ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

MESHING OCEAN DOMAINS FOR COASTAL ENGINEERING APPLICATIONS

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Keywords: Mesh Generation, Geographical Information Systems (GIS), Computer Aided Design (CAD), Tidal Renewable Power, Severn Estuary, Tidal Lagoon.

Abstract. *As we continue to exploit and alter the coastal environment, the quantification of the potential impacts from planned coastal engineering projects, as well as the minimisation of any detrimental effects through design optimisation, are receiving increasing attention. Geophysical fluid dynamics simulations can provide valuable insight towards the mitigation and prevention of negative outcomes, and as such are routinely used for planning, operational and regulatory reasons. The ability to readily create high-quality computational meshes is critical to such modelling studies as it impacts on the accuracy, efficiency and reproducibility of the numerical results. To that end, most (coastal) ocean modelling packages offer tailored mesh generation utilities. Geographical Information Systems (GIS) offer an ideal framework within which to process data for use in the meshing of coastal regions. GIS have been designed specifically for the processing and analysis of geophysical data and are a popular tool in both the academic and industrial sectors. On the other hand Computer Aided Design (CAD) is the most appropriate tool for designing coastal structures and is usually the user interface to generic three–dimensional mesh generation frameworks. In this paper we combine GIS and CAD with a view towards mesh generation for an impact study of the proposed Swansea Bay Tidal Lagoon project within the Bristol Channel and Severn Estuary. We demonstrate in this work that GIS and CAD can be used in a complementary way to deliver unstructured mesh generation capabilities for coastal engineering applications.*

1 INTRODUCTION

Geophysical domains are geometrically complex, with shorelines the most commonly known example of fractal geometry in nature [1]. Many transient features in oceanic flow emerge due to the multi–scale nature of the domain geometry. Therefore, the predictive accuracy of geophysical fluid dynamics simulations will depend on an appropriately accurate and efficient representation of a wide range of features present in the geometry. In addition to natural features, in the area of coastal engineering a further critical small–scale geometrical feature is that of the infrastructure: pipes, piers, tidal dams and wave defence structures being typical examples. The minimisation of environmental impact as well as the resilience of infrastructure are of such importance that policy frameworks increasingly regulate these aspects of coastal infrastructure projects. This has led to the adoption of hydrodynamic coastal modelling as a necessary tool in the infrastructure design process. Resolving coastal structures in a computational mesh, or at least accurately parameterising their effect on the flow, is necessary to achieve high predictive accuracy in simulations. However, the impact of many coastal structures can be seen at much larger scales, especially when linked to tidal power generation [2, 3, 4]. Therefore, the simulation domain must extend over much greater scales. In fact, the desire for high resolution in parts of a large multi–scale domain, is common in coastal as well as ocean modelling [5, 6, 7].

Unstructured meshes are well suited to the efficient tessellation of complex, multi–scale coastal domains, by allowing the element size to vary by orders of magnitude. Unstructured mesh generation methods have matured and can produce high–quality meshes for domains typically encountered in coastal ocean modelling. However, most generic mesh generation tools have been developed within the wider realm of *Computational Fluid Dynamics (CFD)* and are not geared towards ocean and coastal modelling, as typically a *Computer Aided Design (CAD)* interface is available to the user. CAD is ubiquitous in coastal engineering and an essential component in industrial fluid dynamics applications. The native ability of CAD to accurately specify coastal structures or other infrastructure, often with reference to set standards, is necessary in the design as well as construction processes. However, CAD is not the best framework for the description of geophysical data, where *Geographical Information Systems (GIS)* are far better suited. The flexibility, extensibility and robustness of GIS, and in particular the ability to process and analyse complex and multi–scale geophysical information, has led to their integration with data visualisation, mesh generation [8, 9] and data management [10] frameworks.

In this paper we focus on the generation of multi–scale unstructured meshes in the context of coastal engineering applications and present a framework to achieve this, combining GIS and CAD. In the following sections we outline the developed framework, and discuss how it relates to mesh generation in coastal engineering. A preliminary application to the Bristol Channel and Severn Estuary follows, where numerous projects on renewable tidal power generation have been proposed. Most such projects require significant coastal infrastructure design and development. We close with a discussion of our key findings and outlook on future work.

