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Waves and wrecks: A computational fluid dynamic study in an underwater archaeological site

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Abstract

The modification of waves by shipwrecks and the resulting scour play important roles in shipwreck site formation, and conservation of archaeological sites. The oscillatory flow induced by waves and its interaction with the hull structure at a historic shipwreck site was analyzed using a two phase 2D model based on the Reynolds averaged Navier-Stokes equations and shear stress transport (SST) k-Omega turbulence model, with inputs from field-based bathymetric survey. The relative importance

and seasonal variation in hydrodynamic processes were investigated (flow velocity increase, coherent structures and vortex shedding, turbulence and steady current induced by the non linearity of waves). Results demonstrate that frictional velocity and flow increase dominate morphological change in the low wave energy period (LEP), whereas turbulent shear stress and large coherent structures dominate scouring in the high wave energy period (HEP). Furthermore, flow acceleration around the hull structure and recirculation cells originated by wave non-linearities become more prominent in the HEP, modifying the trajectory of the shedding vortex and increasing its capacity to transport sediment. The results demonstrate, for the first time, that computational fluid dynamics is a valuable tool in assessing the wave structure interaction in full scale and realistic morphological conditions at complex shipwreck sites.

Keywords: Computational fluid dynamics; Multi-beam echo-sounder; Shipwreck; Site formation processes; Hydrodynamics; scouring

1 Introduction

In the last decades, advances in technology have led to the development, exploitation and exploration of the seabed resulting in the discovery of a considerable number of shipwrecks and other archaeological sites (Besrgstrand and Godfrey, 2007). Simultaneously, marine environmental conditions and their relationship to underwater cultural heritage (UCH) have provoked considerable interest due to the direct link to the status of underwater cultural heritage and the perspective of conservation *in situ* (Leino, 2011; Wheeler, 2002). In particular, physical processes have been proposed by various authors as dominant in early stages of site formation

(Quinn, 2006; Ward et al., 1999), and the coupling between water and sediment dynamics controlling the sediment budget is considered as fundamental in site formation studies (Smyth and Quinn, 2014).

Quantifying sediment budgets at wreck sites is important, as sediment offers physical stability to shipwrecks, and the deposition and erosion of sediment at sites modifies the geochemical characteristics which control chemical degradation and the biological activity influencing the decay of UCH materials (Ruuskanen et al., 2015; Ward, 1999).

Sediment budgets at shipwreck sites depend on the sediment availability and characteristics, the hydrodynamic regime, and its interaction with the shipwreck structure. Scour takes place when an obstacle modifies the flow pattern in its immediate neighbourhood causing an increase in local sediment transport. Given the importance of scour in the sediment budget around shipwrecks and in site formation and conservation studies, the scouring process has received increased attention from the scientific community in the last decade (e.g. Astley et al., 2016; Baeye et al., 2016; Fernández-Montblanc et al., 2016; Smyth and Quinn, 2014; Quinn, 2006; Quinn and Smyth, in press).

Thus, several research projects have focused on understanding shipwrecks under steady flow conditions, including sediment dynamics and associated scour pit formation. These studies used different data and methodologies, and can be subdivided by type into accretion-erosion models (Astley et al., 2016; Bates et al., 2011; Quinn and Boland, 2010), scaled physical models (Saunders, 2005) and computational fluid dynamics (CFD) models in combination with high resolution multibeam echosounder bathymetric data (Smyth and Quinn, 2014; Quinn and Smyth, in press).

76 However, the fate of shipwrecks dominated by oscillatory flow and
77 associated scouring has been considerably less studied. A real-world case
78 study of shipwreck scouring under shoaling waves based on side scan sonar
79 data is outlined in Quinn (2006). The burial-exposure of different artefacts
80 in an archaeological context is described in McNinch et al. (2006) using
81 numerical modelling, calibrated by sediment and hydrodynamic
82 observations. More recently, wave propagation and hydrodynamic modelling
83 in combination with time-lapse bathymetric surveys and hydrodynamic
84 measurements was used to characterize scour and seasonal
85 morphodynamic changes in an energetic shallow water shipwreck site where
86 part of the hull has been preserved (Fernandez-Montblanc et al., 2016).
87 Conversely, the scouring due to wave and obstacle interaction has been
88 widely studied in other scientific fields such as coastal engineering, with
89 applications to breakwaters (Sumer et al.; 2001, 2005, Young and Testik,
90 2009), pipelines and mines (Mattioli et al., 2013; Sumer, 1990; Voropayev,
91 et al., 2003), or offshore structures mounted on the seabed (Nielsen,
92 2012). As a result, scouring can be estimated through simple empirical
93 equations. However, those studies have been performed usually assessing
94 the flow interaction with relative simple geometries, as those are commonly
95 used in coastal and offshore engineering. The majority of these studies are
96 based on scaled physical models with inherent limitations. Therefore, due to
97 its importance in site formation and *in-situ* conservation of UCH, there is a
98 need to further investigate the oscillatory flow interaction with complex
99 geometrical structures (i.e. shipwrecks). It is important for these models to
100 incorporate real and complex morphological scenarios to reflect those found
101 in nature, and to use field data to calibrate and validate them.

In this context, CFD represents a reliable and cost-effective way of calculating the flow pattern around complex geometrical structures. Increasing computing power and resulting simulation efficiency allows the application of CFD to large domains representing complex three dimensional seabed structures, natural or man-made, where the scour and morphodynamic behaviour are associated with near-bed turbulent flow. This study focuses on the application of CFD to investigate the interaction between a historic shipwreck and wave-induced oscillatory flow, with the aim of assessing the relative importance of different mechanisms that originate and control scouring in these environments. CFD modelling is validated with field-based hydrodynamic data.

