects on the local flow field.

A comprehensive survey programme was undertaken to examine the wake created by a submerged natural pinnacle (Horse Rock) in Ramsey Sound under spring tide conditions. To date, the majority of research related to TSTs has focussed on their performance rather than their wake characteristics. Understanding the influence of natural obstructions on wake development and decay has important implications for tidal stream energy as it informs developers of aspects that should be considered at design stage, i.e. lateral displacement and longitudinal extent, to help prevent the performance or structural integrity of the devices from being compromised.

The benefits of using in-situ velocity measurements of the wake generated by a naturally occurring feature are twofold: 1) it provides an assessment of the influence of an obstruction to flow in energetic coastal environments without having to install a device, which is costly and impractical, and 2) it provides an insight into the effect an artificial structure (with an inoperative rotor) of a similar scale will have on the flow field. Although Horse Rock is geometrically dissimilar to a TST, understanding the effect a submerged natural feature has on the local flow field provides useful

information regarding wake characteristics that could help tidal energy developers with their designs. Furthermore, this information includes hydrodynamic parameters (velocity shear, vertical velocities, spatial variability, directionality, turbulence, etc.), which are heavily influenced by the local bathymetry, and therefore useful for the calibration and validation of numerical models, which typically comprise a flat bed and a uniform velocity profile (or plug flow).

Plots of the longitudinal  $(\bar{u})$  velocities at different phases of the tide have shown that wake recovery is largely controlled by the velocity magnitude in the longitudinal (x)direction with greater velocities resulting in a longer wake recovery. However, velocity alone is not solely responsible for controlling wake recovery, the local bathymetric and coastline configuration also influences wake recovery, particularly in the lateral (y-direction), deflecting the tidal velocities from the principal flow axis, thereby causing the wake to migrate from the centreline. In an idealised model (if the bed were flat and the coastline straight as was the case for the laboratory experiments) the lateral wake profile would follow a symmetric Gaussian-style profile shape. However, in macrotidal channels such as Ramsey Sound the irregular seabed results in an asymmetric profile shape. These lateral profiles show that velocity deficit is greatest closest to the pinnacle and decreases with downstream distance.

Velocity profiles along the wake centreline have shown the existence of a recirculation zone (flow reversals) in the longitudinal velocities downstream of the pinnacle, suggesting the presence of an eddy structure. These reversals were more intense during the flood tide, suggesting that greater velocities result in greater negative longitudinal  $(\bar{u})$  velocities. Similarly, vertical velocities were more intense during the flood tide. This demonstrates that the magnitude of flow reversals and vertical velocities is a function of the longitudinal  $(\bar{u})$  velocity. Velocity profile  $(\bar{u}, \bar{w})$  uniformity is also controlled by the longitudinal  $(\bar{u})$  velocity with greater uniformity at lower longitudinal velocities. Uniformity also increases with downstream distance from the pinnacle, away from the turbulent near wake region.

In summary, these data have shown that wake recovery in the longitudinal direction is predominantly controlled by longitudinal ( $\bar{u}$ ) velocities with greater velocities creating a longer wake in the longitudinal (x) direction. Lateral displacement from the wake centreline is influenced to a greater extent by the local bathymetry.

A laboratory investigation was subsequently undertaken to supplement the field data with the aim of isolating the effects of relative submergence on both wake recovery and the flow structures within the near wake region. These features are difficult to isolate and resolve through the field-based measurements due to the constantly changing tidal conditions (water level, velocity magnitude) and distance between the transects, respectively, and as such, these experiments permitted both the influence of relative submergence and the complex flow structures in the near wake region to be examined in greater detail.

Two submergence levels were investigated to isolate the influence of submergence on the flow characteristics in the near wake as well as examine its effect on wake recovery in the far wake. The laboratory experiments showed that submergence level (H/h) was an important parameter controlling the wake structure and extent, and that changes in submergence level affect both the 3-D flow structure in the near wake and the 2-D far wake of islands. The near-wake velocity field was different for both submergence levels, however, both conditions display similarities in the general flow structures (i.e. large scale motion) in the wake of the island. For both flow depths, a closed recirculation zone with a greater lateral and longitudinal extent for the submerged case was observed immediately downstream of the island. This recirculation zone was characterised by strong flow reversals and strong upward velocities for both submergence levels. This zone was also associated with smaller mean velocities and greater turbulence. Arch vortices were observed within the recirculation zone at a number of elevations for the submerged condition but only close to the island halfheight during the surface-piercing condition, suggesting that there are critical locations within the water column that experience these shedding flow structures. A stronger horizontal shear layer (around the side of the island) existed for the surface-piercing condition. A vertical shear layer was present for the submerged condition, however, this was not shown for the surface-piercing condition due to the limitation of the ADV device. In the far wake, it was shown that wake recovery was faster for the submerged condition. The results of this study are useful in the validation of CFD models to further improve the understanding of the shallow wakes and the influence of submergence level, which would be beneficial from a practical engineering perspective.

The flow reversals downstream of Horse Rock were more intense at greater longitudinal ( $\bar{u}$ ) velocities. However, the experimental data show slightly greater flow reversals during the lower velocity submerged condition. Furthermore, although the longitudinal extent of this recirculation zone was difficult to fully quantify via the field measurements (given the spacing between the transects), the extent of the recirculation

zone in the longitudinal direction was reduced at lower velocities, which is contrary to the laboratory results where a slightly longer recirculation zone was observed during the lower velocity submerged condition. This suggests that in addition to velocity magnitude, relative submergence also controls on the intensity of these flow reversals and the longitudinal extent on the recirculation zone.

Both the field and experimental data showed that the intensity of vertical velocities downstream of the obstruction were greater at higher longitudinal ( $\bar{u}$ ) velocities with the strength of these velocities decreasing with downstream distance as the wake tends to the upstream / unobstructed velocities. The uniformity of the longitudinal ( $\bar{u}$ ) and vertical ( $\bar{w}$ ) velocity profiles was seen to be controlled by the unobstructed velocities with greater uniformity at lower longitudinal velocities and downstream distance. This was true for both the field and experimental data.

**Objective 2:** To investigate the hydrodynamic parameters pertinent to macrotidal straits.

It was identified from the outset of this study that there was a general lack of information relating to the physical and hydrodynamic characteristics of macrotidal straits that experience high Reynolds numbers (which here had a diameter Reynolds number that ranged from approximately  $1.75 \times 10^7$  to  $1.32 \times 10^8$  in the vicinity of Horse Rock) for TST deployment. The majority of first-order appraisals of potential tidal energy sites are based on locating areas that experience fast-flowing currents. However, few studies have examined other important physical (bed slope and water

depth) and hydrodynamic (velocity magnitude, vertical shear, vertical velocities, tidal asymmetry, directionality) parameters that potentially constrain TST deployment sites. All of these parameters affect the available power in the system.

This study has identified that the northern portion of Ramsey Sound has a strong flooddominated tidal asymmetry, which raises questions regarding whether a TST device incorporating a yaw system in this location is required. From a structural integrity perspective, it may be more practical to have a yaw system despite there being a strong tidal asymmetry in the area in order to direct the turbine into the oncoming current to reduce the loading on the turbine. Site-specific resource assessments of any potential tidal energy area should therefore be undertaken prior to deciding on the TST design. A 2-D depth-averaged numerical model of the area has shown that the southern portion of Ramsey Sound (to the south of The Bitches reef) is ebb-dominated as flow draining through the Sound to the south accelerates as it is constrained through this narrow passage.

Vertical velocities are undesirable hydraulic structures, which subject a TST to unnecessary loadings. Vertical velocities vary in magnitude across the Sound, with the greatest occurring in the vicinity of Horse Rock and within the deep channel to the west. The magnitude of these vertical velocities is greatest during the flood tide where the velocities are greater, which suggests that upwelling and downwelling increases at greater velocities.

Velocity shear increases in areas with an abrupt change in bathymetry, i.e. in the vicinity of Horse Rock but remained relatively uniform away from this pinnacle. The

magnitude of the variance in shear increases with increasing tidal velocity. The variance in vertical shear is directly related to the velocity with increased velocities resulting in a greater variance in shear.

Directionality has been shown to be an important parameter to consider for tidal energy developers. Velocities greater than  $2 \text{ m s}^{-1}$  within the central portion of Ramsey Sound generally fall within this  $20^{\circ}$  tolerance; however, below this velocity directional spread from the principal flow axis is greater, indicating that there is a greater variation in flow direction at lower tidal velocities. This suggests that as the velocity increases, the flow tends to align with the principal flow axis. However, bathymetry and coastline configuration are again highly influential on both the flow magnitude and direction.

Depth-averaging longitudinal velocity data over the entire water column in these macrotidal environments generally underestimates the velocities and therefore the available energy in the system compared to averaging just over the TST swept area. This is likely to result in an inaccurate estimation of the available energy in the system. Therefore, relying on 2-D depth-averaged numerical models in dynamic tidal regions should be avoided and substituted with a 3-D model. Despite this, 2-D models can be useful once calibrated for preliminary investigations of the tidal resource as they provide a less computationally expensive insight of the local hydrodynamics. However, if a model is to be relied upon for TST site selection, particularly if the flow is subject to high shearing through the water column, then a 3-D model, albeit more computational expensive, should be used. Converting a 2-D model to 3-D baroclinic model does not simply involve a direct extrapolation since the equations involved in the simulations differ.