2 MESHING FOR COASTAL ENGINEERING APPLICATIONS

The domain in simulations of coastal and ocean flows is usually best described in a topologically two–dimensional space, where the domain is bounded by shorelines and open boundaries. Mesh generation in two dimensions is the natural and obvious choice in cases where a two–dimensional framework, such as the depth–averaged shallow water equations, can be used to express the phenomena under study. In cases where a three–dimensional framework must be used (e.g. when non–hydrostatic effects are important) a topologically two–dimensional description of the domain will typically suffice. Most three–dimensional models will only require a two–dimensional mesh, over a reference surface, and construct a vertically structured three–dimensional mesh by projecting the surface mesh vertices towards the ocean floor. GIS is therefore ideal for describing domains in realistic geophysical simulations [11], since one of the primary purposes of GIS is to store, manipulate and analyse geographical, topologically two–dimensional information. In order to meet the demand for robust mesh generation of geophysical domains several utilities have been developed, adopting GIS methodologies. For example, *BlueKenue*, *MIKE Zero* and *RGF-Grid* are mesh generation and post–processing utilities used by the *Telemac*, *MIKE* and *Delft3D (Flexible Mesh)* models respectively. In this paper we use the utilities described by Avdis et al. [9] which interface the QGIS suite [12] and the Gmsh mesh generator [13], by linking similar abstractions used in both GIS and mesh generators: *vector* data structures are used to describe domain boundaries and *raster* data structures are used to express fields such as the spatial distribution of the desired element edge size.

Unlike GIS, CAD is predominantly aimed at designing three–dimensional entities, and an explicit reference to a geographical coordinate reference system need not be given. Particular emphasis is put on construction or manufacture processes, where determination of materials and construction methods are often aided by the more general *Computer Aided Engineering (CAE)* framework which includes interfaces to industrial fluid dynamics solvers and mesh generation suites. However, the use of both CAD and GIS in planning and construction of infrastructure, as well as the recent trends of increasing accuracy demands from geo–location services has led both GIS and CAD to adopt features and capabilities from one another. Mesh generation for coastal engineering is an example of this complementary relationship, where both CAD and GIS must be used; detailed descriptions of coastal structures and their construction can only be made in a CAD framework, while only a two–dimensional description of the surrounding environment is necessary. In this study we used CAD to extract broad features of the coastal infrastructure and define the relevant shoreline boundaries, identifying an acceptable approximation to the wetting line. In general, the definition of shoreline boundaries can only be made on a case by case basis, accounting for tidal or other inundation variations. These boundaries were then imported into GIS and were used in the domain definition and mesh generation.

3 TIDAL LAGOONS IN THE BRISTOL CHANNEL

The large tidal range in the Bristol Channel and Severn Estuary has inspired many proposals for renewable energy extraction [17]. Several plans have proposed building dams spanning the estuary (for example [18])–proposals collectively known as the Severn Barrage. Sections of the structure house sluice gates and hydro–turbines, in order to control the flow of the water and in particular to form and harness a potential energy difference across the dam wall. However, construction cost and concerns over potential environmental impacts [19] have been major failing points. Tidal lagoons are similar in construction and operation, but at a smaller scale. A tidal lagoon proposal currently being considered by the UK Government is the Swansea Bay Tidal Lagoon [20, 21]. Figures 1(d,e) and 2 show its location and outline the proposed structure. As shown, a sea wall with appropriate turbine and sluice gate housings encloses a large area within the estuary. Since the structure of a tidal lagoon is local and does not cross the estuary, tidal lagoons are thought to result in smaller environmental impacts [22]. The appraisal of tidal lagoons must include environmental impact studies and the design must limit these. Although the level of commercial fishing activity within the Severn Estuary and Inner Bristol Channel is low when compared to other British inshore fisheries [23], the channel is an important nursing ground for commercially sensitive fishery species such as sole and bass. These juvenile fish populations