2 Theoretical background

An object placed on the seabed changes the flow pattern in the immediate vicinity. Changes may result in flow contraction, promoting streamline convergence and flow acceleration, vortex formation around the structure (with or without vortex shedding behind the structure), increased turbulence, and modification of wave characteristics (occurrence of reflection and diffraction or breaking). As a result, shear stress is increased on the seabed, promoting sediment transport around the object and leading to scour (Sumer and Fredsøe, 2002). The process continues until a new quasi-equilibrium state is reached, in which the increase in bed shear stress due to the presence of the structure is balanced as a direct consequence of depth increment and/or the loss of fine sediment in the scoured area. If the eroding seabed is composed of fined-grained (clay-silt) material, suspension

transport carries the sediment far away from the structure (Whitehouse et al., 2011b), but if the seabed is composed of coarse-grained (sand-gravel) sediment, the sediment is deposited near the structure (Smyth and Quinn, 2014).

Oscillatory flow adds time-dependence to the above phenomena. The wave boundary layer, horizontal and vertical velocity changes, turbulence, and the large coherent structures (LCS) formed around the object vary along a wave cycle. Studies on oscillatory flow around submerged breakwaters and horizontal cylinders on the seabed indicate that the flow pattern and scour are mainly controlled by the Keulegan-Carpenter (KC) number (Vorapayev, 2003):

$$KC = 2\pi a/D,$$

where D is the characteristic length of the object (i.e. diameter for a cylinder), $a = U_{mo}T/2\pi$ is the amplitude of the free stream motion, and T is the wave period. Sumer (1991) analysed the vortex dynamics around a horizontal cylinder on the wall at high Reynolds (Re) numbers (mostly at $Re \sim 10^5$):

$$Re = U_{mo} D / \nu,$$

where ν is the kinematic viscosity of water and U_{mo} the maximum value of the free stream velocity. Sumer (1991) found that for small values of KC no flow separation occurs. However, increasing KC to 4 promotes flow separation and symmetrical vortex formation upwave and downwave of the cylinder, and for $4 > KC > 7$, asymmetry in the formation and motion of the vortices is introduced into the system. At $KC > 7$, vortex shedding occurs. Similar results were found in a physical experiment with sinusoidal forcing

at $Re=300-500$, carried out by Testik et al. (2005). They found horseshoe vortices of opposite rotation formed periodically on both sides of the cylinder. For $KC = 8.4$, the vortex formed on each side washed over the cylinder in the following half cycle and formed a vortex pair with the initial one (with the opposite vorticity sign) and shed away periodically as a paired structure. In the case of physical experiments forced with waves, instead of sinusoidal forcing, no shedding of the paired structure was found in experiments with $7 > KC > 23$ and Re ranging from $3 \cdot 10^3$ to $2.6 \cdot 10^4$ (Mattioli et al., 2013). Investigations on scour around vertical piles exposed to waves have shown the increment in bed shear stress due to horseshoe vortex development, especially in the turbulent bottom boundary layer (Sumer et al., 1997). Although the onset of scour is related to the lee-wake vortex and vortex shedding, flow sweeps the sediment into the core and the shedding vortex carries the sediment away from the pile as it is advected downstream (Sumer et al., 1993). A more recent scour study around a half-buried sphere under steady flow showed that the increase in turbulence beneath the horseshoe vortex enhances bed shear stress amplification and has a notable contribution to the scour (Dixen, 2013).

In addition, the steady current generated by nonlinear effects induced by waves results in a secondary flow in the form of steady streaming and undertow. The steady streaming flow generated by wave propagation over the structure is the result of the non-uniform oscillatory action in presence of the structure. Its relevance in the scouring process has been revealed for a vertical pile and oscillatory flow (Sumer and Fredsoe, 2001) and in a submerged breakwater (Sumer et al., 2005). Steady streaming $O(10^{-1} \text{ m}\cdot\text{s}^{-1})$ transports and redistributes the sediment that the oscillatory flow $O(10^0$

m·s⁻¹) brings into suspension. Also the non uniformity in vertical distribution of spanwise velocity generates a steady flow known as undertow; a gravity driven current with the maximum located near the seabed and oriented seaward. Undertow is induced by two mechanisms: (1) rollers that carry water shoreward in the upper water column under breaking conditions, and (2) eulerian drift in the case of non-breaking conditions.

Finally, various authors have noted the increment in sediment transport produced by turbulence, whether internally generated turbulence (Nelson, 1995), or externally generated due to flow structure-interaction (Sumer, 2003). The turbulence makes the transport of momentum more effective (as well as mass and energy) between fluid layers (Dixen, 2013) with a consequent increment in sediment transport. In addition, turbulence promotes the settling delay (Murray, 1970), which favours the sediment transport in suspension and increases scour.

All near wall processes and characteristics, such as the boundary layer structure, thickness, the point of vortex and flow separation, friction velocity and turbulence are conditioned by the roughness of the seabed (sand-grain and bed form roughness) and the roughness characteristics of the of the obstacle.

3 Methodology

3.1 Study site

Fougueux, a 74-gun Temeraire-class French ship-of-the-line, took part in the Battle of Trafalgar in October 1805, where the British fleet defeated the combined French-Spanish fleet off the coast of Cádiz. *Fougueux* was

203 wrecked after the battle, when she was driven onto a rocky shoal. The
204 wreck site is characterized by low to moderate wave energy conditions, with
205 the exception of high the energetic winter storms from WSW. Partial burial
206 in sediment has resulted in the preservation of a considerable portion of the
207 wooden hull structure ($15 \times 7 \text{ m}^2$) along with 31 cannons and a large anchor
208 (Rodríguez Mariscal et al., 2010).

