**The role of computational fluid dynamics in understanding shipwreck site formation processes**

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**Abstract**

Studies indicate that physical processes commonly dominate the initial stages of wreck site formation. Detailed knowledge and understanding of hydro- and sediment- dynamics are therefore imperative for studies dealing with site formation and *in-situ* preservation. In this investigation, the results of computational fluid dynamic modeling over a shipwreck site are presented, using a high-resolution surface derived from multi-beam echo-sounder data and boundary conditions constrained by field measurements (sediment samples and flow measurements). Simulation of the 3-dimensional flow velocity field around the wreck site, and secondary products derived from the computational model, confirm that flow velocity and turbulence are both amplified by the presence of the wreck, causing changes in the morphology of the flow regime. Flow contraction, the formation of lee-wake vortices behind the structure (accompanied by vortex shedding) and increased turbulence are all observed. Shear-stress and TKE amplification three to four times greater than ambient values are recorded downstream of the wreck structure. Benefits of this approach for studies of site-formation and *in-situ* conservation include the inexpensive, open-source, and desk-based nature of the investigation.

**1. Introduction**

The past two decades have seen remarkable advances in acoustic seafloor mapping, with high-resolution acoustic imaging now routinely used in archaeological studies (e.g. Plets et al., 2011; Westley et al., 2011). Technological and methodological advances in acoustic imaging and digital rendering are such that shipwreck sites and individual artifacts can now be imaged at centimetric resolution in tens or hundreds of metres of water (Quinn et al., 2005). Beyond using acoustics as a mere prospection tool for locating wreck sites, researchers are increasingly exploiting the quantitative aspects of these data, for example deriving secondary products from high-resolution multi-beam echo-sounder (MBES) bathymetric data in the form of accretion-erosion plots (Quinn and Boland, 2010) and from MBES backscatter data in the form of automated classifications (Masetti and Calder, 2012).

In conjunction with these developments in underwater imaging, computational fluid dynamics (CFD), the analysis of fluid flow using computer simulations, has similarly benefited from increased computing power. In CFD modeling, the interaction of liquids with surfaces defined by specific boundary conditions is analyzed. Whilst CFD modeling is now commonplace in engineering and industrial sectors (e.g. Versteeg et al., 2006), it is only within the last decade that 3-dimensional flow simulations have been applied to natural systems in which morphological change is driven by near surface/bed flow such as rivers (Zhang and Shen, 2008), sand dunes (Smyth et al., 2012; Jackson et al., 2013) and snow fields (Beyers et al., 2004). Ongoing developments have therefore improved the accuracy and speed of complex simulation scenarios, such as turbulent flows that act on and around submerged structures.

In this paper, we summarize the results of CFD modeling over a shipwreck site (the Arklow Bank wreck), using a high-resolution surface derived from MBES surveys and boundary conditions constrained by field measurements. This topic is of interest because an understanding of hydro- and sediment- dynamics is particularly important for site formation studies and *in-situ* conservation of shipwrecks. To our knowledge, this is the first reported study in the peer-reviewed literature to combine CFD modeling and MBES data in an archaeological context.

**2. Theoretical background**

The ongoing focus on wreck site formation theory (Muckelroy, 1978; O’ Shea, 2002; Quinn, 2006; Quinn and Boland, 2010; Stewart, 1999; Ward et al., 1999) and an acceptance that physical processes dominate wreck site formation in the early stages (Quinn, 2006; Ward et al., 1999) suggest that a greater understanding of linked hydro- and sediment- dynamic processes at wreck sites is fundamental to site formation studies. The introduction of a ship to the seafloor leads to an increase in flow velocity and turbulence (Whitehouse, 1998), causing changes in the flow regime in its immediate environs (Figure 1), resulting in one or a combination of: flow contraction; the formation of a horseshoe vortex in front of the structure; the formation of lee-wake vortices behind the structure (sometimes accompanied by vortex shedding); turbulence; the occurrence of reflection and diffraction waves; wave breaking; and sediment liquefaction promoting material loss from the site (Sumer et al., 2001).