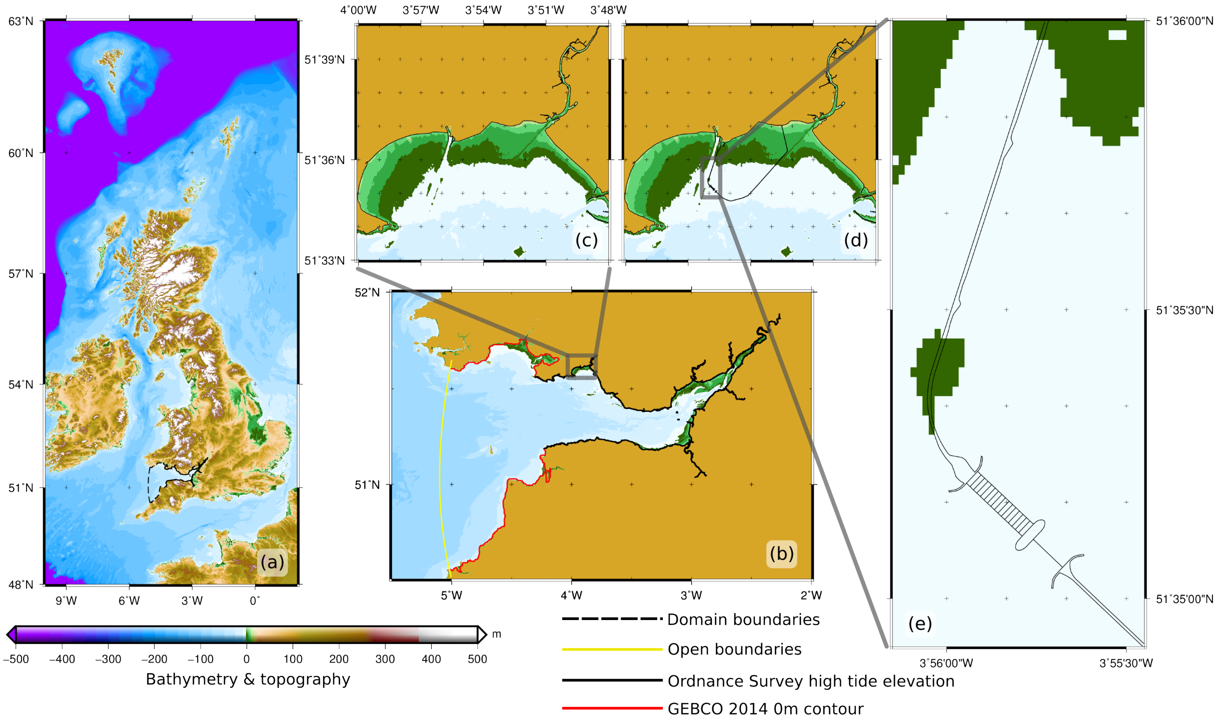

Figure 1: The domain boundaries and bathymetry for simulations of the Severn Estuary and Bristol Channel, with and without the Swansea Bay Tidal Lagoon structure: (a) Map of GEBCO 2014 bathymetry [14] over the UK and Ireland, with the simulation domain boundaries; (b) The simulation domain boundaries, without the tidal lagoon, identifying the source of the boundaries; (c) Detail of the Swansea Bay area; (d) Detail of the Swansea Bay area with the tidal lagoon boundaries, derived from [15]; (e) Detail of the tidal lagoon boundaries showing the housing of the tidal turbines and sluice gates. The Digimap marine bathymetry [16] is shown in panels (b,c,d,e).

must be preserved. The estuary is also notably rich in fish species, being home to more than 100 variations [24]. In addition to the environmental concerns, building tidal lagoons requires significant capital, leading to investors (including the state) requiring estimates on return with sufficient accuracy and ample supporting evidence [25]. Accurate optimisation studies of tidal lagoon structures, in order to minimise environmental impacts and maximise return, are therefore important. Numerical simulations of the flow over the wider region resolving the structure and its effects can be a valuable tool in appraisal and design (as carried out, for example, in [26]). Here we present the construction of a mesh as well as simulation results over the Severn Estuary and Bristol Channel, resolving the tidal lagoon structure.

3.1 Mesh Generation

Panels (a,b,c) in figure 1 show the domain boundaries superimposed on bathymetry maps of the simulation domain without the tidal lagoon structure. Panel (a) shows an overview of the whole domain in relation to the United Kingdom, while panel (b) identifies the sources of the domain boundaries with differing fidelities. The domain boundaries have been selected to be suitable for simulations aimed at identifying the effects of the Swansea Bay tidal lagoon on the Severn Estuary, so high mesh and shoreline geometry resolution was used in the inner part of the Bristol Channel and the Severn Estuary. The Western part of the Bristol Channel is included in the simulation, in order to place the open boundary away from the region of interest. As shown in figure 1(b), the UK Ordnance Survey shoreline data [27], and in particular the high-tide

