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TRADITIONAL TURBULENCE METHODS AND NOVEL VISUALISATION TECHNIQUES FOR COASTAL FLOW MODEL IN ORDER TO DEPLOY TIDAL STREAM TURBINES

I. MASTERS*, E. ZANGIABADI†, M. EDMUNDS†, I.A. FAIRLEY†, M. TOGNERI†, A. J. WILLIAMS† AND T. N. CROFT

*†Marine Energy Research Group
Swansea University
Singleton Park, Swansea, UK
E-mail: I.Masters@swansea.ac.uk,
Web page: http://www.swansea.ac.uk/engineering/marine-energy/

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Abstract. Characteristics of flow in the coastal regions are strongly influenced by the topography of the seabed and understanding of these features is necessary before installation of tidal stream turbines (TST). In this paper, the bathymetry of a potential TST deployment site is surveyed using an echosounder and the resulting data is used in the development of the geometric model. The steady state k-ε and transient Large Eddy Simulation (*LES*) turbulence methods are employed.

The stream surface visualisation method employed has important inherent characteristics that can enhance the visual perception of complex flow structures [1]. In this method lighting and shading reinforce the perception of shape and depth, images or textures can be mapped to the surface primitives providing additional visual information, colour and transparency can be used to convey additional data attributes.

The results of all cases are compared with the flow data transect gathered by Acoustic Doppler Current Profiler (ADCP). It has been understood that the k-ε method can predict the flow pattern with relatively good accuracy near the main features of the domain and the *LES* model has the ability to simulate some important flow patterns because of the bathymetry.

1 INTRODUCTION

Modelling of the flow in an estuary or a channel depends on several parameters such as the bed friction factor and topography of the seabed. Other features like boulders and pinnacles can also affect the shape of the velocity profile and therefore affect the overall performance of a TST [2]. Any model which is used to characterise the flow in a proposed TST deployment site has to have the ability to capture the small scale turbulences. Turbulence effects on the structure of the turbine blades have been of interest for both wind and tidal energy [3, 4, 5]. In order to overcome this problem, ADCPs have been used to provide a better understanding of the flow properties [6, 7, 8, 9]. Research has been also done to use the ADCP data to generate the turbulence synthetically to be used as an input to a Blade Element Momentum Theory to assess the TST performance in a very turbulent condition [10].

The decision to choose an appropriate modelling technique is dependent on the requirements of the problem. Since the generation of eddies due to the seabed geometry is the area of interest for this research, turbulence has to be modelled. To model the small scale turbulence, oceanographic models are not suitable as they only model the general patterns of the flow and small scale turbulence (with a scale smaller than the grid cells) was neglected. It is necessary to employ the turbulence models that can quantify the flow fluctuation in all directions as well as the important parameters which define the turbulence (Turbulence Kinetic Energy, Turbulence Dissipation Rate, Turbulence length scale, etc.).

In general, it is possible to categorise the turbulence models as steady state or transient. Among the steady state frameworks, the two-equation turbulence methods (k-ε and k-ω) are the most commonly used ones [11] and for the transient simulation *LES* methods provides good results along with a lower computational cost in comparison to the direct numerical simulation (DNS). Over the years a large amount of research has been done to model small scale sub-grid turbulence [12, 13, 14, 15]. Since resolving of turbulence is computationally costly the majority of turbulence models, particularly the transient ones, have been applied to small scale channel test cases and their results have been validated against the laboratory tests or benchmarked models. Almost all of them did not consider the effect of real bathymetry in their efforts for small scale turbulence modelling.

This research will concentrate on modelling flow over a rigid surface with consideration of the seabed geometry and without considering any vegetation and sediment transport.

In addition to the novel flow analysis, this paper describes a novel visualisation system. Stream surfaces [1, 16] have important inherent characteristics that can enhance the visual perception of complex flow structures. Lighting and shading reinforce the perception of shape and depth, images or textures can be mapped to the surface primitives providing additional visual information, colour and transparency can be used to convey additional data attributes. Stream surfaces are able to not only capture the features within the flow, but also have the inherent ability to convey further information about the local attributes of the flow. This combined with the reduction in visual clutter when compared to using glyphs or streamlines, significantly enhances their utility for practitioners.