The horseshoe vortex is formed by the rotation of the incoming flow. Under the influence of the adverse pressure gradient produced by the structure, the boundary layer on the bed up-flow of the structure undergoes a three-dimensional separation, rolls up to form a swirling vortex around the structure and trails off down-flow (Sumer et al., 1997). The morphology of horseshoe vortices can be strongly distorted, resulting in complicated flow patterns. One such result is vortex shedding, where self-propelling, closed ring structures are formed and transported by the flow (Testik et al., 2005). Lee wake vortices are formed by the rotation in the boundary layer over the surface of the object. End effects (from the tips of the structure, in this case the bow and stern of a submerged vessel) play a dominant role in the flow pattern and strongly modify the structure of vortices (Testik et al., 2005). Lee wake vortices emanating from the surface of the structure are brought together in the vicinity of the structure due to flow convergence (Testik et al., 2005). Additionally, two counter-rotating vortices form a vortical region in the near wake on the lee side of the structure (Testik et al., 2005).

In turn, these processes increase local sediment transport and subsequently lead to scour (Sumer et al., 2001). Scouring subsequently results in the lowering of the seabed from some previously obtained equilibrium (or quasi-equilibrium) level, due to the flow velocity increase near the object, a resulting increase in the local Shields parameter (a non-dimensional number used to calculate the initiation of motion of sediment in a fluid flow), and subsequent divergences in the sediment transport regime (Voropayev et al., 2003). When scour occurs on fine-grained (silt or clay) seabeds, the eroded material is carried away from the wreck site in suspension, leaving a seafloor depression that may not be readily infilled by natural processes (Whitehouse et al., 2011b). Where scouring takes place in coarse-grained deposits (sand or gravel), it usually results in local deposition (often comprising the eroded material) in addition to scour. Scouring ultimately leads to wreck site instability and material loss.

**3. Material and methods**

3.1 Study site

In the western Irish Sea, on the south-eastern seaboard of Ireland, a series of coast-parallel north-south trending offshore sand banks are located in 20-30 m of water (Wheeler et al., 2001). The banks, in quasi-equilibrium with tidal and wave conditions, offer wave protection to the coast and have a strong control on tidal flow pathways (Wheeler et al., 2001). The Arklow Bank (Figure 2), orientated roughly north-south, is approximately 25 km long and 0.7 km wide between the 10 m contours. The seabed comprises sand, with gravel, shell, and/or cobbles in varying proportions. Strong currents result in the waters in this area being well-mixed, commonly having high levels of suspended matter. Tidal range in the area is approximately 2 m and surface currents exceed 1.5 m s-1 at times. Thick deposits of sand (> 20 m) are reported on the Arklow Bank and adjacent sandbanks (Wheeler et al., 2001) with sediment cores indicating the sub-surface on the Arklow Bank comprises ‘dense sand’ and ‘very dense sand’ to a minimum depth of 14m (Seacore, 2003).

The shipwreck at the centre of this investigation was discovered by Titan Environmental Surveys Ltd during acoustic surveys conducted as part of an environmental impact assessment in advance of the Arklow Bank Wind Park development in 2003. The intact wreck, located in 10-14 m of water (Figure 2) on the inshore flank of the Arklow Bank, rests on a homogeneous sand-substrate. Dive-truthing of the geophysical data confirmed that the unidentified wreck is of wooden construction, dating to the early 19th Century. Although the Arklow Bank wreck is of limited archaeological interest, the site represents an ideal opportunity to investigate the effectiveness of CFD modeling in understanding shipwreck site formation processes as it is one of the few sites with the combination of good quality high-resolution MBES data, with livebed processes in operation and available field measurements to calibrate a CFD model.

3.2 MBES bathymetric data

Subsequent to discovery, the wreck site was surveyed on 12th August 2003 using a *GeoAcoustics* GeoSwath system operating at 250kHz with a beamwidth of 1°, providing a theoretical vertical resolution of 0.0175m (Quinn, 2006; Quinn and Boland, 2010). The resultant MBES bathymetric data were processed to correct for tidal variation, using corrections derived from a tide gauge at Arklow, and a digital elevation model (DEM) of the wreck site was derived from these data at 0.25 m resolution in ESRI ArcGIS v10.1.

3.3 Computational fluid dynamic modeling

Simulations in this study were performed using the open source software *OpenFOAM* and its large time-step transient solver for incompressible flow, *PIMPLE*. Flow was calculated using Reynolds-Averaged Navier-Stokes (RANS) equations producing an average of fluid motion over time. Turbulence in the flow was modeled using the two-equation Re-Normalised Group (RNG) κ-ε turbulence model, due to its validation with comparisons of 3D measured flow in meandering rivers (Zhang and Shen, 2008) and complex sand dune topography (Smyth et al., 2013).