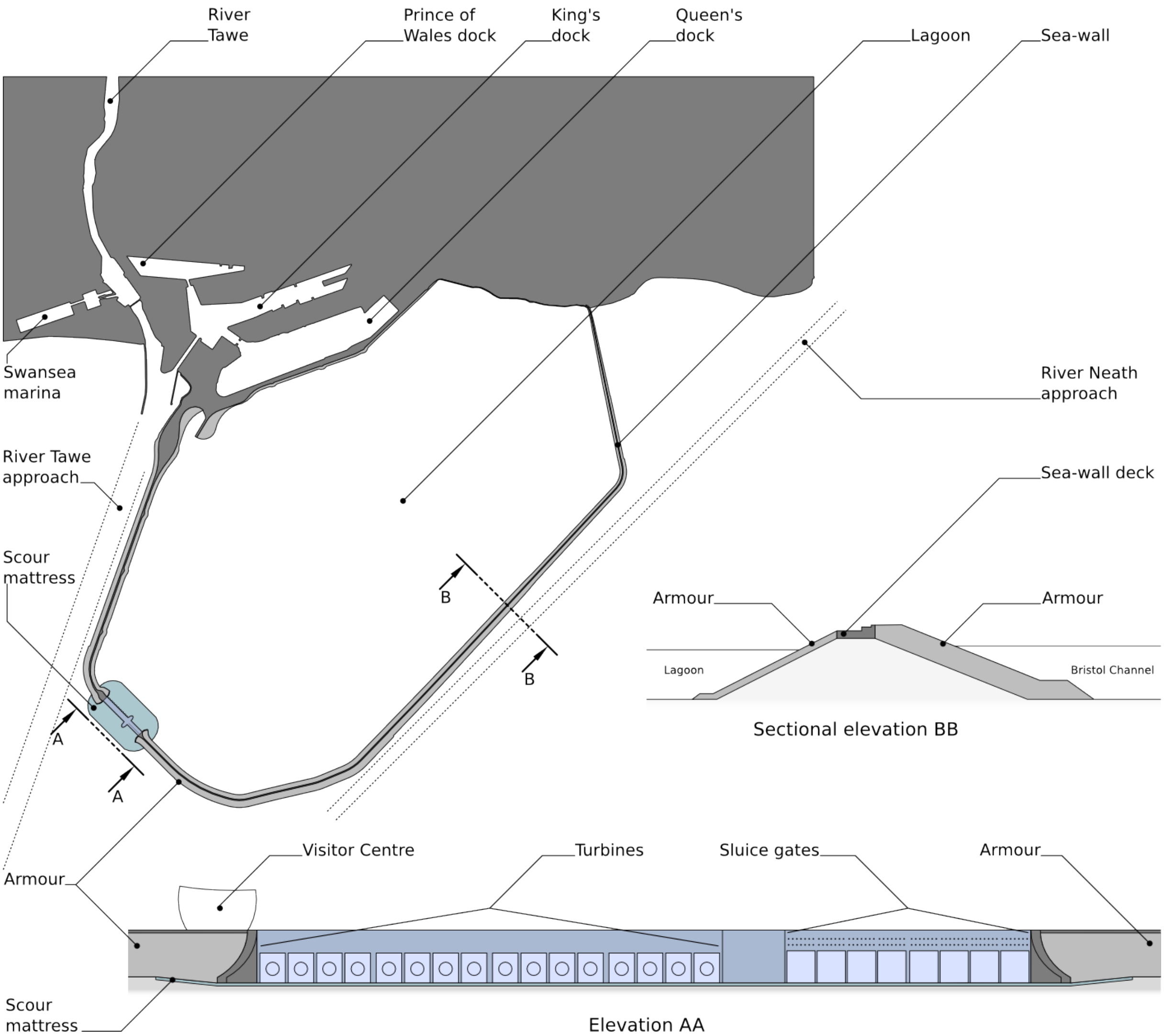

Figure 2: Schematic diagrams of the Swansea Bay tidal lagoon showing lagoon location, and broadly outlining lagoon construction, based on technical drawings of the proposed lagoon [15]. The plan view shows the location of the lagoon relative to the Swansea Docks, Swansea Marina, River Tawe and the approximate locations of the approach channels to the rivers Tawe and Neath. Elevation AA shows the housing of the 16 turbines and 8 sluice gates, viewed from the Bristol Channel. Sectional elevation BB outlines the construction of the sea–wall, identifying the armour either side and sea–wall deck.

boundary was used in the inner part of the Bristol Channel and Severn Estuary. The zero–elevation contour extracted from the GEBCO 2014 30-minute arc gridded bathymetry [14], shown in figure 1(a), was used in the portion close to the open boundary. The open boundary was formed by linearly blending two loxodromes (lines of constant bearing): The loxodrome starting from the Welsh coast at $5°$ East, $51.65°$ North, at a bearing $170°$ West, up to a latitude $51.0°$ North and the loxodrome starting from the Cornish Peninsula at $5°$ East, $50.5°$ North, at a bearing $30°$ West, up to a latitude $51.0°$ North.

The proposed Swansea Bay tidal lagoon would extend dock infrastructure into the Swansea Bay, as outlined in figure 2. As suggested by the bathymetry in figure 1(c,d) and figure 2 a $9.5km$ sea wall will follow the direction set out by existing dredged approach channels leading to rivers Neath and Tawe, and impound an area South of the Swansea Docks. As shown in figure 2, the structure is planned to include sixteen turbines and eight sluice gates at a purpose built housing unit, located at the South–West side of the lagoon. The boundaries for the lagoon structure used here were obtained from technical drawings in [15]. Thus, as discussed in sections 1 and 3 the specification of the tidal lagoon structures was only available in a form originating from a CAD/CAE framework. Furthermore, only drawings of the structure were available, which were digitised as a first step, extracting the boundaries of the sea–wall deck, identified in the sectional elevation of figure 2. The digitisation was carried out within QGIS using geo–referencing utilities, so as to accurately locate the lagoon structures in relation to the Ordnance Survey boundaries [27]. The armour either side of the wall, identified in figure 2, is ignored in this case and the domain extends over the armour, up to the seawall crest. The qCAD open–source package was used to accurately edit the digitised boundaries and define the domain boundaries over the turbines and sluice gates.