2 THEORY AND METHOD

In this research the turbulence in the flow is modelled using the k-ε method for steady state problems and the LES method for transient problems. The reason for choosing the k-ε method is that it is proven to provide accurate results in most cases and this makes it by far the most popular two-equation turbulence model [11]. Large Eddy Simulation is used as it can model the instantaneous turbulence properties of the flow with good approximation without having the extensive computational costs of Direst Numerical Simulations (DNS) and the near solid boundary simplifications of Detached Eddy Simulation (DES) [11]. These methods will be discussed in detail in the following sections.

2.1 Standard *k-ε* turbulence model

One of the most commonly used RANS turbulence models is the standard k-ε turbulence model. The time averaged form of Navier-Stokes Equations can be written as:

$$\nabla \cdot (\rho \vec{u}) = 0 \tag{1}$$

$$\nabla.(\rho \vec{u} u_i) = -\frac{\partial P}{\partial x_i} + \nabla \cdot (\mu_{lam} + \mu_{turb}) \nabla u_i + S_i \tag{2}$$

where ρ is density , P is the pressure, u_i is the i'th component of the velocity vector, μ_{lam} and μ_{turb} are the dynamic laminar and turbulent viscosities respectively and S_i is any additional sources[17].

The main focus of the *k-ε* model is on the mechanism of turbulent kinetic energy and can be expressed by two transport equations. The main parameters are *k* which is the turbulence kinetic energy and *ε* which is the turbulent dissipation rate:

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho \vec{u} k) = \nabla \cdot \left[\left(\mu_{lam} + \frac{\mu_t}{\sigma_k} \right) \nabla(k) \right] + G\mu_{turb} - \rho\varepsilon \tag{3}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \vec{u} \varepsilon) = \nabla \cdot \left[\left(\mu_{lam} + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla(\varepsilon) \right] + C_{1\varepsilon}\mu_{turb} G \frac{\varepsilon}{k} - C_{2\varepsilon}\rho \frac{\varepsilon^2}{k} \tag{4}$$

The values $C_{1\varepsilon}$, $C_{2\varepsilon}$, σ_k and σ_ε are the closure constants, which are found empirically and are 1.44, 1.92, 1.0 and 1.3 respectively[18] [19]. The turbulent generation rate G is defined by:

$$G = 2\left(\left[\frac{\partial u}{\partial x}\right]^2 + \left[\frac{\partial v}{\partial y}\right]^2 + \left[\frac{\partial w}{\partial z}\right]^2 \right) + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right)^2 \tag{5}$$

The dynamic turbulent viscosity μ_{turb} is calculated using [20]:

$$\mu_{turb} = \rho\, C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

The parameter C_μ is a constant with the value of 0.09. The coupling between turbulence and momentum equations is achieved through the dynamic viscosity which is a sum of the laminar and turbulent values. In all of the equations, since the flow is incompressible, the derivative of density over time is zero [2].

The turbulence length scale gives a better understanding of turbulent flow. This is representative of the large scale turbulence and is defined as "physical quantity describing the size of the large energy-containing eddies in a turbulent flow" [21]. The following equation is used to calculate this parameter which is used in this work to obtain the inlet boundary conditions for a CFD simulation:

$$l = C_\mu^{3/4} \frac{k^{3/2}}{\varepsilon} \tag{7}$$

2.2 Large Eddy Simulation (*LES*)

To solve the large eddies explicitly a filtered approach to the Navier-Stokes equation is used in which the filter is defined by the grid size. The small eddies are modeled implicitly by using a subgrid-scale model (SGS model) [22].