**Objective 3:** To develop a TST suitability tool which examines the effects of velocity, water depth and bed slope on power availability within a macrotidal coastal area.

Without a sound understanding of the bathymetric configuration and local hydrodynamics, it is likely that devices will be installed in unfavourable locations, which will result in low power-output and / or high structural loadings, thereby reducing the design life of a TST. The suitability tool developed as part of this research is unique as it uses a GIS-based platform, which offers a flexible approach to examine a site's hydrodynamic (velocity) and physical (water depth and bed slope) characteristics. This tool can be expanded to include other parameters beyond the scope of this research, including thresholds relating to vertical velocities, velocity shear, and directionality for example. Furthermore, calibrated and verified numerical modelling results could be imported into this tool to expand its coverage (see Section 5.2).

Based on a survey that encompassed a significant portion of Ramsay Sound, very few suitable areas exist (at least with the specifications of the device intended for Ramsey Sound) when longitudinal velocity  $(\bar{u}_v)$ , bed slope and water depth are accounted for. These parameters are typically overlooked but essential to extractable resource estimates and for insight into realistic TST performance. Locating a flat area of seabed to install devices with a large footprint is difficult in areas with an irregular bathymetry. Designing a device with a smaller footprint would allow a greater area of the channel to be exploited. The TST design is therefore an important consideration since this ultimately dictates viable locations for deployment. Technological advances are starting to facilitate lower velocities for economic viability and as such, it is likely that certain devices could generate economically viable power with velocities lower than 2 m s<sup>-1</sup>. Furthermore, certain devices have a smaller footprint, i.e. a monopole (similar to Marine Current Turbine's Seagen device). This design would remove the low bed slope requirement.

Finally, water depth can restrict deployment from shallow water areas, especially if these areas are used by deep-draughted vessels. This study has shown that velocities within the Sound are relatively uniform through the water column (with the exception of those near the seabed and in the vicinity of Horse Rock). This prevents the need to set the turbines high in the water column and therefore enables a larger developable area. It is therefore advisable to design devices once the hydrodynamics and physical constraints have been identified rather than design a device and subsequently find suitable locations that suit a device's requirements. This approach allows a greater area to be developed and prevents the omission of sites based on one or more of these physical parameters. Furthermore, it would enable the installation of a larger number of TSTs, which would result in more energy production and a greater economic return.

Although the data used to inform this thesis are related to Ramsey Sound, many other tidal regions exhibit similar physical and hydrodynamic characteristics. These findings are therefore transferrable and can be used to help understand the hydrodynamics at other macrotidal areas, which will ultimately dictate the feasibility of and most suitable location for TSTs. The interest of the work presented here therefore goes beyond this macrotidal strait, and ultimately the same methodology for a range of TST designs can be applied elsewhere.

#### 5.2 Recommendations for future research

## 5.2.1 Free-stream velocity determination

Determining the free-stream velocity in macrotidal straits is a challenge given the irregular bathymetry and coastal configuration, which can lead to significant spatial variability of the tidal velocities. To quantify wake recovery and lateral displacement from the centreline of Horse Rock, it is advisable that a reference velocity is used.

## 5.2.2 Field measurements of the near wake region

This study has also identified the difficulties in quantifying the near wake of a natural obstruction via vessel-mounted ADCP measurements. Establishing the level of turbulence and velocity structures immediately downstream of an obstruction of this scale in the field is challenging given the sampling frequency of ADCPs and transect spacing respectively. Unless a dense grid of ADCPs are deployed, it is inherently difficult resolve these flow structures with single boat surveys. A minimum spacing of 80 m between moored units is, however, likely to prevent these flow structures from being captured. Examining the wake of an obstruction through field data ultimately depends on the adopted survey methodology.

## 5.2.3 Field survey methodology

The vessel-mounted ADCP survey approach adopted for this study was based on a primary objective of quantifying the wake of a submerged pinnacle with a secondary objective of examining the tidal resource in combination with other hydrodynamic and physical parameters to assess the suitability of the area for TST exploitation. It is now understood that both objectives require slightly different survey methodologies. For the wake-related studies, it is recommended, if safety permits, to incorporate an upstream survey transect into the vessel-mounted ADCP circuit to help determine the approach, or free-stream velocity. Upstream survey transects close enough to the submerged object are often impractical (as was the case for the study site) due to the risk of collision with the obstruction. Alternatively, a moored ADCP could be positioned upstream of the obstruction to provide continuous velocity data while the survey vessel/s collect velocity measurements downstream. It is important to ensure that the upstream transect is sufficiently far enough upstream to avoid measuring the decelerations in the velocities caused by the obstruction but close enough to ensure that the approach velocities are representative and not influenced by bathymetric anomalies further upstream. To overcome this (and if cost were no object), a grid of moored ADCPs could be deployed upstream of the obstruction as a sensitivity test to examine the changes in velocity with distance upstream.

That being said, the bathymetric configuration of fast-flowing, macrotidal straits, such as Ramsey Sound, often comprises an irregular seabed and as such, determining wake recovery is difficult since the approach velocity is likely to differ from the unobstructed flow downstream. Although each circuit only took approximately 0.5 hours to complete, shortening the transect length would increase the temporal resolution of the data. The rationale in extending the transects to the outer margins of the Sound was twofold: 1) to understand the complicated hydrodynamics of the area from a resource perspective, and 2) to ensure the lateral migration of the wake downstream of Horse Rock was captured. Moreover, using moored ADCPs to quantify the wake of Horse Rock would require a grid of ADCPs of sufficient width (*y*- direction) and length (*x*-direction) to capture the lateral wake displacement and longitudinal wake recovery respectively. Not only would this be a costly exercise, there would be interference from the 20° acoustic beam angles for ADCPs of the same acoustic frequency if placed within 80 m of one another. Furthermore, these units have to be orientated such that they are directed towards the water surface; any offset from this plane would result in unrepresentative data. The bathymetry in the vicinity of Horse Rock is very irregular and therefore deploying these units here would be difficult. Given these constraints, the only practical way of accurately resolving the flow and turbulent structures in the near wake region would be through laboratory experiments and numerical modelling, albeit with a simpler bathymetric and coastal configuration. It is therefore recommended that field wake studies of submerged islands be measured via a combination of vessel-mounted and moored applications.

Examining the complex near wake velocity and turbulent structures is inherently difficult with single boat surveys. A dense grid of moored ADCPs would help capture the flow structures in this near wake region, however, the minimum spacing of 80 m between units is likely to prevent these flow structures from being captured.

For a tidal resource assessment it is advised that the survey methodology should, if feasible, use the same survey transects for both the flood and ebb tidal velocity data. The existence of Horse Rock prevented this survey design from being adopted since there was a risk of collision on the upstream transects. Similar survey constraints as those encountered for wake studies apply, i.e. transects within a circuit should be of sufficient length to allow the tidal resource of an area to be measured. Furthermore, the number of transects within a circuit should be limited in order to reduce the temporal resolution. If numerous transects were incorporated into a circuit, the time lag between the start and end of the circuit would be such that it would not represent a "snapshot" in time.

The question therefore is whether to employ moored or vessel-mounted ADCPs. The former offers high temporal resolution but comparatively limited spatial resolution; the latter offers the opposite. A comprehensive survey of the tidal velocity field in northern portion of Ramsey Sound would require a gridded array of approximately 200 (eighteen in the lateral, *v*, direction and twelve in the longitudinal, *u*, direction) moored ADCPs since each ADCP would have to be deployed with a minimum spacing of 80 m. Hypothetically, the survey would run continuously for a complete lunar cycle at the shortest, but ideally for multiple cycles (and perhaps over multiple years). Although this relatively dense grid would capture the variability of the measured data, data gaps would still exist.

Limitations to both survey techniques therefore exist: boat surveys offer high spatial resolution (particularly in the lateral direction) at the cost of the temporal resolution, while moored surveys provide a high temporal resolution but lack the spatial resolution even with a gridded array. Perhaps a compromise would be the deployment of two or more survey vessels to measure the tidal flow over a circuit simultaneously in order to increase the temporal resolution while still maintaining a high spatial resolution. This would more accurately capture the variability of the measured data, which is not possible from these data without smoothing. Furthermore, this would provide the most complete indication of spatial and temporal patterns in the flow field,

which depth-averaged numerical models cannot resolve and a single boat survey / moored ADCPs can only partially define.

The most favourable survey technique, however, is likely to be a combination of vessel-mounted and moored ADCP measurements conducted simultaneously in order to maximise both the temporal and spatial resolution of the current velocity measurements. The moored ADCP data should be gathered at a minimum period of a lunar month in order to derive accurate velocity profile data and instantaneous maximums. Vessel-mounted ADCP surveys should, at a minimum, be undertaken over a complete spring and neap tidal cycle (i.e. a continuous 13-hour circuit) in order capture both the flood and ebb flow conditions and thus identify any tidal asymmetries. Furthermore, collecting velocity measurements in the vicinity of the moored ADCPs (assuming no interference in the acoustic beams) allows validation of and therefore confidence in the measured velocities. In any case, the inherent nature of measured data means that data gaps will always exist, especially in areas subject to navigational constraints.