The computational domain simulated measured 153 m wide, 143 m long and 20 m in depth. The peak current recorded on the Arklow Bank during construction of the wind park was 2.0 m s-1 (Whitehouse et al., 2011a). Computational boundaries to the west and south were defined as inlets permitting flow to enter the domain at 1.5 m s-1 close to the bed and increasing logarithmically to 2.0 m s-1 at the water’s surface. Sediment samples indicate the surface sediment on the Arklow Bank is mainly medium sand (Panigrahi et al., 2009). Accordingly, the total roughness length (ks) of the seabed was set a uniform value of 0.0034 m based upon a grain size for medium sand of 0.5 mm, whereby ks ≈6.8D50 (Hey, 1979; Bray, 1982). The water surface was modeled using a fixed-lid approach analogous to Carney et al. (2006) modeling flows in a coarse-grained stream whilst the kinematic viscosity of the fluid simulated was set to 1.307 x 10-6 m2 s-1, characteristic of water at 10°C.

Simulations were run in parallel on 40 processors at the high performance computer facility ‘Colossus’ at Flinders University. Grid refinement tests were performed to ensure that simulated results were independent of mesh resolution. Three simulations were completed using a coarse (1.1 million cells), medium (2 million cells) and fine (3.5 million cells) mesh. Flow velocity was compared at 6,841 common points within the lowest 5 m of the computational domain and mean absolute percentage differences were calculated. A 0.32% difference was found between the coarse and medium meshes, and a difference of 0.17% between medium and fine meshes. The results in this paper are extracted from the fine mesh as the difference between the medium and fine results are minor, indicating no further refinement was required and it is assumed that the ‘fine’ mesh with highest resolution was the most accurate.

**4. Results**

4.1 Digital elevation model (DEM)

The Arklow Bank wreck is imaged as a 44 x 16.5 m structure in the MBES data, with a square stern section (Figure 2). The wreck is orientated NW-SE, with associated scour and depositional features extending NNE from the bow and stern, parallel to peak flow (Figure 2). Side-scan sonar data indicates that the largest of the scour features tapers out approximately 200 m from the wreck. The structure stands proud of the seabed by up to 2 m at midships, with the long axis of the wreck aligned approximately 60o to the dominant flow direction. The migration of a set of flow-perpendicular bedforms across the site indicates live-bed processes participate in development of the site (Quinn, 2006). The primary scour features imaged at the site emanate from the upstream (eastern) end of the vessel, with a maximum-recorded depth of 16.3 m, approximately 3 m below mean bed level. The bathymetric surface used in the *OpenFOAM* simulations was derived from the MBES data using a kriging interpolator at a resolution of 0.25 m.

4.2 CFD outputs

Figure 3 shows the 3-dimensional streamline pattern immediately above the bed successfully simulated in the CFD model. Flow is accelerated by 1.5 m s-1 over the wreck (from an ambient velocity of 2.0-2.5 m s-1), with peak values to the northeast of the wreck structure. Secondary flow in the lee of the wreck is slower (1.0 to 2.0 m s-1) than primary incident flow (2.0 to 2.5 ms-1) and forms well-defined corkscrew vortices in the lee of the central section of the wreck. Looser vortices developed to the south, become steered north with distance from the wreck. Both these zones of helical secondary flow coincide with deep zones of scouring. Streamlines are steered toward the scour hollow in the lee of the centre of the wreck due to the zone of low pressure that is developed there (Figure 4).

Along the southeastern section of the hull structure, isolated zones of low pressure (Figure 4) are caused by flow stagnation due to the abrupt change in bathymetry at this point. A distinct corridor of low pressure (-2.00 kg m-1 s-2) in the lee of the wreck coincides with the large scour pit.Pressure in the zone of scouring in the lee of the southern edge of wreck remains high as flow remains predominantly attached. However, a number of much looser corkscrew vortices are also generated.At the southern extreme of the wreck, flow becomes steered north into the scour and again forms some loose corkscrews.

Turbulent kinetic energy (TKE), the mean kinetic energy per unit mass associated with eddies in turbulent flow, is highest on the northeast edge of the hull structure (Figure 5).TKE is also high along the northeast axis of the scour pit, in the lee of the central section. These patches coincide with points where helical (corkscrew) flow comes close to the seabed (Figure 4). TKE amplification is noted across the entire wreck site, with a fourfold increase in TKE values from ambient values of 0.025 m2s-2 upstream to values in excess of 0.100 m2s-2 downstream of the structure.