The filtered continuity and momentum equations use filtered variables

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho \tilde{u}_j}{\partial x_j}=0 \tag{8}$$

and

$$\frac{\partial \rho \tilde{u}_i}{\partial t}+\frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j}=-\frac{\partial \tilde{p}}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\frac{\partial \sigma_{ij}}{\partial x_j} \tag{9}$$

in which

τ_{ij} is the filtered stress tensor.

σ_{ij} is the subgrid-scale Reynolds stresses.

Physically, the dynamic coupling between large and small scales in turbulence is described by the SGS stress. Dimensionally, it scales quadratically with turbulent velocity differences at scales of order Δ [23]. To solve the SGS model one of the most commonly used approaches is the Smagorinsky [24] model.

$$\mu_{turb}=\left(C_S \Delta\right)^2 \sqrt{2 S_{ij} S_{ij}} \tag{10}$$

where

μ_{turb} is the turbulent viscosity

Δ is the length scale of the filter

S_{ij} is the filtered strain-rate tensor.

C_S is the Smagorinsky constant

The length scale of the filter, Δ, usually considered to be cube root of the volume of the cell [22].

Choosing the right inlet boundary condition is important for *LES* because it affects the quality of the results. In the steady-state models, a uniform inflow speed along with the turbulence parameters is defined whereas for the *LES* method a turbulent unsteady inlet condition is needed [25]. The Vortex Method has been developed for generating inlet velocity fluctuations [26]. This method, instead of applying random noise at the inlet, provides some spatial correlations for the fluctuations. In this method random vortices are created on the inlet flow plane (normal to the streamwise velocity) in a way that the wall-normal components gives a spatial correlation, and the Lagevin equation [27] is used to provide a temporal correlation not only for the generation of the streamwise component but also for the other two cross-stream components [22]. The vortex method is based on a Lagrangian formulation of Navier-Stokes. The centres of the vortices are transported and the velocity is given a certain distribution [22].

In the Vortex Method the vorticity is calculated by defining a circulation parameter, intensity of which, is quantified as a function of the turbulent kinetic energy that can be calculated from a RANS calculation [28]. For each vortex a characteristic time (which is also known as the turbulent time scale $= k/\varepsilon$) is defined which represents the life time of a vortex. If the time exceeds this characteristic time, then it is destroyed and another random vortex is created on the 2D plane in the inlet. The diameter of the vortices can be set to a fixed number or can be calculated by using a turbulent length scale approach $l = k^{2/3}/\varepsilon$. Then the vortices carry a random walk in the inlet plane to develop fluctuation in time [22].

2.3 Visualisation technique

A streamline is a curve which is tangent to the velocity field at every point along its length. Streamlines show the direction fluid flows within a steady state flow domain. If $v(P)$ is a three dimensional vector field, the streamline through a point, P_0, is the solution $I_s(P_0,t)$ to the differential equation:

$$\frac{d}{dt} I_s(P_0,t) = v(I_s(P_0,t)) \tag{16}$$

Where, in the case of a steady state flow field, t is time, and the initial condition $I(P_0,0) = P_0$. A stream surface [1] is the trace of a one dimensional seeding curve, C, through the flow. The resulting surface is everywhere tangent to the local flow. A stream surface, S, is defined by:

$$S(s,t) := I_s(C(s),t) \tag{17}$$

S is the union or continuum of integral curves passing through the seeding curve C. $S(s,-)$ coincides with an individual integral curve, and $S(s,-)$ coincides with individual time lines.

3 DOMAIN

One suitable site in the UK for deployment of TSTs is Ramsey Sound in Pembrokeshire, Wales. The Sound is confined by the Irish Sea to the north and south and it is approximately 3 km long. The width of the channel varies between about 500 m to approximately 1600 m [29]. Kinetic energy of the water has been analysed with a regional coastal model and an estimate of the amount of power available in Ramsey Sound is 74.9 GWh/y [30]. It is going to be the site of DeltaStream, Wales' first tidal stream turbine, which has consent to install a 1.2 MW pre-commercial prototype device for 12 months [31, 32].