To overcome this, one option could be the development of a numerical model for a given site using site bathymetry and in situ flow measurements for calibration purposes. This calibrated modelling tool could subsequently be used to confidently predict the flow variability over fortnightly cycles. Although numerical modelling is a valuable supplement to survey data, given its broader coverage and greater spatial and temporal resolution, these models should never serve as a substitute to measured data, which provide real time tidal information at specific locations. The drawback of utilising hydrodynamic models for tidal resource characterisation is that their spatial

resolution is not usually high enough to capture the effects of small-scale features than an ADCP can detect, which are essential when assessing a tidal energy site. Combined, both methods are valuable as they allow for an estimation of the velocity and its spatial variability over daily, monthly and yearly timescales.

#### 5.2.4 Laboratory experiments

The laboratory experiments could be extended by examining the effects of a variety of submergence levels on the wake of a conical island, i.e. a deeply submerged condition. More realistic geometries and increased bed roughness could also be incorporated to investigate the influence these parameters have on both wake extent and structure. The data collected as part of this thesis could also be supplemented by PIV techniques as well as CFD modelling to capture the flow dynamics in the upper portion of the water column, which was not possible due to the instrumental constraints.

#### 5.2.5 TST suitability tool

The suitability tool has shown that attractive tidal energy sites are not always viable for TST deployment. When important parameters in addition to velocity magnitude are considered (bed slope, water depth), very few areas based on a 15 m diameter TST within this tidal strait exist. Given its flexibility, this tool could be used at any tidal energy site where data exists. It could also be extended such that it incorporates other parameters such as horizontal and vertical shear, misalignment angle, and vertical velocities, which are often overlooked but are critical in determining the structural loading on a device. Each device differs to some degree and will therefore have different threshold requirements. This tool can therefore be device-specific. For instance, a TST consisting of a single monopole (similar to the Marine Current Turbine's 'Seagen' device located in Strangford Lough) would not be as reliant on bed slope as a device comprising a wide base, such a TEL's 'DeltaStream' device. As technology advances, the threshold velocity for economic viability will inevitably reduce, increasing the number of suitable areas. However, until this time these relatively narrow macrotidal sites will continue to be attractive to tidal energy developers despite their hydrodynamic and bathymetric constraints.

The 2-D TELEMAC oceanographic model of Ramsey Sound is currently being converted into a 3-D layered model. Once calibrated with existing measured ADCP data, the suitability tool developed as part of this study could be expanded to incorporate this modelled data for the whole of the Sound and beyond in order to identify suitable TST locations at a greater geographical extent.

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## **APPENDIX A: MATLAB SCRIPTS**

Self-recording current meter averaging script

```
clear all
clc
a = xlsread('test_excel.xls');
b = a(:,1)
l = 1:length(b);
x = find(b>0)
b(any(isnan(b),2),:)=[];
```

```
y = interpl(x, b, l)
```

## Laboratory data filtering script

```
% Script to batch proccess Vectrino II data using Peter J. Rusello's
% 'standardVectrinoIIScreening.m' file.
% All rights reserved.; make sure the folder you are
% working in is on your Matlab path - use command
addpath('C: \....')
% Copyright (c) <2012>, <Paul Evans, Evansps3@cardiff.ac.uk>
% All rights reserved.
22
filenames=x110mm_sideways_RevB.txt; % Use the import data to import
the .txt file comprising the names of datasets and then change the
name of the filelist here.
for ii=1:length(filenames);
    f1=strcat([char(filenames(ii)) '.mat']);
    load(f1);
    [DataS, status] = standardVectrinoIIScreening(Data);
    DataS.Profiles VelX(~DataS.Profiles DataQualityAllBeams)=nan;
    DataS.Profiles VelY(~DataS.Profiles DataQualityAllBeams)=nan;
    DataS.Profiles VelZ1(~DataS.Profiles DataQualityAllBeams)=nan;
    DataS.Profiles_VelZ2(~DataS.Profiles_DataQualityAllBeams)=nan;
    f out name=strcat([char(filenames(ii)) ' Screened.mat']);
    save(f out name, 'DataS', 'Config', '-mat');
    clear f1 Data DataS Config
end
```

```
function [Data, status] = standardVectrinoIIScreening(Data,
snrThreshold, correlationThreshold, outlierThreshold)
if nargin == 1
   snrThreshold = 15
   correlationThreshold = 70
   outlierThreshold = 3.5
end
if ~isfield( Data, 'Profiles_DataQualityAllBeams' )
    % standard Vectrino II screening for XYZ velocities
   for beam = 1:4
        dqField = [ 'Profiles_DataQualityBeam' num2str( beam ) ];
        maskField = [ 'Profiles SNRBeam' num2str( beam ) ];
        Data.( dqField ) = Data.( dqField ) | Data.( maskField ) <</pre>
snrThreshold;
       maskField = [ 'Profiles CorBeam' num2str( beam ) ];
        Data.( dqField ) = Data.( dqField ) | Data.( maskField ) <</pre>
correlationThreshold;
   end
   Data.Profiles DataQualityAllBeams =
Data.Profiles DataQualityBeam1 | ...
Data.Profiles DataQualityBeam2 | ...
Data.Profiles DataQualityBeam3 | ...
Data.Profiles DataQualityBeam4;
   for rangeCell = 1:length( Data.Profiles Range )
        rangeCellDataX = ragf( Data.Profiles VelX( :, rangeCell ) );
        rangeCellDataY = ragf( Data.Profiles VelY( :, rangeCell ) );
        rangeCellDataZ1 = ragf( Data.Profiles VelZ1( :, rangeCell )
);
        rangeCellDataZ2 = ragf( Data.Profiles VelZ2( :, rangeCell )
);
        rangeCellNaNs = isnan( rangeCellDataX ) | ...
                        isnan( rangeCellDataY ) | ...
                        isnan( rangeCellDataZ1 ) | ...
                        isnan( rangeCellDataZ2 );
        Data.Profiles DataQualityAllBeams( :, rangeCell ) =
Data.Profiles DataQualityAllBeams( :, rangeCell ) | rangeCellNaNs;
   end
   Data.Profiles DataQualityAllBeams =
~Data.Profiles DataQualityAllBeams;
   for beam = 1:4
        Data.( [ 'Profiles DataQualityBeam' num2str( beam ) ] ) =
~Data.( [ 'Profiles DataQualityBeam' num2str( beam ) ] );
   end
   status = 1;
else
   disp( ['Data has already been screened.' ] )
   status = 0;
end
```

```
function [ Xg, nbadvecs ] = ragf(X, thresh, datalimits);
% load('X.mat')
% Robust adapative Gaussian filter
% Based on the spread of data instead of strict definitions of
variance
% If data is multiple columns, they are treated as dependent
variables and
% each will be filtered based on outlier removal in all variables
if nargin == 1
    thresh = 5;
end
[rows columns] = size(X);
if rows < columns % transpose so dependent variable goes down the
columns
    X = X';
    [rows columns] = size(X);
end
len = 1:rows;
for c = 1:columns
    Xworking = [X(:,c) len(:)];
    Xworking = sortrows (Xworking, 1);
00
     figure(1)
8
     [nOriginal, xOriginal] = hist(Xworking(:,1),1001);
8
     plot(xOriginal, nOriginal, 'k.-')
8
     grid on
    i=1;
    nbadvecs(1,:) = -32768;
    converge=-99;
    while converge~=1
        if i == 1
            midpointWorking = nanmedian(Xworking(:,1));
            if nargin == 3
              disp(['i = ' num2str(i)])
8
                lowerDataLimit = midpointWorking - datalimits(1);
                upperDataLimit = midpointWorking + datalimits(2);
                outerlimitsind = find(Xworking(:,1) <=</pre>
lowerDataLimit...
                     Xworking(:,1) >= upperDataLimit);
                Xworking(outerlimitsind,1) = NaN;
            end
        else
            midpointWorking = nanmean(Xworking(:,1));
        end
        % estimates of the standard deviation based on student's t
        % distribution
        N = sum(~isnan(Xworking(:,1)));
        Xworking = sortrows(Xworking,1);
        %max(Xworking)
        plo = tcdf(-1, N);
        phi = tcdf(1, N);
```

```
Nplo = floor(plo*N);
        Nphi = ceil(phi*N);
        if isnan( Nplo ) | isnan( Nphi )
            Xg = NaN * zeros(size(X));
            nbadvecs = NaN;
            return
        end
        loX = midpointWorking - Xworking( Nplo, 1 );
        hiX = Xworking( Nphi, 1 ) - midpointWorking;
        upperlimit = midpointWorking + thresh * abs(hiX);
        lowerlimit = midpointWorking - thresh * abs(loX);
        toolargevalues = find(Xworking(:,1) > upperlimit);
        toosmallvalues = find(Xworking(:,1) < lowerlimit);</pre>
        nans = find(isnan(Xworking(:,1))==1);
        badvector indices = union(toolargevalues,toosmallvalues);
        badvector indices = union (badvector indices, nans);
        Xworking(badvector indices,1) = NaN;
        Nnew = sum(~isnan(Xworking(:,1)));
        nbadvecs(i,:) = N-Nnew;
        if i > 1 & (nbadvecs(i,:) == 0)%(nbadvecs(i,:) ==
nbadvecs(i-1,:))
            converge = 1;
        end
        i=i+1;
00
          [nOutlayed, xOutlayed] = hist(Xworking(:,1),xOriginal);
8
          hold on
8
          nzInd = find(nOutlayed);
8
          s color = 'bgycm';
8
          plot(xOutlayed(nzInd), nOutlayed(nzInd),[s color(i) '.-'])
8
          hold off
    end
    Xtemp = sortrows(Xworking,2);
    Xg(:,c) = Xtemp(:,1);
end
8{
[Nq, bq] = hist(Xq(:, 1), 101);
[Nq2, bq2] = hist(Xq(:, 2), 101);
8}
nanInd = sum(isnan(Xq), 2);
badInd = find(nanInd);
for c = 1:size(Xg,2)
    Xg(badInd, c) = NaN;
end
8{
[Ngg, bg] = hist(Xg(:, 1), bg);
[Ngg2, bg2] = hist(Xg(:, 2), bg2);
figure
plot(bg,Ng,'k.-',bg,Ngg,'r.-')
figure
plot(bg2,Ng2,'k.-',bg2,Ngg2,'r.-')
8}
```