209 The *Fougueux* wreck site is located on the south-western seashore of the
210 Iberian Peninsula (Gulf of Cádiz), in a shoal seaward of the Sancti Petri sand
211 spit (Figure 1a). The seafloor around the wreck is gently sloping from 5-10
212 m depth (Figure 1a), and comprises unconsolidated well-sorted fine quartz
213 sand ($D_{50} = 1.8 \cdot 10^{-4} \text{ m}$) with bedrock areas where Plio-quadernary shelly
214 conglomerate crops out (Gracia et al., 2008). The scattered wreck remains
215 are located in an energetic shallow-water environment, where wave
216 oscillatory flow promotes scouring resulting in inshore pits (maximum depth
217 of 0.77 m) scoured deeper than offshore pits (0.35 m depth) (Figure 1a).
218 Seasonal changes are observed, showing accretion during a low wave-
219 energy period (LEP) from May to September and net erosion around the hull
220 structure during a high-energy period (HEP) from November to April
221 (Fernández-Montblanc et al., 2016). At the deepest point at the centre of
222 the wreck site ($x \sim 192$) minor seasonal variations were found (Figure 1a
223 and Figure 1c). The mean wave height at the site is 0.67 m during LEP and
224 1.18 m in HEP, whereas the maximum wave height is 4 m, and is limited by
225 local depth. Mean bottom orbital velocity fluctuates from $0.30 \text{ m} \cdot \text{s}^{-1}$ during
226 LEP to $0.68 \text{ m} \cdot \text{s}^{-1}$ during HEP. The maximum value of near-bed wave orbital
227 velocity, calculated by a wave propagation model, rises to $2 \text{ m} \cdot \text{s}^{-1}$ during
228 winter storms. The area is meso-tidal (mean tidal spring range of 2.96 m),

with a dominant semidiurnal tidal variability. Peak currents are orientated NNW and SSE at flood and ebb tide conditions respectively, with mean values 0.15-0.25 m·s⁻¹. Velocities above this value, directed NNW, correspond to a SE wind. In contrast, current velocities greater than 0.25 m·s⁻¹, directed SSE, are related to wind drift (Fernández-Montblanc et al., 2016).

3.2 Field data

Bathymetric data

In order to collect bathymetric data corresponding to the low energy wave period (LEP; summer conditions) and high energy wave period (HEP; winter conditions), two successive surveys were conducted. The LEP survey was performed on 11.09.2013 using an Ohmex Sonarmite v3.0 singlebeam echosounder operating at 235 kHz (sample rate 1 Hz and theoretical vertical resolution 0.05 m). A HEP survey was conducted on 23.11.2013, using a Reson Seabat 8124 multibeam echosounder operating at 200 kHz (1.5° beam width, 0.01 m vertical resolution and 39.89 Hz sample rate). In both cases, positional data were acquired using an RTK-GPS Leica 1200, from which tidal and wave corrections were taken. Two digital elevation models were derived from the LEP and HEP surveys, and two 250 m long bathymetric profiles (AA') were extracted and used as a bottom boundary in the CFD study (Figure 1b, Figure 1c).

Figure 1. (a) Location map of the study site in the Gulf of Cadiz and detail of the *Fougueux* site from the multibeam bathymetric data. (b) Location of bathymetric profile in multibeam bathymetry. (c) Detail of bathymetric profiles corresponding to LEP and HEP at the *Fougueux* site.

3.3 CFD study

The CFD modelling of the *Fougueux* site was performed using OpenFOAM ® software, an open source toolbox that allows users to solve problems of turbulence and complex fluid flows using finite volume discretization. The InterFoam solver was employed in this study, solving the three-dimensional Reynolds averaged Navier-Stokes equations for two incompressible phases (sea-water and air in our case represents a free surface flow solver) using a finite volume discretization and the volume of fluid method. Flow turbulence is represented by a two-equation SST K-Omega model (Menter, 1994). This model combines the use of a k-epsilon turbulence model in the free flow regions and a k-omega turbulence model inside the boundary layer, avoiding the problem of the high sensitivity to the inlet boundary condition of the k-omega model (Bozorgnia et al., 2014). IHFoam was used to implement the boundary conditions for wave generation and absorption, reducing the

problem of reflexion in the boundaries without an extension of the domain (Higuera et al., 2013).

Figure 2. Computational domain used in numerical simulation along with boundary conditions (BC).

The numerical experiments were carried out in a full scale 2D computational domain, measuring 350.0 x 14.5 m² and the reference system was set as illustrated Figure 2. The reference system was placed at the furthest point offshore (A) (Figure 1b). The x axis is positive in the wave propagation direction (AA') Figure (1b). The z axis for the domain was located at the deepest point furthest offshore, being positive upward (Figure 1c). The model domain was subdivided into regions with different resolutions to reduce the number of cells and computational time (Figure 2). Region R4, where wave propagation takes place, has cell sizes of $\Delta x = 0.10$ m and $\Delta z = 0.05$ m. Region R1 and R3 have cell sizes of $\Delta x = 0.10$ m and Δz varying from 0.02 m at bottom to 0.10 m at top. Region R2, where the wreck-wave interaction is focused, comprises an unstructured prismatic mesh of 0.005 m cell size, allowing the mesh to adapt to the complex geometry of the wreck. The smooth changes in mesh resolution in the transition areas (R1-R2 and R2-R3) reduces the drastic changes in the near surface boundary flow. The friction coefficient at the seafloor was set as uniform in the whole domain as a rough wall function dependent on Nikuradse roughness length (k_s). A grain size value of $D_{50} = 1.8 \cdot 10^{-4}$ m from measurement on five

sediment samples collected at the shipwreck site was used to calculate a k_s
 $= 4.5 \cdot 10^{-4} \text{m}$ using the relation proposed by Soulsby (1997) for a flat bed
($k_s \sim 2.5 \cdot D_{50}$). Water density was set equal to 1025 kgm^{-3} corresponding to
 20°C and 35 PSU salinity. Air density was taken as 1 kgm^{-3} . The surface
tension in the air-water system was given a value of 0.07 kgs^{-2} . Numerical
simulations were run in parallel on a high performance computing facility
using 32 processors (2.6 GHz), of 2 CPUs subdividing the domain into 32
subdomains. During the simulation, a variable time step was specified with
a Courant number lower than 0.5 ensuring numerical stability.