For flow modelling, an area in the vicinity of the installation site was chosen which is located between Ramsey Island and the mainland with an area of approximately 800×1800 m^2. The bathymetry data was collected during the "Celtic Odyssey Operation", by using an echosounder [31]. As the quality of data was not assured in all locations, it was decided to use two additional datasets and recreate the bathymetry. One of the datasets was provided by SeaZone®. This satellite data has a resolution of 30 m which means that the surface that is created by this dataset is very smooth and does not include the pinnacles and small rocks. The second dataset used was a historic dataset made available by the Royal Navy. This dataset which is measured by using a lead line is very old and belongs to the early years of 20th century. It is not a very precise representation of the area but it could be used to confirm the geometry of the seabed and construct the regions for which less information is available. To create the final geometry, it was decided to use all three datasets in a way that the final geometry provides a good quality with an accuracy which could reasonably represent the area – See Figure 1.

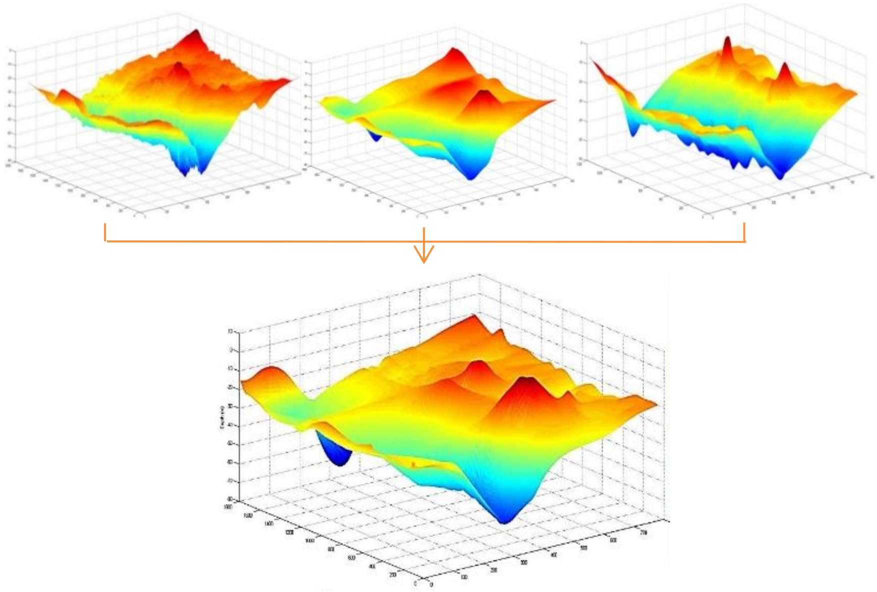

Figure 1 The bathymetry (bottom) created with the combination of the Boat (Top left), SeaZone® (Top Centre) and Royal Navy (Top Right) data sets (The elevation was exaggerated to show the features clearly)

The elevation for the selected area varies between +5 m and -74 m considering that the zero altitude has been set to be the highest peak on the seabed. The decision to have 5 m of water above the peak is based on considerations of the height of the high tide inside the sound. In order to capture the eddies generated by the seabed and Horse Rock a fine discretised domain is considered that consists of more than 36.3 million elements (combination of tetrahedral, brick, pyramid and surface triangular). In this mesh, the size of the first four layers of elements above the seabed is set to be 25 cm and then doubled for each level above up to 5 m height (i.e. 5th layer 50 cm, 6th layer 1m, etc.). This geometry is used for both the *k-ε* and *LES* turbulence models. The simulation uses the commercial code ANSYS FLUENT®. The inlet velocity for the *k-ε* case is set to be 1.5 m/s and with the turbulent intensity of 20 % and turbulent viscosity ratio of 100. For the bed boundary condition a no slip wall with roughness height (k_s) of 5.4 meters with roughness constant of 0.9 is selected. In ANSYS FLUENT® the roughness constant is a value to define how uniformly the sand grains are distributed on the surface. A suitable value is usually between 0.5 and 1.0 and the smaller number means that the sand grains (here rocks) are placed on the surface more uniformly. ANSYS FLUENT® uses the logarithmic law of wall to solve the wall-bounded turbulent flows [21]. The reason to select these values (5.4 for roughness height and 0.9 for roughness constant) is that the model has simplification in terms of the exact shape of the bed and also in the terms of the inlet boundary condition. In the real world, the inlet has a very turbulent boundary condition because of the big rocks located in the south of the sound (known as the bitches). To model the free surface, a flat plane of symmetry boundary condition (i.e. zero shear non slip wall) is applied to the upper surface of the domain. This rigid lid approach has been used in various research papers to model the turbulent flow in channels [33, 34, 35].