The magnitude of shear stress calculated on the wreck site is illustrated in Figure 6, indicating low levels of shear stress in the central section of the hull and in the lee of the bow and stern sections. A zone of high shear stress is concentrated along the northeastern section of the hull structure, coincident with the highest points on the wreck. Low shear stress shadows are apparent along the steep slope in the lee of the hull and at the centre of the wreck in line with the scour pit. A linear zone of high shear stress is developed within the scour zone, where the helical flow impinges on the sea floor. Similar to the patterns noted in the TKE plot, shear stress amplification is noted across the site, with shear stress ranging from ambient values of 0.01 m2s-2 on the upstream side to 0.03 m2s-2 on the downstream side.

**5. Discussion**

Previous site formation studies attempting to characterize hydrodynamic flow at submerged shipwreck sites have relied on laboratory-based physical models (e.g. Saunders, 2005) or field instrumentation deployments (e.g. Dix et al., 2007). Lab-based flume experiments using scaled models, although very useful, are usually limited by scaling factors in an attempt to replicate the natural environment. Field-based experiments, using high-resolution acoustic doppler current profiler deployments, are expensive and logistically difficult. Here, we offer a relatively inexpensive, open-source, high-resolution and adaptable method to accurately characterize the 3-dimensional flow velocity field around a shipwreck site using CFD modeling and MBES data. Hydrodynamic flows simulated in the model correlate well with erosional and depositional signatures in the MBES data.

The results confirm that the presence of a shipwreck on the seafloor leads to an increase in flow velocity and turbulence, causing changes in the flow regime in its immediate environs. In this study, flow contraction, the formation of lee-wake vortices behind the structure (accompanied by vortex shedding) and turbulence are all simulated and quantified. Shear stress and TKE amplification three and four times greater than ambient values are recorded on the downstream side of the wreck site. As much of the wreck structure under consideration in this study is buried in sediment, higher values of shear stress and TKE amplification are likely at more exposed sites.

Primary model output in the form of streamline velocity models and secondary products derived from the modeling (including maps of TKE, pressure- and shear stress) are shown to provide deeper understanding of the hydrodynamic factors that influence site formation at fully submerged shipwreck sites. The results presented herein indicate that it is perhaps the secondary products derived from the modeling that are crucial in understanding the areas and components of wreck sites most at risk by natural forcing, and therefore those elements that should be prioritized when it comes to *in-situ* conservation. For example, areas of wreck sites identified as experiencing elevated or amplified TKE, pressure and/or shear stress are most under-threat from mechanical stress, and therefore might be targeted in the early stages of preservation and *in-situ* conservation. Relatedly, after protecting a site (using additional sediment, sandbags or geotextiles, see for example Manders et al., 2009), a repeat MBES survey could be conducted and a new CFD model could be run to test the effectiveness of conservation measures.

The practical and theoretical applications and potential of CFD modeling in the context of underwater archaeology are many and diverse. This study demonstrates the role that CFD modeling has to play in studies of site formation and conservation on a broad-scale. A natural extension of this methodology is to ‘seed’ the CFD model with individual artifacts or structural elements to investigate primary and secondary depositional contexts. Similarly, the methodology could be extended to submerged archaeological landscapes, in an attempt to hind-cast palaeo-oceanographic conditions at previous sea-levels, with a focus on understanding the exploitation of that landscape and to further investigate archaeological deposits and their preservation in the sedimentary record. On the theoretical front, CFD modeling could be used as a controlled environment to simulate the 3-dimensional flow patterns around shipwrecks at different angles of incidence with a view to understanding erosional and depositional patterns in the lee of these structures.

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**Figure captions**

Figure 1: Schematic model of the flow lines, vortices and scour patterns around a fully submerged shipwreck site in response to hydrodynamic forcing (modified from Quinn, 2006).

Figure 2: Location map and digital elevation model (DEM) of the Arklow Bank wreck site derived from the MBES survey data (Irish Grid reference system). Illumination is from the northwest.

Figure 3: 3-dimensional streamline pattern around the wreck site immediately above the bed as simulated in the CFD model.

Figure 4: Pressure map of the seafloor draped on the DEM.

Figure 5: Turbulent kinetic energy map of the seafloor draped on the DEM.

Figure 6: Shear stress map of the seafloor draped on the DEM.