A two–dimensional, shallow–water approximation, discussed in section 3.2, was chosen for simulating the flow in the domain. Turbines and sluice gates cannot be represented by the shallow–water framework, due to their complex three-dimensional geometry. Instead, only their effect on the larger scales can be captured. The energy extraction from the turbines is usually parameterised as a sub–grid–scale process, applied only to mesh elements in the vicinity of the device [28]. Therefore, the turbines are here represented by adjacent rectangles (see figure 1(e)), that will be covered by mesh elements, while the mesh is conforming to polygon boundaries (see figure 4(d)). Appropriate parameterisations can be applied in elements inside the turbine–representing regions. The definition of adjacent, meshed, polygons creates a number of *internal boundaries*. The flow through the turbines is also controlled by turbine gates. The effect of the turbine gates can be captured by appropriate conditions on the flux through the edges lying on the internal boundaries between the lagoon and turbine regions. The sluice gates are represented as internal boundaries between the lake and the Bristol Channel.

A small element edge length is required for an accurate representation of the detail present in the shorelines obtained from the Ordnance Survey, whereas a lower resolution is desired close to boundaries described by the $0m$ contour from the GEBCO 2014 bathymetry. The distribution of element size is shown in figure 3 and is based on the proximity to the shorelines. The mesh at the boundaries obtained from the Ordnance Survey has an element edge length of $10m$. This resolution is maintained up to a distance of $150m$ from the boundary. The edge length then increases to an edge length of $10km$ over a distance of $25km$. An identical element size distribution was chosen towards the boundaries of the tidal lagoon structure. A $1km$ element edge size is prescribed at the boundaries expressed as a $0m$ contour of the GEBCO 2014 bathymetry [14]. This resolution is maintained up to a distance of $2km$ from the boundary and then increases to $10km$ over a distance of $15km$. Panel (a) in figure 4 shows the mesh *without* the tidal lagoon structure and panels (b,c,d) show the mesh *with* the tidal lagoon structure. The mesh in the lagoon and the turbine polygons are coloured differently highlighting the individual regions and internal boundaries.

3.2 Simulation Results

In order to show the utility of the meshes shown in figure 4, the Telemac package was used to simulate the tidal flow using the mesh shown in figure 4(a). The “depth–velocity” formulation

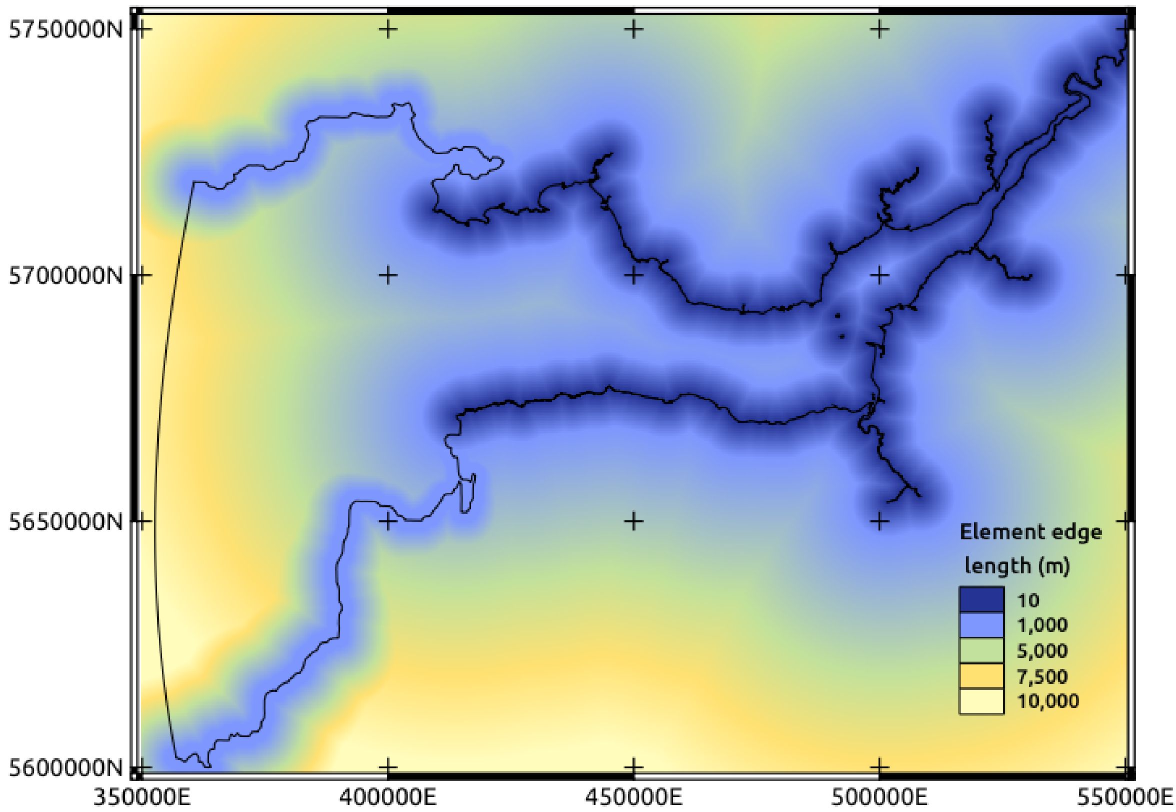

Figure 3: Map of user–specified mesh size metric (element edge length) in the UTM30 coordinate reference system, for the simulation domain without the tidal lagoon.