Table 1 outlines the numerical experiments conducted in the study. Five
different wave conditions typical of the *Fougueux* site were simulated using
the two bathymetric settings (LEP and HEP). In the first pair of simulations,
a case representing mean storm conditions in the area (E1_HEP and
E1_LEP) was run. The second pair represents the response to a fading
storm (E2_HEP and E2_LEP). Swell wave conditions were simulated for
experiment 3 (E3_HEP, E3_LEP), and wave breaking conditions for
experiment 4 (E4_HEP, E4_LEP). Finally, a simulation of offshore wave
breaking was conducted (E5_HEP, E5_LEP).

Assuming that wave propagation takes place along the x axis which is
perpendicular to the shoreline (Figure 1a and Figure 1b), the set of wave
parameters (wave phase, wave height and wave periods) were used as
inputs at the inflow boundary location (Inlet BC) (Figure 2). IHFoam was
used to realistically generate waves at Inlet BC according to different wave
theories (see Higuera et al. (2013) for further details). In this set of
numerical experiments E1_LEP and E1_HEP were conducted using Stokes II

theory, and cnoidal theory was used for the rest of the experiments,
according to the range proposed by Le Méhauté (1976).

Wave characteristics					Bathymetry		Water level
Name	Wave type	H (m)	T (s)	Wave Conditions	HEP	LEP	Depth(m) on hull Remains(x=195m)
E1_LEP	Regular	1.5	6	Mean Storm conditions		X	5.52
E1_HEP	Regular	1.5	6	Mean storm conditions	X		5.52
E2_LEP	Regular	3.0	9	Fading storm		X	6.84
E2_HEP	Regular	3.0	9	Fading storm	X		6.84
E3_LEP	Regular	2.4	15	Swell wave conditions		X	5.52
E3_HEP	Regular	2.4	15	Swell wave conditions	X		5.52
E4_LEP	Regular	3.5	15	Wave breaking		X	5.52
E4_HEP	Regular	3.5	15	Wave breaking	X		5.52
E5_LEP	Regular	4.0	9	Offshore wave breaking		X	5.52
E5_HEP	Regular	4.0	9	Offshore wave breaking	X		5.52

Table 1. Wave characteristics, bathymetric conditions and water depth used in the numerical experiments.

3.4 Data analysis

The modelled time series of the horizontal and vertical velocity components in all grid nodes were processed to extract the mean and fluctuating terms from instantaneous data, according to

$$\mathbf{u}(x, z, t) = \bar{\mathbf{u}}(x, z, t) + \mathbf{u}'(x, z, t); \quad (1)$$

where $\mathbf{u}$ is the instantaneous velocity, $\bar{\mathbf{u}}$ is the mean (steady) component and $\mathbf{u}'$ is the fluctuating (turbulent) component of the instantaneous velocity. Several methods can be applied to separate the mean and turbulent components from an instantaneous velocity (Longo, 2002). These methods include high-pass filtering (Sawamoto et al., 1982), phase averaging (Ting and Kirby, 1996), moving phase averaging (Nadaoka, 1989; Standy and Feng, 2005), ensemble averaging (Chang and Liu, 1999) and differencing method (Scott et al., 2005). In the commonly used phase and

moving phase methods, the wave breaking variation from wave to wave can affect the accuracy of averaging results (Chang and Liu, 1999). Therefore, and considering the high repeatability of the flow field, the ensemble averaging method was applied. To that end the time series of instantaneous velocity ($\mathbf{u}$) was divided into wave cycles by applying the zero up crossing method from the free surface elevation signal, where each wave corresponds to the record between two successive zero up crossings, that is when the wave-perturbed sea surface moves upward crossing the zero reference level. Then the ensemble average was computed fixing the time ($\hat{t}$) and arithmetically averaging all the N wave cycles simulated (Eq. 2). Subsequently, the random residual turbulent component of the flow was calculated by subtracting the ensemble phase velocity to the instantaneous velocity (Eq.3). Thus, for regular waves the kinematics could be split into periodic component (mean oscillatory flow) with repetitive vortical structures (LCS), and those related to the turbulent motion.

$$\langle \mathbf{u}(x, z, \hat{t})_N \rangle = \frac{1}{N} \sum_{n=1}^N \mathbf{u}_n(x, z, \hat{t}); \quad (2)$$

$$\mathbf{u}'(x, z, \hat{t}) = \mathbf{u}(x, z, \hat{t}) - \langle \mathbf{u}(x, z, \hat{t})_N \rangle; \quad (3)$$

In order to evaluate the number of wave cycles required to construct the averaged ensemble, convergence tests were performed following the methodological approach in Melville et al. (2002) for the square mean velocity and the turbulent kinetic energy. The tests included all morphological scenarios and wave conditions, and demonstrated that 10 wave cycles are enough to guarantee proper separation of steady and turbulent components.

Oscillatory flow characterization.

The mean flow was characterized through the streamwise variation of the horizontal velocity profiles and the bottom boundary layer thickness (δ), defined as the distance from the bottom to the height of maximum horizontal velocity $\langle U_{mo} \rangle$ at the wave phase 90° (Jensen et al., 1989). As well as the oscillatory Reynolds number defined as $Re = aU_{mo} / \nu$, where $\langle U_{mo} \rangle$ the maximum value of the free stream velocity, ν the kinematic viscosity (Jensen et al., 1989), $a = U_{mo}T/2\pi$ is the amplitude of the free stream motion where T is the wave period.

Large coherent structures

LCS are defined as connected, large-scale turbulent fluid parcels with phase-correlated vorticity over their spatial extent. These are a characteristic feature of turbulent shear flows, and are responsible for the large-scale transport of mass, heat and momentum (Hussain, 1983). Although several mechanisms can induce LCS, we are interested in the horseshoe vortex, the lee-wake vortex, and vortex shedding, which are strongly related to the presence of an obstacle in a flow. Vortex dynamics contribute to the scouring process since bed shear increases under the vortexing.