## Laboratory data re-structuring script

```
%% Get all file locations and file names in order to perform
averaging.
%OPEN FILES OF 110 FLOW DEPTH AND VERTICLE ADCP ORIENTATION
[filename110v, pathname110v, filterindex110v] = uigetfile('*.mat',
'Pick first data file to process for 110 flow depth, verticle
ADCP.');
cd (pathname110v);
%Access files of the
%form('flowdepth'mm x'inlet' y'sidewall' z'bottom'.???.??.Vectrino-
II.00000 Screened.mat)
S110v=what;
                            %'what' returns an array with the folder
directory and file names organised by file type.
Data110v = S110v.mat;% write .m file names to Data.N110v = size(Data110v , 1);% count the number of .m files
to process.
%OPEN FILES OF 142 FLOW DEPTH AND VERTICLE ADCP ORIENTATION
[filename142v, pathname142v, filterindex142v] = uigetfile('*.mat',
'Pick first data file to process for 142 flow depth, verticle
ADCP.');
cd (pathname142v);
%Access files of the
%form('flowdepth'mm x'inlet' y'sidewall' z'bottom'.???.??.Vectrino-
II.00000 Screened.mat)
                            %'what' returns an array with the folder
S142v=what;
directory and file names organised by file type.
Data142v = S142v.mat; % write .m file names to Data.
                                   % count the number of .m files
N142v = size(Data142v , 1);
to process.
%OPEN FILES OF 110 FLOW DEPTH AND SIDEWAYS ADCP ORIENTATION
[filename110s, pathname110s, filterindex110s] = uigetfile('*.mat',
'Pick first data file to process for 110 flow depth, sideways
ADCP.');
cd (pathname110s);
%Access files of the
%form('flowdepth'mm x'inlet' y'sidewall' z'bottom'.???.??.Vectrino-
II.00000 Screened.mat)
                           %'what' returns an array with the folder
S110s=what;
directory and file names organised by file type.
Data110s = S110s.mat; % write .m file names to Data.
                                   % count the number of .m files
N110s = size(Data110s , 1);
to process.
%OPEN FILES OF 142 FLOW DEPTH AND SIDEWAYS ADCP ORIENTATION
[filename142s, pathname142s, filterindex142s] = uigetfile('*.mat',
'Pick first data file to process for 142 flow depth, sideways
ADCP.');
cd (pathname142s);
%Access files of the
%form('flowdepth'mm x'inlet' y'sidewall' z'bottom'.???.??.Vectrino-
II.00000 Screened.mat)
```

```
%'what' returns an array with the folder
S142s=what;
directory and file names organised by file type.
Data142s = S142s.mat;
                                    % write .m file names to Data.
                                   % count the number of .m files
N142s = size(Data142s , 1);
to process.
%% PREALLOCATIONS!!!!!!
Avdat110v=zeros((N110v*35),13);
Avdat142v=zeros((N142v*35),13);
Avdat110s=zeros((N110s*35),13);
Avdat142s=zeros((N142s*35),13);
a=61;
FlowAveraged=struct;
%% Perform averaging for flow depth 110 and verticle ADV orientation
and build holding array avdat.
cd (pathname110v);
for dr = 1:1:N110v
                                                             %for
loop incrementing through the data array and opening each file in
the folder slected.
    fname=(Data110v{dr,1});
    Pos = sscanf(fname, '%dmm_x%d_y%d_z%d');
                                                        %for each
file read the position data hedl in the fole name and save in 'pos'
variable
    load(Data110v{dr,1}, 'DataS');
                                                             %Load
the DataS structural array.
    Vel X= getfield(DataS, 'Profiles VelX');
                                                          %Load
velocity arrays into variables
    Vel Y= getfield(DataS, 'Profiles VelY');
                                                         %Load
velocity arrays into variables
    Vel Z1= getfield(DataS, 'Profiles VelZ1');
                                                        %Load
velocity arrays into variables
    Vel Z2= getfield(DataS, 'Profiles VelZ2');
                                                        %Load
velocity arrays into variables
    Mean x=nanmean(Vel X);
                                                        %Calculate
time average velcities at each depth in the x
   Mean y=nanmean(Vel Y);
                                                        %Calculate
time average velcities at each depth in the y
    Mean z1=nanmean(Vel Z1);
                                                        %Calculate
time average velcities at each depth in the z1
    Mean z2=nanmean(Vel Z2);
                                                        %Calculate
time average velcities at each depth in the z
    SD x=nanstd(Vel X)';
    SD y=nanstd(Vel Y)';
    SD z1=nanstd(Vel Z1)';
    SD z2=nanstd(Vel Z2)';
    TKE=0.5*sqrt((SD x).^2+(SD y).^2+(SD z1).^2);
    TI=SD x./sqrt(Mean x'.^2);
Rstressy=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Y,Me
an y));
Rstressz=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Z1,M
ean z1));
    L=size(Mean x,2);
                                                        %Get the
number of differemt depth measurements
```

```
Pos=Pos';
                                                        %Transpose
the position array
        if dr==1
                                                             %for
the first file the indexes of the array range from 1 to 35.
           S=1;
                                                             %Create
indexes for storage array 'Avdat'
           F=L;
                                                            %Create
indexes for storage array 'Avdat'
        else
           S=(dr-1)*35+1;
                                                              %for
subsequent files the indexes of the data are given by the following
expression.
            F=S+L-1;
         end
    Z=linspace(Pos(4)-40,Pos(4)-39-L,L)';
                                                           %Icrement
depth measurement for 1 cm from vectrino head to required depth
(35mm)
   Avdat110v(S:F, 1) = Pos(1);
                                                           %input
flow depth position into avdat holdding array.
   Avdat110v(S:F, 2) = Pos(4);
                                                           %Input
ADV depth into array
   Avdat110v(S:F, 3) = Pos(2);
                                                           %input x
position into avdat holding array.
   Avdat110v(S:F, 4)=Pos(3);
   Avdat110v(S:F, 5) = Z;
                                                           %inpit z
postion into avdat holdinhg array.
   Avdat110v(S:F,6)=Mean x';
                                                            %Time
average velocity into holding array.
   Avdat110v(S:F,7)=Mean y';
                                                            %Time
average velocity into holding array.
   Avdat110v(S:F,8)=Mean z1';
                                                            %Time
average velocity into holding array.
   Avdat110v(S:F,9)=Mean z2';
                                                            %Time
average velocity into holding array.
   Avdat110v(S:F,10)=TKE;
   Avdat110v(S:F,11)=TI;
   Avdat110v(S:F,12)=Rstressy;
   Avdat110v(S:F,13)=Rstressz;
end
%% %% Perform averaging for flow depth 142 and verticle ADV
orientation and build holding array avdat.
cd (pathname142v);
for dr = 1:1:N142v
                                                            %for
loop incrementing through the data array and opening each file in
the folder slected.
    fname=(Data142v{dr,1});
    Pos = sscanf(fname, '%dmm x%d y%d z%d'); %for each
file read the position data hedl in the fole name and save in 'pos'
variable
    load(Data142v{dr,1}, 'DataS');
                                                            %Load
the DataS structural array.
    Vel_X= getfield(DataS, 'Profiles VelX');
                                                        %Load
velocity arrays into variables
    Vel Y= getfield(DataS, 'Profiles VelY');
                                                        %Load
velocity arrays into variables
    Vel Z1= getfield(DataS, 'Profiles VelZ1'); %Load
velocity arrays into variables
```

```
Vel Z2= getfield(DataS, 'Profiles VelZ2');
                                                         %Load
velocity arrays into variables
    Mean x=nanmean(Vel X);
                                                         %Calculate
time average velcities at each depth in the x
   Mean y=nanmean(Vel Y);
                                                         %Calculate
time average velcities at each depth in the y
   Mean z1=nanmean(Vel Z1);
                                                         %Calculate
time average velcities at each depth in the z1
   Mean z2=nanmean(Vel Z2);
                                                         %Calculate
time average velcities at each depth in the z
%Calculate time average velcities at each depth in the z
    SD x=nanstd(Vel_X)';
    SD y=nanstd(Vel Y)';
    SD_z1=nanstd(Vel_Z1)';
    SD_z2=nanstd(Vel_Z2)';
    TKE=0.5*sqrt((SD x).^2+(SD y).^2+(SD z1).^2);
    TI=SD x./sqrt(Mean x.^2');
Rstressy=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Y,Me
an y));
Rstressz=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Z1,M
ean z1));
    L=size(Mean x,2);
                                                          %Get the
number of differemt depth measurements
   Pos=Pos';
                                                          %Transpose
the position array
         if dr==1
                                                               %for
the first file the indexes of the array range from 1 to 35.
            S=1;
                                                               %Create
indexes for storage array 'Avdat'
           F=35;
                                                               %Create
indexes for storage array 'Avdat'
         else
            S=(dr-1)*35+1;
                                                                %for
subsequent files the indexes of the data are given by the following
expression.
            F=S+L-1;
         end
    Z=linspace(Pos(4)-40,Pos(4)-39-L,L)';
                                                             %Icrement
depth measurement for 1 cm from vectrino head to required depth
(35mm)
    Avdat142v(S:F, 1) = Pos(1);
                                                             %input
flow depth position into avdat holdding array.
    Avdat142v(S:F,2) = Pos(4);
    Avdat142v(S:F, 3) = Pos(2);
                                                             %input x
position into avdat holding array.
    Avdat142v(S:F,4)=Pos(3);
    Avdat142v(S:F, 5) = \mathbb{Z};
                                                             %inpit z
postion into avdat holdinhg array.
    Avdat142v(S:F,6)=Mean x';
                                                              %Time
average velocity into holding array.
    Avdat142v(S:F,7)=Mean y';
                                                              %Time
average velocity into holding array.
    Avdat142v(S:F,8)=Mean z1';
                                                              %Time
average velocity into holding array.
    Avdat142v(S:F,9)=Mean_z2';
                                                              %Time
average velocity into holding array.
    Avdat142v(S:F, 10) = TKE;
    Avdat142v(S:F,11)=TI;
```

```
Avdat142v(S:F,12)=Rstressy;
    Avdat142v(S:F,13)=Rstressz;
end
%% %% Perform averaging for flow depth 110 and sideways ADV
orientation and build holding array avdat.
cd (pathname110s);
for dr = 1:1:N110s
    fname=(Data110s{dr,1});
    A = length(fname);
    if A<=a
        Pos = sscanf(fname, '%dmm x%d y%d z%d');
                                                            %for
each file read the position data hedl in the fole name and save in
'pos' variable
       load(Data110s{dr,1}, 'DataS');
%Load the DataS structural array.
       Vel X= getfield(DataS, 'Profiles VelY');
                                                           %Load
velocity arrays into variables
       Vel Y= getfield(DataS, 'Profiles VelZ1');
                                                               %Load
velocity arrays into variables
       Vel Z1= getfield(DataS, 'Profiles VelX');
                                                             SLoad
velocity arrays into variables
        Vel Z2= getfield(DataS, 'Profiles VelZ2');
                                                             %Load
velocity arrays into variables Mean x=nanmean(Vel X)';
%Calculate time average velcities at each depth in the x
       Mean x=(-1) *nanmean(Vel X);
%Calculate time average velcities at each depth in the x
       Mean y=(-1) *nanmean(Vel Y);
%Calculate time average velcities at each depth in the y
       Mean z1=nanmean(Vel Z1);
%Calculate time average velcities at each depth in the z1
       Mean z2=nanmean(Vel Z2);
                                                          %Calculate
time average velcities at each depth in the z2
        SD x=nanstd(Vel X)';
        SD y=nanstd(Vel Y)';
        SD z1=nanstd(Vel Z1)';
        SD z2=nanstd(Vel Z2)';
        TKE=0.5*sqrt((SD x).^2+(SD y).^2+(SD z1).^2);
        TI=SD x./sqrt(Mean x'.^2);
Rstressy=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Y,Me
an y));
Rstressz=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Z1,M
ean z1));
        L=size(Mean x,2);
%Get the number of different depth measurements
       Pos=Pos';
%Transpose the position array
             if dr==1
%Create indexes for storage array 'Avdat'
               S=1;
%Create indexes for storage array 'Avdat'
               F=35;
%Create indexes for storage array 'Avdat'
             else
                S=(dr-1)*35+1;
                F=S+L-1;
```
```
end
        y=linspace(Pos(3)+41,Pos(3)+40+L,L)';
%Icrement depth measurement for 1 cm from vectrino head to required
depth (35mm)
       Avdat110s(S:F,1)=Pos(1);
%input flow depth position into avdat holdding array.
        Avdat110s(S:F,2)=Pos(4);
       Avdat110s(S:F, 3)=Pos(2);
%input x position into avdat holding array.
       Avdat110s (S:F, 4) =y;
                                                                8
Input y position
       Avdat110s(S:F, 5) = Pos(4);
%inpit z postion into avdat holdinhg
       Avdat110s(S:F,6)=Mean x';
%Time average velocity into holding array.
       Avdat110s(S:F,7)=Mean y';
%Time average velocity into holding array.
       Avdat110s(S:F,8)=Mean z1';
%Time average velocity into holding array.
       Avdat110s(S:F,9)=Mean z2';
%Time average velocity into holding array.
       Avdat110s(S:F,10)=TKE;
       Avdat110s(S:F,11)=TI;
       Avdat110s(S:F,12)=Rstressy;
       Avdat110s(S:F,13)=Rstressz;
   elseif A>=a
       Pos = sscanf(fname, '%dmm x%d y%d %ddeg z%d');
%for each file read the position data hedl in the fole name and save
in 'pos' variable
       load(Data110s{dr,1}, 'DataS');
%Load the DataS structural array.
       Vel X= getfield(DataS, 'Profiles VelY');
                                                           %Load
velocity arrays into variables
       Vel Y= getfield(DataS, 'Profiles VelZ1');
                                                               %Load
velocity arrays into variables
       Vel Z1= getfield(DataS, 'Profiles VelX');
                                                             %Load
velocity arrays into variables
       Vel Z2= getfield(DataS, 'Profiles VelZ2');
                                                             %Load
velocity arrays into variables Mean x=nanmean(Vel X)';
х
       Mean x=nanmean(Vel X);
%Calculate time average velcities at each depth in the x
       Mean y=nanmean(Vel Y);
%Calculate time average velcities at each depth in the y
       Mean z1=nanmean(Vel Z1);
%Calculate time average velcities at each depth in the z1
       Mean z2=nanmean(Vel Z2);
%Calculate time average velcities at each depth in the z2
        SD x=nanstd(Vel X)';
        SD y=nanstd(Vel Y)';
        SD z1=nanstd(Vel Z1)';
        SD_z2=nanstd(Vel_Z2)';
        TKE=0.5*sqrt((SD x).^2+(SD y).^2+(SD z1).^2);
        TI=SD x./sqrt(Mean x'.^2);
Rstressy=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Y,Me
```

```
an_y));
```

```
Rstressz=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Z1,M
ean z1));
       L=size(Mean x,2);
                                                             %Get the
number of differemt depth measurements
       Pos=Pos';
%Transpose the position array
            if dr==1
%Create indexes for storage array 'Avdat'
                S=1;
%Create indexes for storage array 'Avdat'
                F=35;
%Create indexes for storage array 'Avdat'
             else
                S=(dr-1)*35+1;
                F=S+L-1;
             end
        y=linspace(Pos(3)-41,Pos(3)-40-L,L)';
                                                           %Icrement
depth measurement for 1 cm from vectrino head to required depth
(35mm)
       Avdat110s(S:F, 1) = Pos(1);
%input flow depth position into avdat holdding array.
       Avdat110s(S:F,2)=Pos(5);
       Avdat110s(S:F, 3)=Pos(2);
%input x position into avdat holding array.
       Avdat110s(S:F, 4) = y;
                                                                2
Input y positions
       Avdat110s(S:F,5)=Pos(5);
%inpit z postion into avdat holdinhg array.
       Avdat110s(S:F,6)=Mean x';
%Time average velocity into holding array.
      Avdat110s(S:F,7)=Mean y';
%Time average velocity into holding array.
       Avdat110s(S:F,8)=Mean z1';
%Time average velocity into holding array.
       Avdat110s(S:F,9)=Mean z2';
%Time average velocity into holding array.
       Avdat110s(S:F,10) = TKE;
        Avdat110s(S:F,11)=TI;
        Avdat110s(S:F,12)=Rstressy;
        Avdat110s(S:F,13)=Rstressz;
   end
end
%% Perform averaging for flow depth 142 and sideways ADV orientation
and build holding array avdat.
cd (pathname142s);
for dr = 1:1:N142s
    fname=(Data142s{dr,1});
    A = length(fname);
    if A<=a
        Pos = sscanf(fname, '%dmm x%d y%d z%d');
                                                           %for
each file read the position data hedl in the fole name and save in
'pos' variable
        load(Data142s{dr,1}, 'DataS');
%Load the DataS structural array.
       Vel X= getfield(DataS, 'Profiles VelY');
                                                   %Load
velocity arrays into variables
        Vel_Y= getfield(DataS, 'Profiles VelZ1');
                                                               %Load
velocity arrays into variables
```

```
Vel Z1= getfield(DataS, 'Profiles VelX');
                                                             %Load
velocity arrays into variables
        Vel_Z2= getfield(DataS, 'Profiles VelZ2');
                                                             %Load
velocity arrays into variables Mean x=nanmean(Vel X)';
%Calculate time average velcities at each depth in the x
       Mean x=(-1) *nanmean(Vel X);
%Calculate time average velcities at each depth in the x
       Mean y=(-1) *nanmean(Vel Y);
%Calculate time average velcities at each depth in the y
       Mean z1=nanmean(Vel Z1);
%Calculate time average velcities at each depth in the z1
       Mean z2=nanmean(Vel Z2);
%Calculate time average velcities at each depth in the z2
        SD x=nanstd(Vel X)';
        SD y=nanstd(Vel Y)';
        SD z1=nanstd(Vel Z1)';
        SD z2=nanstd(Vel Z2)';
        TKE=0.5*sqrt((SD x).^2+(SD y).^2+(SD z1).^2);
        TI=SD x./sqrt(Mean x'.^2);
Rstressy=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Y,Me
an y));
Rstressz=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Z1,M
ean z1));
        L=size(Mean x,2);
                                                             %Get the
number of differemt depth measurements
       Pos=Pos';
%Transpose the position array
             if dr==1
%Create indexes for storage array 'Avdat'
               S=1;
%Create indexes for storage array 'Avdat'
               F=35;
%Create indexes for storage array 'Avdat'
             else
                S=(dr-1)*35+1;
                F=S+L-1;
             end
        y=linspace(Pos(3)+41,Pos(3)+40+L,L)';
%Icrement depth measurement for 1 cm from vectrino head to required
depth (35mm)
        Avdat142s(S:F, 1) = Pos(1);
%input flow depth position into avdat holdding array.
        Avdat142s(S:F,2) = Pos(4);
       Avdat142s(S:F, 3) = Pos(2);
%input x position into avdat holding array.
                                                                 8
       Avdat142s(S:F,4)=y;
Input y position
       Avdat142s(S:F, 5) = Pos(4);
%inpit z postion into avdat holdinhg array.
       Avdat142s(S:F,6)=Mean x';
%Time average velocity into holding array.
       Avdat142s(S:F,7)=Mean y';
%Time average velocity into holding array.
       Avdat142s(S:F,8)=Mean z1';
%Time average velocity into holding array.
       Avdat142s(S:F,9)=Mean z2';
%Time average velocity into holding array.
        Avdat142s(S:F,10)=TKE;
```

```
Avdat142s(S:F,11)=TI;
        Avdat142s(S:F,12)=Rstressy;
        Avdat142s(S:F,13)=Rstressz;
   elseif A>=a
        Pos = sscanf(fname, '%dmm x%d y%d %ddeg z%d');
%for each file read the position data hedl in the fole name and save
in 'pos' variable
       load(Data142s{dr,1}, 'DataS');
%Load the DataS structural array.
       Vel_X= getfield(DataS, 'Profiles_VelY');
                                                           %Load
velocity arrays into variables
       Vel Y= getfield(DataS, 'Profiles VelZ1');
                                                               %Load
velocity arrays into variables
       Vel Z1= getfield(DataS, 'Profiles VelX');
                                                             %Load
velocity arrays into variables
       Vel Z2= getfield(DataS, 'Profiles VelZ2');
                                                             %Load
velocity arrays into variables Mean x=nanmean(Vel X)';
       Mean x=nanmean(Vel X);
%Calculate time average velcities at each depth in the x
       Mean y=nanmean(Vel Y);
%Calculate time average velcities at each depth in the y
       Mean z1=nanmean(Vel Z1);
%Calculate time average velcities at each depth in the z1
       Mean z2=nanmean(Vel Z2);
%Calculate time average velcities at each depth in the z2
       SD x=nanstd(Vel X)';
        SD y=nanstd(Vel Y)';
        SD z1=nanstd(Vel Z1)';
        SD z2=nanstd(Vel_Z2)';
        TKE=0.5*sqrt((SD x).^2+(SD y).^2+(SD z1).^2);
        TI=SD x./sqrt(Mean x'.^2);
Rstressy=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Y,Me
an y));
Rstressz=nanmean(bsxfun(@minus,Vel X,Mean x).*bsxfun(@minus,Vel Z1,M
ean z1));
       L=size(Mean x,2);
                                                             %Get the
number of differemt depth measurements
       Pos=Pos';
%Transpose the position array
             if dr==1
%Create indexes for storage array 'Avdat'
               S=1:
%Create indexes for storage array 'Avdat'
               F=35;
%Create indexes for storage array 'Avdat'
             else
                S=(dr-1)*35+1;
                F=S+L-1;
             end
        y=linspace(Pos(3)-41,Pos(3)-40-L,L)';
                                                           %Icrement
depth measurement for 1 cm from vectrino head to required depth
(35mm)
        Avdat142s(S:F, 1) = Pos(1);
%input flow depth position into avdat holdding array.
        Avdat142s(S:F,2)=Pos(5);
       Avdat142s(S:F, 3) = Pos(2);
%input x position into avdat holding array.
```