of the shallow water (Saint-Venant) equations [29] was used:

$$\frac{\partial h}{\partial t} + u_i \frac{\partial h}{\partial x_i} + h \frac{\partial u_i}{\partial x_i} = 0 \,, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\, g \frac{\partial Z_s}{\partial x_i} + \frac{1}{h} \frac{\partial}{\partial x_j} \left(h \nu_e \frac{\partial u_i}{\partial x_j} \right) + C_i + S_f u_i \,, \tag{2}$$

where repeated indices imply summation, ν_e is the effective viscosity and h is the total water depth measured from the free-surface to the ocean floor. Z_s is the free surface elevation measured from the UTM30N vertical datum and Z_f denotes bathymetry, such that $h = Z_s - Z_f$. C_i are the Coriolis force terms, defined as:

$$\begin{aligned} C_1 &= f u_2 \,, \\ C_2 &= -f v_1 \,, \end{aligned} \tag{3}$$

where $f = 1.1 \times 10^{-4} s^{-1}$, valid for a latitude of approximately $50°$. S_f in equation 2 is the floor friction term, expressed by the Chézy law:

$$S_f = -\frac{g}{\cos(a) h C^2} \sqrt{u_1^2 + u_2^2} \,, \tag{4}$$

where $C = 62.6 m^{\frac{1}{2}} s$.

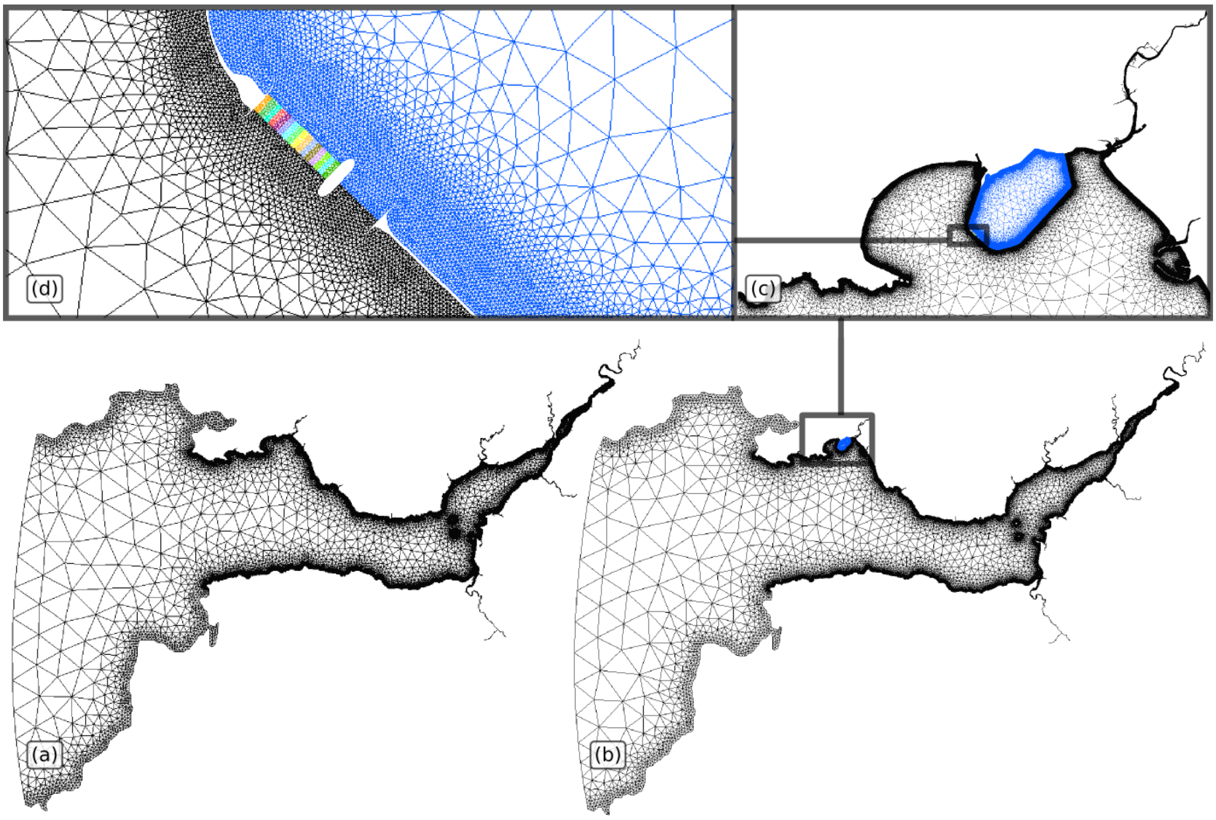

Figure 4: Multi–scale unstructured meshes over the Bristol Channel and Severn Estuary simulation domain, in UTM30: (a) Mesh of the domain without the tidal lagoon, containing $1,166,851$ vertices, $2,246,905$ triangles; (b) mesh of the domain with the tidal lagoon, containing $1,205,631$ vertices, $2,323,049$ triangles; (c) mesh detail over the Swansea Bay and tidal lagoon; (d) detail over the Swansea Bay Tidal Lagoon, showing the mesh around the sea–wall and the mesh over the turbines and sluice gates.