The LCS can be separated from the background flow field through the use of an approximated criterion based on the Okubo-Weiss parameter W:

$$W = S_n^2 + S_s^2 - \omega^2 \quad (6), \quad S_n = d\langle u \rangle / dx - d\langle w \rangle / dz; \quad (7)$$

$$S_s = d\langle w \rangle / dx + d\langle wu \rangle / dz \quad (8), \quad \omega = d\langle w \rangle / dx - d\langle u \rangle / dz; \quad (9)$$

where S_n is the normal strain, S_s is the shear strain, ω is the vorticity, $\langle u \rangle$ is the ensemble averaged horizontal velocity, and $\langle w \rangle$ is the ensemble averaged vertical velocity.

The velocity field can be partitioned into three regions according to the magnitude of this criterion. Rotation dominates regions with $W < -W_0$, where the vortices are located. Intermediate regions are characterized by small positive and negative values of W ($|W| \leq W_0$) where the vorticity and strain rate are balanced. The strain dominated regions, with $W > W_0$, are located outside the vortices. The threshold value is $W_0 = 0.2 \sigma_w$, where σ_w is the standard deviation of W in the analyzed domain (Pasquero et al., 2001). The application of this criterion depicts the general structure of the vortex, with an eddy core in a vorticity-dominated inner region, and a circulation cell in the strain-dominated outer region (Elhmaïdi et al., 1993). The core edge is identified by the closed lines with $W=0$. The W parameter sign for the extraction of eddy cores has been successfully employed in complex fluid flows (Jeong and Hussain, 1995), oceanography (Isern-Fontanet, 2004) and oscillatory flow analysis (Mattioli et al., 2013).

The values of the dimensionless vorticity (ω^* ; computed as $\omega^* = \omega T$) and dimensionless Okubo-Weiss parameter (W^* ; computed as $W^* = W T^2$) are calculated from the ensemble averaged velocities.

Turbulence

The streamwise variation in the vertical distribution of Reynolds stresses ($-\rho \overline{u'w'}$) was computed under different wave conditions (shoaling progressive waves and breaking waves). The results are analysed with streamwise distribution of bed shear stress and mean flow characteristics.

Steady current generated by nonlinear effects induced by waves

(SCw): Undertow and steady streaming

The steady current, generated by nonlinear effects induced by waves, includes steady streaming and undertow. This wave-induced steady current is estimated by averaging the time series of velocity components in each grid cell over 10 wave periods after the steady state was reached in each simulation.

Bed shear stress

Bed shear stress and friction velocity are fundamental variables in sediment transport and scour investigations. Several criteria are employed to determine the initiation of motion, among them the Shields threshold parameter (Shields, 1936) and the so-called wave mobility number (Nielsen, 1992), which can be used to calculate the critical bed shear stress as a function of sediment characteristics. Analysis of spatial variation of bed shear stress, and the mechanisms involved in its increment around the wreck, was conducted. Bed shear stress for the wave conditions and bathymetric profiles was calculated as $\tau = \rho \nu du/dz$, where dz is the size of the first grid cell ($\sim 0.005\text{m}$).

The threshold Shields parameter was calculated according to Soulsby (1997).

$$\theta_{cr} = \frac{0.3}{1+1.2D_*} + 0.055[1 - \exp(-0.02D_*)]; \quad D_* = d \left[\frac{g(\frac{\rho_s}{\rho} - 1)}{\nu^2} \right]^{1/3}; (10)$$

where D_* is the dimensionless grain size, d is the grain diameter, ν is the kinematic viscosity and ρ_s is the sediment grain density assumed as quartz density.

431 The critical bed shear stress follows from the definition of the Shields
432 parameter $\tau_{cr} = dg(\rho_s - \rho)\theta_{cr}$ and is modified for a sloping seabed according
433 to the expressions for downslope flow $\tau_c = \tau_{cr}[\sin(\phi_i - \beta) / \sin \phi_i]$ and upslope
434 flow $\tau_c = \tau_{cr}[\sin(\phi_i + \beta) / \sin \phi_i]$, where β is the bed slope and ϕ_i the angle of
435 repose of the sediment ($\phi_i = 32^\circ$ according to Soulsby (1997)).

436 **4 Results**

437 **4.2 Oscillatory flow characterization**

438 Figure 3 depicts the vertical distribution of horizontal velocity from the
439 numerical experiment conducted using LEP bathymetry. Velocity profiles
440 correspond to different wave phases as a function of t^* , being $t^* = t/T$. Near
441 bottom velocities around the wreck are increased in the first few
442 centimetres above the seabed. The wreck remains act as a splitter, where
443 the velocity amplification produces fluid separation. As the wave height and
444 period increases, flow velocity increases (Figure 3a and Figure 3d). The
445 difference between the upwave ($x=191$) and downwave ($x=198$ m) velocity
446 profiles are notable. The depth reduction at the offshore ($x<190$) sediment
447 accumulation increases near bottom orbital velocity, whereas inshore it was
448 reduced ($x<200$ m). The differences between upwave and downwave areas
449 become more evident with the increase in wave height and period. Wave
450 asymmetry increases as function of H and T , especially for larger periods
451 (Figure 3b and Figure 3c). The unperturbed horizontal velocity profile was
452 altered in the nearness of the shipwreck ($x=190$ - 200 m). It is observed
453 upwave and downwave of the wreck (see for example Figure 3b at $t^* = 6/9$
454 and $7/9$ and downwave ($x=198$) at $t^*=2/9$ and $t^*=4/9$).

455

456 Figure 3. Vertical distribution of horizontal velocity at different streamwise locations
 457 for LEP bathymetry. Information relative to the wave phase variation is represented
 458 as a function of the t^* ratio for the different line colours and line styles. The grey
 459 colour marks the location of the hull remains.