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```
Avdat142s (S:F, 4) = y;
Input y positions
        Avdat142s(S:F, 5)=Pos(5);
%inpit z postion into avdat holdinhg array.
        Avdat142s(S:F,6)=Mean x';
%Time average velocity into holding array.
        Avdat142s(S:F,7)=Mean y';
%Time average velocity into holding array.
        Avdat142s(S:F,8)=Mean z1';
%Time average velocity into holding array.
        Avdat142s(S:F,9)=Mean z2';
%Time average velocity into holding array.
        Avdat142s(S:F,10)=TKE;
        Avdat142s(S:F,11)=TI;
        Avdat142s(S:F,12)=Rstressy;
        Avdat142s(S:F,13)=Rstressz;
   end
end
for I = 1:1:size(Avdat110s,1)
    if mod(Avdat110s(I,4),25)~=0
       Avdat110s(I,:)=0;
    end
    if Avdat110s(I,3)<=3450 || Avdat110s(I,3)>=3950
        if mod(Avdat110s(I,4),50)~=0
           Avdat110s(I,:)=0;
        end
    end
    if Avdat110s(I,4) <= 300
       if mod(Avdat110s(I,4),100)~=0
           Avdat110s(I,:)=0;
       end
    end
    if Avdat110s(I,4) == 350
        Avdat110s(I,:)=0;
    end
    if Avdat110s(I, 4) == 375
        Avdat110s (I, 4) = 0;
    end
end
Avdat110s(Avdat110s(:,1)==0,:)=[];
for I = 1:1:size(Avdat142s,1)
    if mod(Avdat142s(I,4),25)~=0
       Avdat142s(I,:)=0;
    end
    if Avdat142s(I,3) <= 3450 || Avdat142s(I,3) >= 3950
        if mod(Avdat142s(I,4),50)~=0
           Avdat142s(I,:)=0;
        end
    end
    if Avdat142s(I,4) <= 300
       if mod(Avdat142s(I,4),100)~=0
           Avdat142s(I,:)=0;
       end
    end
    if Avdat142s(I,4) == 350
        Avdat142s(I,:)=0;
    end
```