To model the subgrid-scale turbulence for the *LES*, the Smagorinsky-Lilly method is selected. Again the same inlet velocity as for the *k-ε* model has been chosen for the flow. By using the Vortex Method to create random fluctuation at the inlet, 1000 vortices are applied at the inlet. Turbulent intensity of 20% along with the turbulent length scale of 1m is chosen. Other boundary conditions are identical to the *k-ε* case.

A constant time step size of 6 seconds is selected. This value is calculated by multiplying the time that it takes for the flow to pass through the smallest element in the streamwise direction by a factor of 10. The maximum number of iterations for each time step is set to be 35. To run this simulation the HPC Wales platform is equipped with Intel Sandy Bridge E5-2690 at 2.9 GHz and 4 GB memory per core. The total problem is run for 25000 time steps and it takes about 72 hours to run the job on 32 cores which is the maximum number of cores available to run the simulations.

4 RESULT

Figure 2 shows the results of velocity contours for the *k-ε* method. It clearly shows the influence of the Horse Rock and Pony Rock (wake) in the flow field. The big velocity drop occurs behind the main feature of the sound, the Horse Rock (775 m from the inlet) and this can be see in the data collected by an ADCP transect as shown in Figure 5. The ADCP data shown here is from a single transect and was collected from a moving vessel at a low sample rate of 1Hz. This may account for the significant amount of noise in the measured data.

The *LES* result (Figure 3) shows that at least one eddy is forming behind the Horse Rock. Also two bodies of water coming from each side of the Rock are circling around the generated eddy before joining each other again further downstream. In Figure 4 it can be seen that the eddy is very flat. It starts its movement upward but then it seems that because of the fast water flowing overhead, it is crushed.

Another reason for this could be the restriction of the domain in the vertical direction. In a free surface model the eddy would propagate to the surface. (Figure 6) shows that near the gully close to the exit of the model the flow coming from both sides rushes down the channel. The general feature of the results in which the flow is very smooth near the surface is observed here as well. Eddies are formed as the flow comes off the edge of the deep valley and then it meets the flow coming from the other side of channel which cause both bodies of water to swirl. This pattern shows that different layers of the flow behave independently and have their own pattern due to the features on the seabed.