460 Figure 4 shows the vertical distribution of horizontal velocity for the
 461 numerical experiment conducted with the HEP bathymetry. The perturbed

462 velocity profiles extend further than in the case of LEP ($x=184\text{m}$ and
463 $x=205\text{m}$), especially downwave of the wreck. A relative increase in
464 maximum near bed velocity is noted with respect to LEP conditions($x=191\text{m}$
465 and $x=194.5\text{ m}$) (Figure 4a to Figure 4d). Wave height increase and longer
466 periods expand this phenomenon up to the toe of the wreck ($x=198$)
467 (Figure 4d). Despite of depth increase, the inshore scour pit does not
468 produce a notable reduction of near bottom velocity ($x=201.5$). HEP
469 upwave and downwave dissimilarities are larger than under LEP conditions,
470 with the exception of the offshore wave breaking (Figure 4e). Amplification
471 of wave asymmetry with the increased H and T is larger than with LEP at
472 the hull remains (see for example Figure 4b and Figure 4c). The shape of
473 the velocity profiles is markedly modified at the toe of wreck ($x=198\text{m}$)
474 (Figure 4b ($t^*=4/9$ to $t^*=7/9$)), and at the deepest scour pit ($x=201.5$)
475 (Figure 4b ($t^*=1/9, 2/9, 7/9, 8/9, 9/9$)).

476

477 Figure 4. Vertical distribution of horizontal velocity at different streamwise locations
 478 for HEP bathymetry. Information relative to the wave phase variation is
 479 represented as a function of the t^* ratio for the different line colours and line styles.

480 Figure 5 shows the wave Reynolds number (Re) (colour scaled) and
481 boundary layer thickness (δ) (black line), under LEP (left panel) and HEP
482 (right panel) conditions. The LEP simulations are dominated by fully
483 turbulent flow, with the exception of the transitional regime observed in
484 E1_LEP (Figure 5a). The wave Reynolds number follows a similar spatial
485 variation in all LEP experiments; amplification over the top of the wreck
486 ($x=194.5$) and at the offshore sand accumulation (Figure 5b, Figure 5d).
487 The boundary layer thickness increases from 3.5 cm in E1_LEP (Figure 5a)
488 to nearly 7 cm in E4_LEP (Figure 5d). Two peaks are identified at the wreck
489 ($x=192.4$ m) and at the toe of wreck remains ($x=197$ m). In addition, in all
490 experiments δ increases over the wreck, reaching a maximum between 5
491 cm (Figure 5a) and 20 cm (Figure 5d) at $x\sim 196$ m, which is probably
492 associated with the flow separation point. In the E3_LEP simulation (Figure
493 5c), a maximum is observed upwave of the wreck. In E5_LEP a progressive
494 increase of δ in the downwave region.

495 The HEP simulations (right panels) also show the predominance of turbulent
496 flow. However, laminar flow at the wreck is observed in E1_HEP (Figure 5f),
497 and a transitional regime in the inshore scour pits and in the offshore scour
498 pits in E2_HEP (Figure 5g). Likewise, a transitional regime was observed at
499 the centre of the wreck site and downwave of the wreck ($x\sim 210$) in
500 E5_HEP. The Re increases over the wreck and in the offshore scour crest,
501 decreasing at the inshore and offshore scour pits. The boundary layer
502 thickness shows values slightly higher than those found for LEP experiments
503 and new peaks associated with the offshore scour crest feature ($x\sim 185$).
504 However, the larger differences appear downwave of the wreck, at the
505 deepest area of the inshore scour pits ($x\sim 200$) and especially beyond the

506 inshore scour pit, where peaks (15 cm-30 cm) are noted (Figure 5f to
507 Figure 5j).

508
509 Figure 5. Wave Reynolds number (Re) colour scale stamped on bathymetry profile
510 (depth left axis) and boundary layer thickness (δ) black line (right axis). Left panel
511 shows numerical experiments for LEP conditions. Right panel shows numerical
512 experiment for HEP conditions. The yellow overlay indicates laminar regime
513 ($Re < 1.5 \cdot 10^5$), the grey overlay marks a transitional regime ($1.5 \cdot 10^5 < Re < 10^6$), and
514 no colour overlay indicate fully turbulent flow ($Re > 10^6$).

515 4.3 Large coherent structures

516 The evolution during the wave phase (as a function of $t^* = t/T$) of
517 dimensionless vorticity (ω^*) is shown in the left panels, and the
518 corresponding values of the dimensionless Okubo-Weiss parameter (W^*) are
519 shown in the right panels in Figures 6-10. In the case of ω^* , the cold colour
520 represents negative vorticity and warm colour represents positive vorticity.
521 In the case of W^* , the red colour indicates strain dominated areas, the blue
522 colour shows areas dominated by vorticity, and white indicates areas
523 characterized by small positive and negative values of W ($|W| \leq W_0$) where
524 the vorticity and strain rate are balanced. Vectors located at position ($x=1$,
525 $Z=195$) in the right panels show the sequence of horizontal velocity

526 registered at 4 m depth at $x=194.5$. It should be noted that variable colour
 527 scales are used to highlight the different LCS.

528

529 Figure 6. Temporal sequence of dimensionless vorticity (left) and the dimensionless
 530 Okubo-Weiss parameter (right) for a mean wave cycle in the E1_HEP experiment.

531 Vectors show the horizontal velocity at 4 m depth at $x=194.5$.

532 The E1_LEP simulation (not illustrated) does not present relevant vortical
 533 structures. On the contrary, in E1_HEP (Figure 6), a vortex K located at the
 534 inshore scour-crest system is flipped over the inshore scour crest ($t^*=2/3$)
 535 moving shoreward during positive flow acceleration. At the leeside of the
 536 inshore scour crest a negative vorticity structure (L) is generated at
 537 ($t^*=5/6$) flipping over the scour crest during the streamwise negative
 538 velocity phase ($t^*=6/6$). A permanent positive vorticity structure (RC^+) is
 539 located downwave and RC^- is found at the inshore scour pits and is present
 540 during all wave phases.

541 In simulation E2_LEP (Figure 7) a counterclockwise rotation vortex (positive
 542 vorticity) originates upwave and flips over the wreck ($t^*=2/6$) to reach the
 543 toe of hull remains at $t^*=4/9$. On the offshore side, a small K' vortex ($\omega^* >$

0) formed above the sediment accumulation moves towards the wreck ($t^*=$
 $2/9 - 5/9$) with shoreward flow and in the opposite direction ($t^*=6/9-8/9$).
 Another small vortex L' ($\omega^* < 0$) produced upwave of the wreck ($t^*=2/9$)
 moves around the hull ($t^*=5/9 - 9/9$). A small eddy L with negative vorticity
 generated ($t^*=2/9$) at the toe of the wreck is dragged shoreward during the
 positive horizontal velocity phase ($t^*=4/9-5/9$). In addition, the location of
 a larger counter-clockwise rotation structure (RC^+) oscillates upwave-
 downwave with the horizontal velocity throughout the whole wave cycle.