```
if Avdat142s(I, 4) == 375
        Avdat142s(I, 4) = 0;
    end
end
Avdat142s(Avdat142s(:,1)==0,:)=[];
%Mirror flume about y axis...
Avdat110vy=Avdat110v;
                                              %Repeat the
measurements in new array appended with y to signify flipped over
central y position
Avdat110vy(:, 4) = (1200) - Avdat110v(:, 4);
                                              %Flip y positions
Avdat110vy(:,7) = (-1.*Avdat110v(:,7));
                                              %change y velocity
orientation.
Avdat110vy(Avdat110vy(:,4)==600 ,:)=[];
                                             %delete the 600 or
central y position in the new array so as not to repeat the
measurement.
Avdat110s(Avdat110s(:,4)>600 ,:)=[];
                                             %Remove ADV
measurements passed the centre point of the flume, SIDEWAYS ONLY.
Avdat110sy=Avdat110s;
                                             %Repeat the
measurements in new array appended with y to signify flipped over
central y position and s to signify sideways adv orientation
Avdat110sy(:,4)=(1200)-Avdat110s(:,4);
                                             %Flip y positions
Avdat110sy(:,7)=(-1.*Avdat110s(:,7));
                                             %change y velocity
orientation. (REPEATED BELOW FOR 142 FLOW DEPTH.
Avdat110sy(Avdat110sy(:,4)==600 ,:)=[]; %delete the 600 or
central y position in the new array so as not to repeat the
measurement.
Avdat142vy=Avdat142v;
Avdat142vy(:,4) = (1200) - Avdat142v(:,4);
Avdat142vy(:,7) = (-1.*Avdat142v(:,7));
Avdat142vy(Avdat142vy(:,4)==600 ,:)=[];
Avdat142s(Avdat142s(:,4)>600 ,:)=[];
Avdat142sy=Avdat142s;
Avdat142sy(:,4) = (1200) - Avdat142s(:,4);
Avdat142sy(:,7) = (-1.*Avdat142s(:,7));
Avdat142sy(Avdat142sy(:,4) == 600 ,:) = [];
Avdat=vertcat(Avdat110v,Avdat110vy,Avdat110s,Avdat110sy,Avdat142v,Av
dat142vy,Avdat142s,Avdat142sy); %Put all data into holding
array, this can be accessed as required to build appropriate arrays
for I = 1:1:size(Avdat,1)
    %BUILD PLAN DATA
    if Avdat(I,1)>0 && Avdat(I,2)>0 && Avdat(I,5)>0
% Y position is less than/equal to 300 therefor take Y points 100mm
apart.
               if
isfield(FlowAveraged,(sprintf('Plan FD%d D %dZ %d',Avdat(I,1),Avdat(
I,2),Avdat(I,5))))==1
row=1+size(FlowAveraged.(sprintf('Plan FD%d D %dZ %d',Avdat(I,1),Avd
at(I,2),Avdat(I,5))),1);
FlowAveraged.(sprintf('Plan FD%d D %dZ %d',Avdat(I,1),Avdat(I,2),Avd
at(I,5)))(row,:)=Avdat(I,:);
               else
FlowAveraged.(sprintf('Plan FD%d D %dZ %d',Avdat(I,1),Avdat(I,2),Avd
at(I,5)))=Avdat(I,:);
               end
    end
```