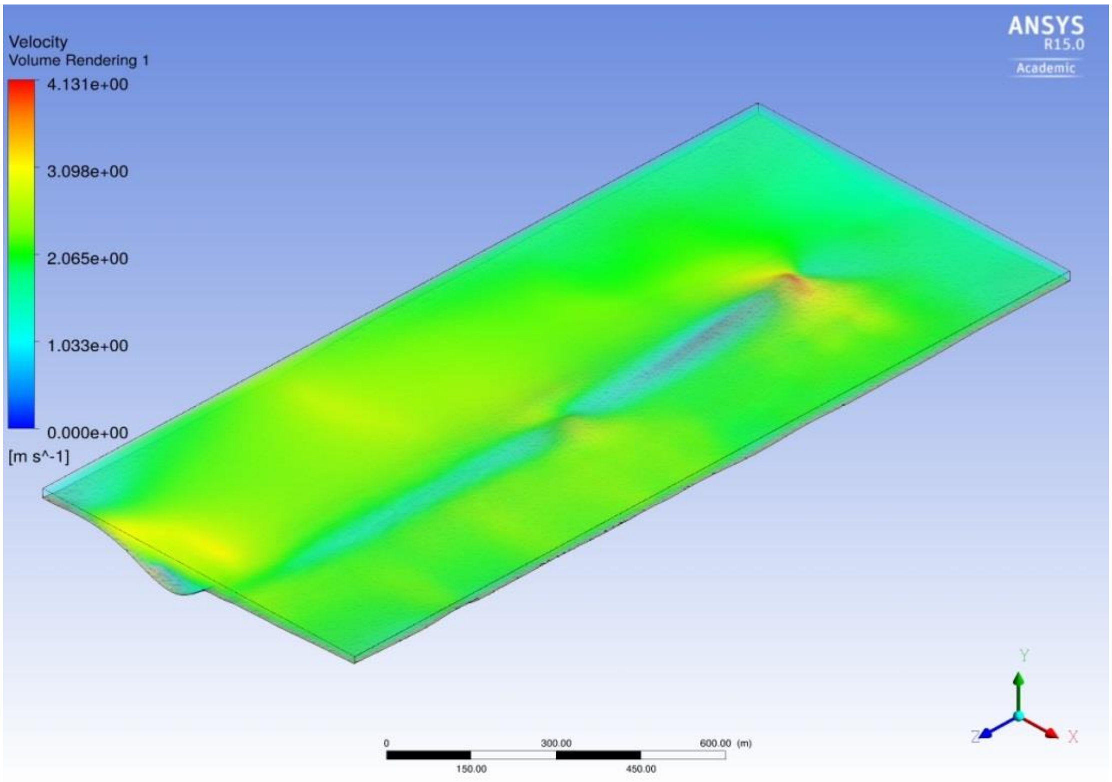

Figure 2 Volume rendering of the velocity for the area (fine mesh, *k*-*ε* Method)

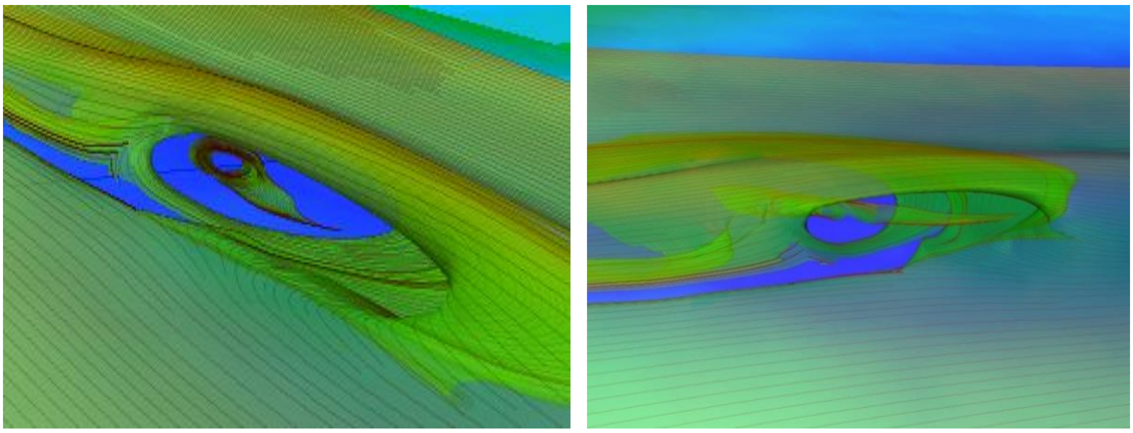

Figure 3 The Eddies forming behind the horse rock. The separation point is also visible (LES method)