Equations 1 and 2 are discretised using a mixed finite element pair, composed of semi–quadratic (*quasi–bubble* in [29]) elements for velocity and linear elements for depth. Time stepping is affected using a fractional step method, where the advective terms are used to calculate intermediate values during a first stage using the method of characteristics detailed in [29]:

$$\begin{aligned}\frac{h^{*}-h^{n}}{\Delta t}+u_i\frac{\partial h}{\partial x_i} &= 0\,,\\ \frac{u_i^{*}-u_i^{n}}{\Delta t}+u_j\frac{\partial u_i}{\partial x_j} &= 0\,,\end{aligned}$$

where superscripts denote time–levels. The primitive variables at the end of the time–step are calculated in a second stage, using a semi–implicit discretisation of the terms with a θ parameter controlling the implicitness of each term:

$$\begin{aligned}&\frac{h^{n+1}-h^{*}}{\Delta t}+\left[h\frac{\partial u_i}{\partial x_i}\right]^{n+\theta_{hp}}=0\,,\\ &\frac{u_i^{n+1}-u_i^{*}}{\Delta t}+\left[h\frac{\partial u_i}{\partial x_i}\right]^{n+\theta_{vp}}=\left[-g\frac{\partial Z_s}{\partial x_i}\right]^{n}+\left[\frac{1}{h}\frac{\partial}{\partial x_j}\left(h\nu_e\frac{\partial u_i}{\partial x_j}\right)\right]^{n+\theta_{vd}}+C_i^{n}+S_f^{n}u_i^{n+1}\,.\end{aligned}$$

In the simulations presented here $\theta_{hp} = \theta_{vp} = 0.55$ and $\theta_{vd} = 1$.

The OTPS tidal dataset over the North–Western European shelf [30] is used to prescribe the depth at the open boundary. The 1 arc–second *Digimap Marine, HydroSpatial One* [16] gridded bathymetry data, shown in panels (b,c,d,e) of figure 1, was used to define the bathymetry in the simulation domain. The Severn Estuary is known to have large *tidal flats*, which are submerged during high tides. The cyclical exposure of tidal flats requires special *wetting-and–drying* algorithms in the solution procedure, and such algorithms are available in the Telemac modelling framework. However, given the focus of this study is mesh generation in the context of coastal engineering, wetting–and–drying algorithms have not been incorporated into the solution procedure. Instead, the bathymetry was modified to be $-10m$ in any areas that exceeded that value. While this may affect the predictive accuracy of the simulation results presented here, the mesh generation procedure has not been altered substantially in ongoing studies incorporating wetting–and–drying.

Five days are simulated, starting at $00 : 00$ 2 July 2011, using a time step of $0.2s$. Figure 5 shows the instantaneous velocity magnitude contours at the end of the simulation. Details over the Severn Estuary and the Swansea Bay are shown. The velocity vectors are also shown in the Swansea Bay area. At the time of the shown instant the flow is in ebb tide and strong velocities are seen in the Bristol Channel, close to the shorelines. In the Severn Estuary high velocities are indicated in the shallow areas. However, the bathymetry modification and lack of wetting–and–drying compromise the predictive accuracy in shallow regions. This also applies to the Swansea Bay results, where the velocity vectors indicate an along–shore flow, with a recirculation region in the lee of the piers around the river Tawe. Nonetheless, the preliminary results presented here show the suitability of the mesh for coastal engineering fluid dynamics simulations.

4 CONCLUSIONS

The use of geophysical fluid dynamics simulations in the context of environmental impact assessment [2, 3, 4, 5, 17, 26] and coastal infrastructure optimisation [31] is becoming common place. Robust mesh generation is therefore required, enabling an adequate representation of coastal infrastructure, within inherently complex geophysical domains. GIS and CAD have both been used as interfaces to mesh generation, but in the context of coastal engineering the complementary capabilities of both frameworks are useful: while CAD can be used to accurately specify the geometry of coastal structures, the impact of coastal structures can be seen on a much larger scale where GIS is the appropriate framework for geometry description and data analysis. We have here shown how the combination of GIS and CAD can form an efficient framework for mesh generation.

The Swansea Bay Tidal Lagoon is a typical example of coastal infrastructure where environmental impact, construction cost and financial return must be quantified and balanced. We have shown how the proposed mesh generation framework can be used to produce meshes with very accurate shoreline representations, including the proposed lagoon structure. On–going work is aimed at understanding the effect of the tidal lagoon on the Severn Estuary, Bristol Channel and Irish Sea, as past studies [3, 2] have shown that a tidal barrage will affect the tidal range in a much wider area. To that end further simulations are needed, incorporating wetting–and–drying, a sediment model [32], realistic operation and parameterisation of sluice gates and turbines, with high mesh resolution over large parts of the Severn Estuary and Bristol Channel.