Figure 7. Temporal sequence of dimensionless vorticity (left) and the dimensionless
 Okubo-Weiss parameter (right) for a mean wave cycle in the E2_LEP experiment.
 Vectors show the variation of horizontal velocity at 4 m depth at $x=194.5$.

556 The results corresponding to the simulation E2_HEP are shown in Figure 8.
557 An eddy with positive vorticity K' generated in the previous wave cycle over
558 the wreck ($x=193$) is washed over the hull remains when the wave
559 propagates and it reaches the toe of the wreck ($t^*=4/9-5/9$) (right panels
560 Figure 8). Subsequently, during the negative horizontal velocity phase, K' is
561 carried seawards over the wreck from $t^* = 5/9$ to $t^* = 9/9$, similar to
562 E2_LEP. The flow acceleration produces elongation of the vortex in the
563 horizontal direction.

564 At the inshore scour pit, a larger K vortex with counterclockwise rotation is
565 observed at $t^*=1/9$, along with the vortex (K_0) developed during the
566 previous wave cycle. K is generated by seaward flow($t^*=6/9$). It flips over
567 the inshore scour crest during a positive horizontal velocity phase, and
568 forms a paired vortex with a small clockwise vortex (L) formed at the top of
569 scour crest ($t^*=2/9$). They subsequently shed, moving seaward ($t^*=2/9-$
570 $t^*=5/9$) as is shown by the vorticity field. At the moment of maximum
571 positive velocity ($t^*=3/9$), after the flow acceleration phase, a new
572 clockwise vortex (M) arises at the lee side of the scour crest ($x=202.5$). The
573 M vortex initially forms a vortex pair with K_2 and it is washed seaward as far
574 as the toe of the wreck. At the offshore scour pit, a small vortex K'' ($\omega^* > 0$)
575 is observed trapped between $x=186$ and $x=188$.

576

577 Figure 8. Temporal sequence of dimensionless vorticity (left) and the dimensionless
 578 Okubo-Weiss parameter (right) for a mean wave cycle in the E2_HEP experiment.
 579 Vector show the variation of horizontal velocity at 4 m depth at $x=194.5$

580 The vortex dynamics corresponding to simulation E3_LEP (not shown) is
 581 similar to E2_LEP without the development of the RC⁺ and L.

582 In the E3_HEP (Figure 9) vortex dynamics is similar to that of E2_HEP at
 583 the inshore scour-crest. However, unlike E2_HEP, the M vortex crosses the
 584 inshore scour pits detached from the seabed, and rises when it reaches the
 585 wreck. Subsequently, at the beginning of the wave cycle ($t^*=1/15$), M₀ (the
 586 vortex M in the previous wave cycle) is transported shoreward (left panel at
 587 $t^*=7/15$, and right panel at $t^*=8/15$). On the other hand, it should be

588 noted that the large L' vortex ($\omega^* < 0$) generated downwave of the wreck
589 during the positive horizontal velocity phase, flips over the wreck ($t^*=6/15-$
590 $14/15$). Also, a L'' vortex (negative vorticity) located upwave of hull remains
591 originates at the the wreck site ($x=192.7\text{m}$) at $t^*=4/15$ and is transported
592 by the mean flow seaward to the offshore scour crest ($t^*=5/15-5/15$).

593 At the offshore scour-crest system, the K'' vortex is identified only at
594 $t^*=1/15-2/15$ at the leeside of scour-crest. Likewise, a vortex L''' is also
595 captured when it flips over the scour-crest ($t^*=7/15-12/15$).

596

597 Figure 9. Temporal sequence of dimensionless vorticity (left) and the dimensionless

598 Okubo-Weiss parameter (right) for a mean wave cycle in the E3_HEP experiment.

599 Vector show the variation of horizontal velocity at 4 m depth at x=194.5

600 E4_LEP vorticity pattern resembles that of E3_LEP, although some
601 differences appear. The eddy with counterclockwise rotation at the toe of
602 the wreck is horizontally elongated, and is eventually split into two vortices
603 ($t^*=6/15$) by the mean flow. Additionally, there is an increase in size in the
604 clockwise vortex at the centre of the wreck site ($t^*=10/15$). The L'' vortex
605 generated at the centre of the wreck site during the deceleration phase of
606 shoreward flow is strained over the sediment accumulation ($x=185$) during
607 the seaward flow phase.

608 The system of coherent structures developed in simulation E4_HEP (Figure
609 10) shows higher complexity than in the other cases. At the inshore scour-
610 crest system, the process of vortex formation and shedding is similar to the
611 E3_HEP experiment. A larger K-type vortex of 1.2 m diameter is located at
612 the inshore scour mark, and an M vortex is generated after the maximum
613 positive velocity downwave of scour crest. In this case, an L and K vortex
614 pair emerge ($t^*=5/15$) at $x\sim 208$. Additionally, a system of small vortices is
615 present at $x=208-210$.

616 In the inshore scour pits the K vortex ($t^*=7/15$) is also divided generating a
617 K_2 vortex. The negative vorticity eddy M created downwave of the inshore
618 scour ridge ($x=202$) at $t^*=3/15$, is larger in size (1.10 m diameter) and it
619 follows a seaward trajectory detached from the seabed.

620 At the wreck, the vortex formation process is better developed than in
621 previous simulation and is accompanied by a new clockwise eddy N
622 ($t^*=7/15-9/15$). The L' vortex splits into smaller vortices as the seaward
623 flow washes over the hull structure ($t^*=7/15-9/15$). Likewise, the L'' vortex
624 formed in the centre of the wreck site divides into smaller eddies.