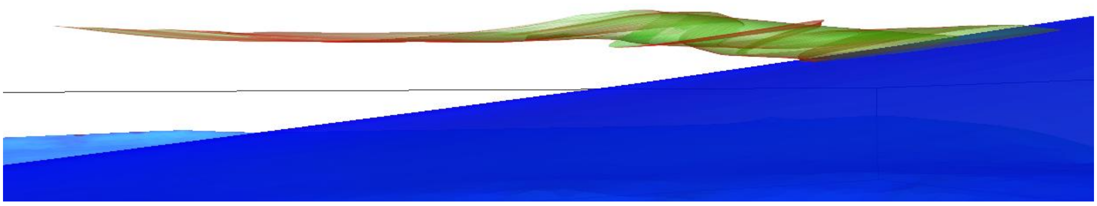

Figure 4 the eddy forming behind the Horse Rock from different angles visible (*LES* method)

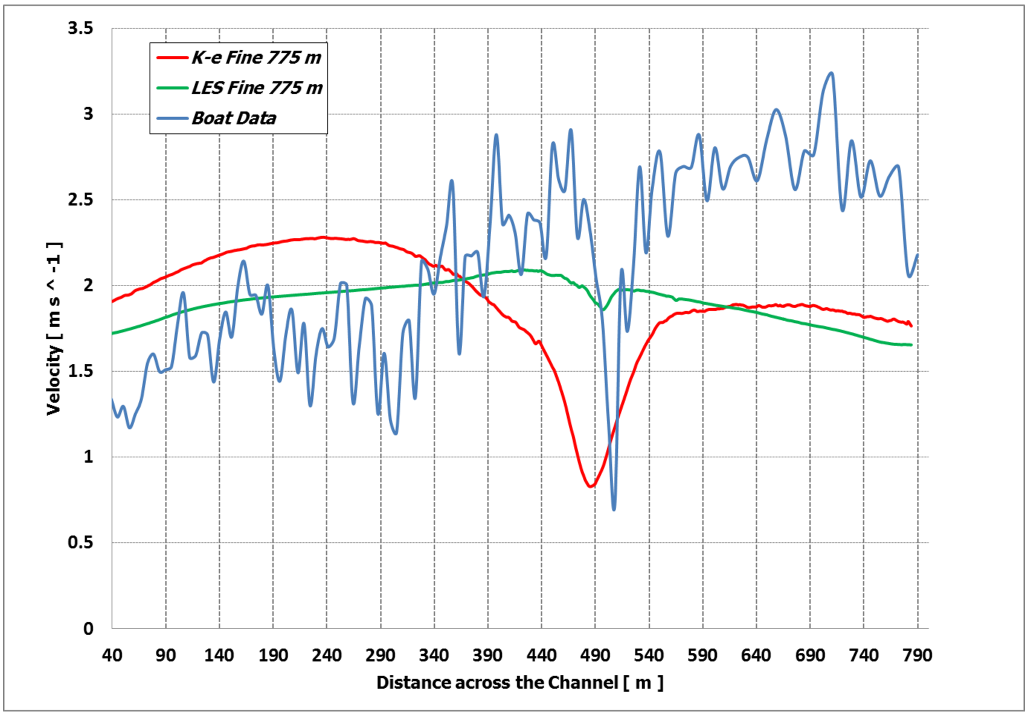

Figure 5 Comparison of the velocity profile across the channel at 775m from the inlet (*k-ε*, *LES, Boat data*)

5 CONCLUSION

In this research the flow modelling and visualisation of a real bathymetry was investigated. The purpose of this model is to apply these methods to give a realistic view about the behaviour of flow in coastal regions before the deployment of tidal turbines.

Two different turbulence models have been investigated for a possible site deployment of TST and the model results were compared with the real flow data acquired from the location. It has been understood that the *k-ε* method can predict the flow pattern with relatively good accuracy near the main features of the domain and although the *LES* model has the ability to demonstrate some expected flow patterns because of the bathymetry, it still needs more investigation before considering it for a possible robust method for solving these kinds of problems. Due to its nature, the *LES* model could provide more precise results in this current problem if there had been more knowledge about the inlet boundary conditions. In ocean modelling the target area is very extensive compared to a usual application of CFD and the vortices created by the vortex method at the inlet are not propagating all along the length of the domain, there it is suggested that a direction for future work would be the definition of a suitable bed boundary condition that can generate such turbulent structures in the flow.