```
%BUILD XELEVATION
    if Avdat(I,1)>0 && Avdat(I,2)>0 && Avdat(I,3)>0 && Avdat(I,5)>0
% Y position is less than/equal to 300 therefor take Y points 100mm
apart
                         i f
isfield(FlowAveraged, (sprintf('XElevation FD%d X %d',Avdat(I,1),Avda
t(I,3))) ==1
row=1+size(FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),A
vdat(I,3))),1);
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(row,:)=Avdat(I,:);
                         else
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
=Avdat(I,:);
                         end
    end
    %BUILD YELEVATION
    if Avdat(I,1)>0 && Avdat(I,2)>0 && Avdat(I,4)>0 && Avdat(I,5)>0
                    if
isfield(FlowAveraged,(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avda
t(I, 4))) ==1
row=1+size(FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),A
vdat(I,4))),1);
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(row,:) = Avdat(I,:);
                    else
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
=Avdat(I,:);
                    end
    end
end
% Remove cross over values for X elevation
for I = 1:1:size(Avdat,1)
    if
isfield(FlowAveraged,(sprintf('XElevation FD%d X %d',Avdat(I,1),Avda
t(I,3))) ==1
       if Avdat(I,1) == 110
        for Z = 12:1:22
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(:, 2) == 62 \&
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(:, 5) == Z, :) = [];
        end
       end
       if Avdat(I,1) == 142
```

```
for Z = 15:1:20
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(:, 2) == 90 \&
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(:, 5) == Z, :) = [];
        end
        for Z = 45:1:50
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(:, 2) == 120 \&
FlowAveraged.(sprintf('XElevation FD%d X %d',Avdat(I,1),Avdat(I,3)))
(:, 5) == Z, :) = [];
        end
       end
    end
end
% Remove cross over values for Y elevation
for I = 1:1:size(Avdat, 1)
    if
isfield(FlowAveraged, (sprintf('YElevation FD%d Y %d',Avdat(I,1),Avda
t(I,4))) ==1
       if Avdat(I,1) == 110
        for Z = 12:1:22
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(:,2) == 62 \&
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(:, 5) == Z, :) = [];
        end
       end
       if Avdat(I, 1) == 142
        for Z = 15:1:20
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(:,2)==90 &
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(:, 5) == Z, :) = [];
        end
        for Z = 45:1:50
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(:,2) == 120 \&
FlowAveraged.(sprintf('YElevation FD%d Y %d',Avdat(I,1),Avdat(I,4)))
(:, 5) == Z, :) = [];
        end
       end
    end
end
```

```
FlowAveraged=orderfields(FlowAveraged);
% DEPTH AVERAGE and full flume
FlowAveraged.Plan FD110 D 87Z 13=[]; % Remove because all NAN
FlowAveraged.Plan FD110 D 87Z 14=[]; % Remove because all NAN
i=1;
j=1;
for Z=1:1:72
   if Z==1
FlowAveraged.Flume FD110=FlowAveraged.(sprintf('Plan FD%d D %dZ %d',
110,62,Z));
    elseif
isfield(FlowAveraged,(sprintf('Plan FD%d D %dZ %d',110,87,Z)))==1
FlowAveraged.Flume FD110=vertcat(FlowAveraged.Flume FD110,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',110,87,Z)));
   elseif
isfield(FlowAveraged,(sprintf('Plan FD%d D %dZ %d',110,62,Z)))==1
FlowAveraged.Flume FD110=vertcat(FlowAveraged.Flume FD110,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',110,62,Z)));
   elseif
isfield(FlowAveraged, (sprintf('Plan FD%d D %dZ %d',110,72,Z)))==1
FlowAveraged.Flume FD110=vertcat(FlowAveraged.Flume FD110,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',110,72,Z)));
   elseif
isfield(FlowAveraged, (sprintf('Plan FD%d D %dZ %d',110,52,Z)))==1
FlowAveraged.Flume FD110=vertcat(FlowAveraged.Flume FD110,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',110,52,Z)));
   end
end
for Z=1:1:110
   if Z==1
FlowAveraged.Flume FD142=FlowAveraged.(sprintf('Plan FD%d D %dZ %d',
142,60,Z));
   elseif
isfield(FlowAveraged,(sprintf('Plan FD%d D %dZ %d',142,60,Z)))==1
FlowAveraged.Flume FD142=vertcat(FlowAveraged.Flume FD142,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',142,60,Z)));
   elseif
isfield(FlowAveraged,(sprintf('Plan FD%d D %dZ %d',142,90,Z)))==1
FlowAveraged.Flume FD142=vertcat(FlowAveraged.Flume FD142,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',142,90,Z)));
   elseif
isfield(FlowAveraged,(sprintf('Plan FD%d D %dZ %d',142,120,Z)))==1
FlowAveraged.Flume FD142=vertcat(FlowAveraged.Flume FD142,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',142,120,Z)));
```

```
elseif
isfield(FlowAveraged, (sprintf('Plan FD%d D %dZ %d',142,110,Z)))==1
FlowAveraged.Flume FD142=vertcat(FlowAveraged.Flume FD142,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',142,110,Z)));
    elseif
isfield(FlowAveraged, (sprintf('Plan FD%d D %dZ %d',142,100,Z)))==1
FlowAveraged.Flume FD142=vertcat(FlowAveraged.Flume FD142,FlowAverag
ed.(sprintf('Plan FD%d D %dZ %d',142,100,Z)));
    end
end
    for x=3350:25:8000
        for y=100:25:1100
Depthaveraged110=FlowAveraged.Flume FD110(FlowAveraged.Flume FD110(:
,3)==x & FlowAveraged.Flume FD110(:,4)==y ,:);
Depthaveraged142=FlowAveraged.Flume FD142(FlowAveraged.Flume FD142(:
,3)==x & FlowAveraged.Flume FD142(:,4)==y ,:);
             if isempty(Depthaveraged110) == 0
FlowAveraged.Depthaveraged FD110(i,:)=[Depthaveraged110(1,3)
Depthaveraged110(1,4) nanmean(Depthaveraged110(:,6))
nanmean(Depthaveraged110(:,7)) nanmean(Depthaveraged110(:,8))
nanmean(Depthaveraged110(:,9)) nanmean(Depthaveraged110(:,10))
nanmean(Depthaveraged110(:,11)) nanmean(Depthaveraged110(:,12))
nanmean(Depthaveraged110(:,13))];
             i=i+1;
             end
             if isempty(Depthaveraged142)==0
FlowAveraged.Depthaveraged FD142(j,:)=[Depthaveraged142(1,3)
Depthaveraged142(1,4) nanmean(Depthaveraged142(:,6))
nanmean (Depthaveraged142(:,7)) nanmean (Depthaveraged142(:,8))
nanmean(Depthaveraged142(:,9)) nanmean(Depthaveraged110(:,10))
nanmean(Depthaveraged110(:,11)) nanmean(Depthaveraged110(:,12))
nanmean(Depthaveraged110(:,13))];
             j=j+1;
             end
        end
    end
%% FILE I/O
%OPEN FILES OF 142 FLOW DEPTH AND SIDEWAYS ADCP ORIENTATION
SaveDirectory = uigetdir('C:\', 'Pick where to save averaged
data:');
Folders = char('Plans', 'XElevations', 'YElevations', 'FlumeWide',
'DepthAveraged');
%Create Folders:
mkdir(SaveDirectory,Folders(1,:));
mkdir(SaveDirectory,Folders(2,:));
mkdir(SaveDirectory,Folders(3,:));
mkdir(SaveDirectory,Folders(4,:));
mkdir(SaveDirectory,Folders(5,:));
cd (SaveDirectory);
```