Future work will be aimed towards mesh generation for simulations requiring detailed description of structures within very large domains. For example, the parameterisation of geo-

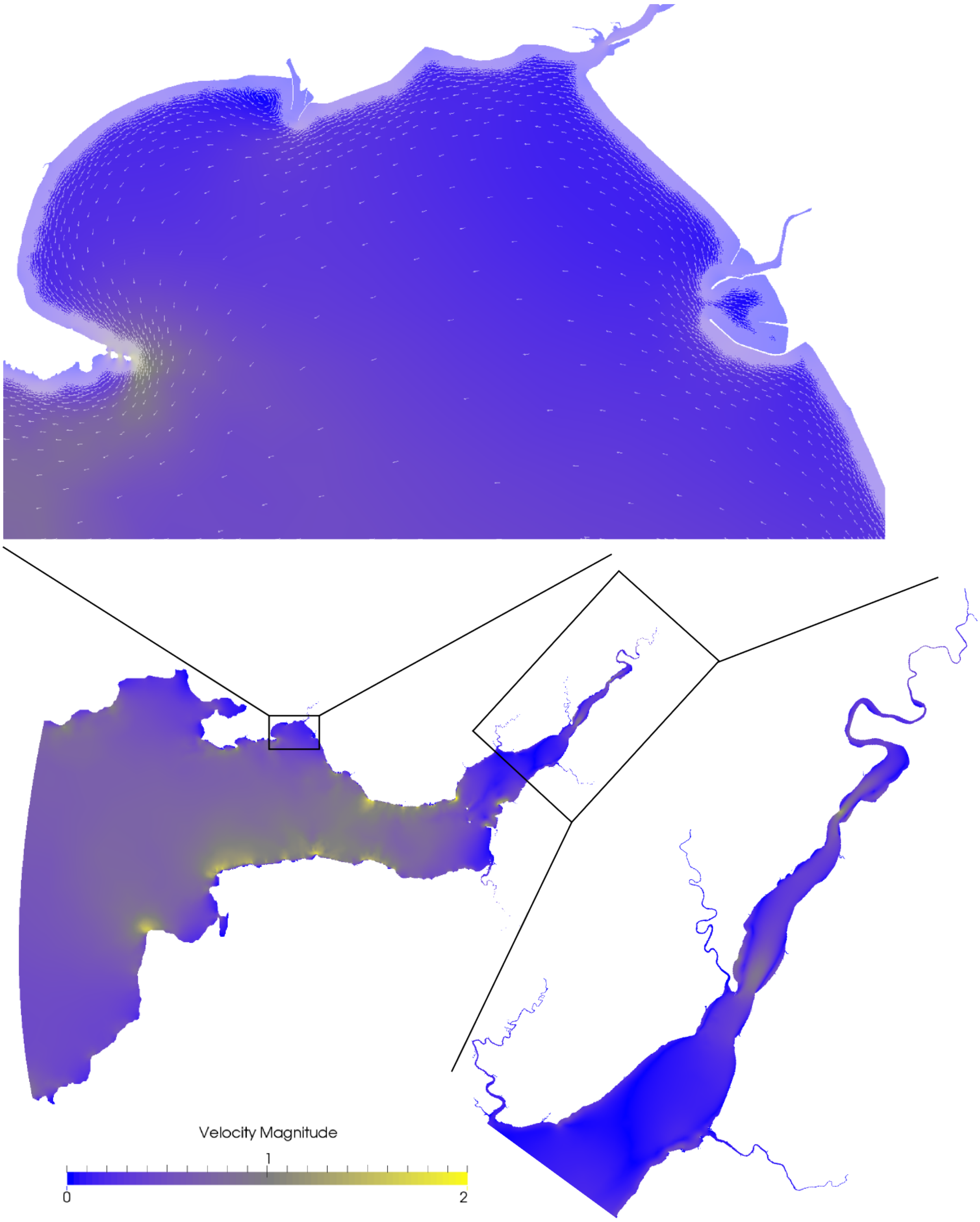

Figure 5: Simulation results, after five days of simulated time, at $00:00$, 7 July 2011: Bottom left panel shows instantaneous velocity magnitude contours in the simulation domain; bottom right panel shows the Severn Estuary; top panel shows the Swansea Bay, also with velocity vectors.

metrically complex turbines has been common practice in studying the impact of tidal power generation arrays on sedimentation patterns [5]. However, recent studies have an increasingly detailed geometric description of the tidal turbines [33], as the focus shifts on tidal device performance, loading, survivability, interaction between devices, and tidal array optimisation in realistic domains. In addition, the numerical framework is envisaged to combine a shallow water representation over the far region, with an accurate, three–dimensional description of the flow around the device.

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