Having the free surface feature helps the model to behave more realistically near the surface. It was shown in Figure 4 that the forming eddy is propagating towards the surface and because in the simulations presented here a rigid lid was placed on the top surface, the propagation of it is restricted. With a free surface model included the eddy may continue to develop toward the sea surface and emerge as a swirl of the surface. It has to be mentioned that despite the simplifications which are applied to the models in this research, the application of steady state and transient turbulence models to a very large domain like Ramsey sound is novel. The simulation showed that although using traditional *k-ε* and *LES* models can give reasonable results, in order to have a more precise model that can cover all the aspects of coastal flows it is necessary to customise the bed roughness parameters in a way that can compensate the effects of simplification of the bathymetry.

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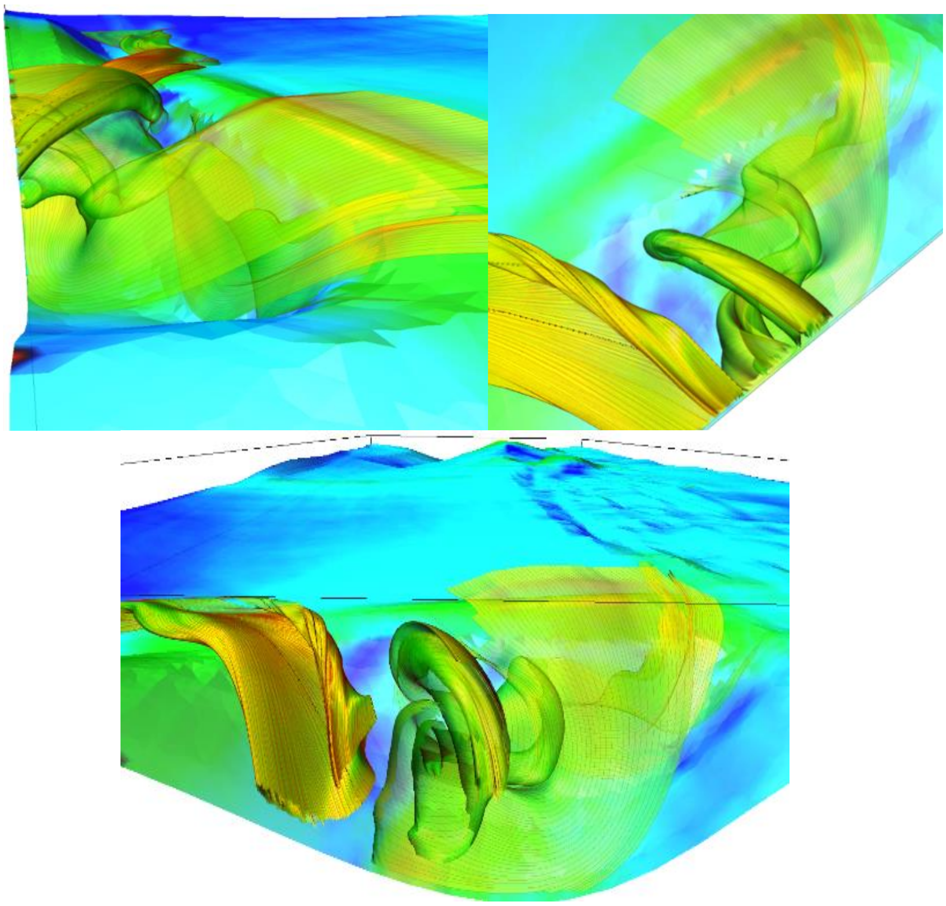

Figure 6 Three different views of the big eddies forming as the water coming from the both side of the channel joining each other (*LES* method fine mesh)

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