```
fields=fieldnames(FlowAveraged);
for i = 1:numel(fields)
      switch (fields{i}(1))
         case 'P'
           SD =sprintf('%s\\%s',SaveDirectory,Folders(1,:));
           cd (SD)
           fileid=fopen(sprintf('%s.dat',fields{i}),'w');
           fprintf(fileid,'FlowDepth, ADVDepth, XPos, YPos,
ZPos, XVel,
           YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
r^n);
           %f,
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
           fileid=fopen(sprintf('%s.csv',fields{i}),'w');
           fprintf(fileid,'FlowDepth, ADVDepth, XPos, YPos,
ZPos, XVel,
           YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
r^n);
           fprintf(fileid,'%f, %f, %f, %f, %f, %f, %f,
                                                        %f,
   %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
%f,
           fileid = fclose('all');
          case 'X'
           SD =sprintf('%s\\%s',SaveDirectory,Folders(2,:));
           cd (SD)
           fileid=fopen(sprintf('%s.dat',fields{i}),'w');
           fprintf(fileid, 'FlowDepth, ADVDepth, XPos, YPos,
           YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
ZPos, XVel,
r^n);
           %f,
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
           fileid=fopen(sprintf('%s.csv',fields{i}),'w');
           fprintf(fileid, 'FlowDepth, ADVDepth, XPos, YPos,
ZPos, XVel, YVel, Z1Vel, TKE, TI, Rstressy, RstressZ \r\n');
           fprintf(fileid,'%f,
                              %f, %f, %f, %f, %f,
                                                       %f.
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
          case 'Y'
           SD =sprintf('%s\\%s',SaveDirectory,Folders(3,:));
           cd (SD)
           fileid=fopen(sprintf('%s.dat',fields{i}),'w');
           fprintf(fileid,'FlowDepth, ADVDepth, XPos, YPos,
           YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
ZPos, XVel,
r^n);
           %f,
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
           fileid=fopen(sprintf('%s.csv',fields{i}),'w');
           fprintf(fileid,'FlowDepth, ADVDepth, XPos, YPos,
ZPos, XVel, YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
r^n';
           fprintf(fileid,'%f, %f, %f, %f, %f, %f, %f,
                                                       %f,
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
          case 'F'
           SD =sprintf('%s\\%s',SaveDirectory,Folders(4,:));
           cd (SD)
           fileid=fopen(sprintf('%s.dat',fields{i}),'w');
```

```
fprintf(fileid,'FlowDepth, ADVDepth, XPos, YPos,
           YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
ZPos, XVel,
r^n);
           %f,
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
           fileid=fopen(sprintf('%s.csv',fields{i}),'w');
           fprintf(fileid,'FlowDepth, ADVDepth, XPos, YPos,
ZPos, XVel,
           YVel, Z1Vel, Z2Vel, TKE, TI, Rstressy, RstressZ
r^n);
           fprintf(fileid,'%f, %f, %f,
                                         %f, %f, %f, %f,
%f, %f, %f, %f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
          case 'D'
           SD =sprintf('%s\\%s',SaveDirectory,Folders(5,:));
           cd (SD)
           fileid=fopen(sprintf('%s.dat',fields{i}),'w');
           fprintf(fileid,'XPos, YPos, XVel, YVel, Z1Vel,
      TKE,
Z2Vel,
           TI, Rstressy, RstressZ \r\n');
           fprintf(fileid,'%f, %f, %f, %f, %f, %f, %f, %f,
      \r\n',FlowAveraged.(fields{i})');
%f, %f
           fileid = fclose('all');
           fileid=fopen(sprintf('%s.csv',fields{i}),'w');
           fprintf(fileid,'XPos, YPos, XVel, YVel, Z1Vel,
      TKE,
           TI, Rstressy, RstressZ \r\n');
Z2Vel,
           fprintf(fileid,'%f, %f, %f, %f, %f, %f, %f, %f, %f,
%f, %f \r\n',FlowAveraged.(fields{i})');
           fileid = fclose('all');
      end
end
%Clear all
```

% WRITE TO FILES AND CREATE FOLDERS.

## **APPENDIX B: LABORATORY MEASUREMENT GRIDS**



**APPENDIX C: LONGITUDINAL WAKE VELOCITIES** 

Time- and depth-averaged longitudinal wake velocities  $(\overline{U})$  in the longitudinal (x) direction along flume centreline downstream of the conical island for the surfacepiercing (H/h = 0.96) and submerged (H/h = 1.24) conditions. The error bars show the standard deviation of the depth-averaged velocity data through the water column.

## **APPENDIX D: LIST OF PUBLICATIONS**

## **Conference Papers**

**Evans, P**., Allmark, M. and O'Doherty, T. 2014. Are Energetic Tidal Straits Suitable for Power Generation? In: *Proceedings of the 13<sup>th</sup> World Renewable Energy Congress (WREC)*. 4 – 8<sup>th</sup> August, London 2014, UK.

**Evans, P.**, Armstrong, S., Wilson, C., Fairley, I., Wooldridge, C. F. and Masters, I. 2013. Characterisation of a highly energetic tidal energy site with specific reference to hydrodynamics and bathymetry. In: *Proceedings of the 10th European Wave and Tidal Energy Conference (EWTEC)*. 2 - 5<sup>th</sup> September 2013, Aalborg, Denmark.

**Evans, P**., Mason-Jones, A., Neill. S., Malki, R., Zangiabadi, E. and Wooldridge, C. F. 2012. Monitoring of hydrodynamics for mapping and modelling. In: *Proceedings* of the 4th International Conference on Ocean Energy (ICOE). 17 – 19<sup>th</sup> October, Dublin, Ireland.

**Evans, P.**, Wooldridge, C. F., Mason-Jones, A., Neill, S., Malki, R. and Zangiabadi, E. 2012. From vessel to model: bridging the gap between real and modelled flow data. In: *Proceedings of the 1<sup>st</sup> Oxford Tidal Energy Workshop*. 29 – 30<sup>th</sup> March, Oxford, UK.

**Evans, P.**, Fairley, I., Wooldridge, C. F. and Willis, M. 2011. ADCP Surveys under environmentally challenging conditions. In: *Proceedings of the Nortek Offshore Renewables Symposium*. 26 – 27<sup>th</sup> October, London, UK.

Mason-Jones, A., **Evans, P.**, Wooldridge, C. F., O'Doherty, D. M., O'Doherty, T. and Fryett, I. 2008. The use of ADCP data from the Inner Bristol Channel, UK and CFD to study power attenuation effects on HATT performance. In: *Proceedings of Hydro8*.  $4 - 6^{\text{th}}$  November, Liverpool, UK.

**Evans, P.**, Mason-Jones, A., O'Doherty, T., O'Doherty, D. M. and Wooldridge, C. F. 2008. The utilisation of ADCP and CFD to investigate the feasibility of siting a tidal stream turbine in the inner Bristol Channel, *UK*. In: *Proceedings of the ECSA Symposium*.  $7 - 9^{\text{th}}$  April.

Mason-Jones, A., **Evans, P**., O'Doherty T. and O'Doherty, D. M. 2008. Characterisation of a Tidal Stream Turbine Design using CFD and ADCP. In: *Proceedings of the World Renewable Energy Congress (WREC)*. 19 – 25<sup>th</sup> July, Glasgow, Scotland, UK.

## **Journal Papers**

**Evans, P**., Mason-Jones, A., Wilson, C. W., Wooldridge, C. F., O'Doherty, T. and O'Doherty, D. M. Constraints on extractable power from energetic tidal straits. Manuscript submitted to Renewable Energy journal.

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

O'Doherty, T., Mason-Jones, A., O'Doherty, D. M., **Evans, P**., Wooldridge, C. F. and Fryett, I. 2010. Considerations of a horizontal axis tidal turbine. *Proceedings of the Institute of Civil Engineers, Energy* 163(3), pp. 119-130.

Willis, M. R., Masters, I., Falconer, R., Cross, M., Horsfall, I., Wooldridge, C. F.,
Syred, N., Fryett, I., Williams, A., Croft, N., O'Doherty, T., O'Doherty, D. M., Lin,
B., Bockelmann-Evans, B., Cross, N., Evans, P., Gallie, R., Fidler, R., Thomas, S.
and Mason Jones, A. 2010. Tidal turbine deployment in the Bristol Channel: a case
study. In: *Proceedings of the Institute of Civil Engineers, Energy* 163(3), pp. 93-105.