625 At the offshore scour crest a similar process takes place, where vortex L'''
626 flips over the offshore crest and divides into smaller structures during the
627 negative velocity phase ($t^*=10/15$).

628

629 Figure 10. Temporal sequence of dimensionless vorticity (left) and the
 630 dimensionless Okubo-Weiss parameter (right) for a mean wave cycle in the E4_HEP

631 experiment. Vector show the variation of horizontal velocity at 4 m depth at
632 $x=194.5$

633 Simulation E5_LEP (not shown) is similar to E2_LEP. In E5_HEP, vortices
634 are only identified in the inshore and offshore scour-crest systems. At the
635 inshore, the two vortex pairs upwave and downwave of the scour crest are
636 observed simultaneously, remaining on or near the scour crest, unlike in
637 previous HEP simulations. Also, the L vortex of the K-L pair downwave of
638 the scour crest grows in size ($t^*=7/9-8-9$).

639 **4.4 Turbulence**

640 Figure 11 shows the vertical distribution of turbulent shear stress from
641 simulations using LEP bathymetry with maximum values located around the
642 wreck ($x=190-200$). Shear stress profiles located at the offshore sediment
643 accumulation show a higher level of turbulence near bed in E3_LEP (Figure
644 11c), E4_LEP (Figure 11d) and E5_LEP (Figure 11e). In the case of E4_LEP,
645 after the wave breaking point ($x=200$) no increment of turbulent shear
646 stress at the seabed is observed. However, in E5_LEP (wave breaking point
647 at $x=89$) higher levels of turbulence are observed on the offshore side of
648 the wreck.

649

650 Figure 11. Vertical distribution of residual horizontal turbulent shear stress
 651 $(-\rho \overline{u'w'})$ at different streamwise locations simulated with the LEP
 652 bathymetry (note that different scales are used in the experiments to
 653 highlight the variation of $-\rho \overline{u'w'}$). Information relative to the wave phase

654 variation is represented as a function of the t^* ratio for the different line
655 colours and styles

656

657 In the case of HEP bathymetry (Figure 12) the areas of maximum shear
658 stress are concentrated downwave of the wreck, in the near bed region.
659 Unlike the LEP simulation, near bed shear stress is reduced upwave of the
660 hull remains with respect to the downwave area. Similar to the LEP
661 simulation, wave breaking introduces higher levels of turbulence into the
662 system as indicated by larger values of shear stress (Figure 12d).

Figure 12. Vertical distribution of residual horizontal turbulent shear stress ($-\rho \overline{u'w'}$) at different streamwise locations simulated with the HEP bathymetry (note that different scales are used in the experiments to highlight the variation of $-\rho \overline{u'w'}$). Information relative to the wave phase variation is represented as a function of t^* ratio for the different line colours and line stile.

4.5 Steady currents generated by nonlinear effects induced by waves (SCw): undertow and steady streaming.

LEP simulations indicate steady currents (Figure 13, left panels) are more intense in the near bed region over the hull remains and the offshore sediment accumulation. The increment in wave height and periods produces SCw intensification (see Figure 13a and Figure 13c). A counterclockwise current cell developed at the toe of the hull ($x \sim 197\text{m}$) and the SCw intensification is observed in the near bottom region in E1_LEP (Figure 13a). In the case of simulation E3_LEP (Figure 13e) the SCw enhancement ($< 0.3 \text{ m} \cdot \text{s}^{-1}$) is mainly restricted to the near bed region. In E4_LEP, wave breaking produces an increase in SCw ($0.3 \text{ m} \cdot \text{s}^{-1}$) over the wreck, at the offshore sand accumulation (from $x = 180$ to $x = 190$) and downwave of the breaking point ($x \sim 200 \text{ m}$). Larger SCw values ($0.4 \text{ m} \cdot \text{s}^{-1}$), especially upwave of the wreck, are simulated in the offshore wave breaking case (Figure 13i).

HEP bathymetry steady currents (right panels of Figure 13) demonstrate a wave-parameter dependence similar to that observed in the LEP bathymetry runs, and SCw intensification above the wreck is again simulated. However, notable differences between the LEP and HEP simulations are also observed. Unlike LEP, in HEP the maxima steady current are located above and downwave of the wreck, with the exception of E5_HEP. In addition, the presence of the recirculation cells increases the magnitude of SCw downwave of the wreck. For the small waves simulation (Figure 13b), a counter clockwise rotation cell forms at the toe of wreck ($\circ$), a clockwise circulation cell ($0.15 \text{ m} \cdot \text{s}^{-1}$) is located in the deepest part of the inshore scour pit, and another counter-clockwise current cell ($x \sim 205\text{m}$) shows a SCw intensity of $0.20 \text{ m} \cdot \text{s}^{-1}$ close to the seabed. In the E2_HEP simulation

695 (Figure 13d), the SWc velocity is increased to $0.3 \text{ m}\cdot\text{s}^{-1}$ in the centre of the
696 inshore scour pits, and the clockwise rotation current cell at the inshore
697 scour mark ($x\sim 202\text{m}$) increases velocity up to $0.3\text{-}0.7 \text{ m}\cdot\text{s}^{-1}$. The counter
698 clockwise rotation cell located at $x\sim 207$ reaches up to $0.35 \text{ m}\cdot\text{s}^{-1}$ near the
699 seafloor. In the E3_HEP simulation (Figure 13f) it is notable how the
700 maximum velocity above the wreck extends to the inshore scour pit, and is
701 associated with the larger current cell with clockwise rotation observed
702 above the inshore scour.

703 The breaking process in E4_HEP produces a volume flux in the shoreward
704 direction within water column (see shoreward direction of vector between 4
705 and 5 m depth in Figure 13h), it restricts the undertow current near to the
706 seabed and intensifies the SCw ($0.15 \text{ m}\cdot\text{s}^{-1}\text{-}0.20 \text{ m}\cdot\text{s}^{-1}$) around the wreck.
707 In addition, a new current cell develops above the offshore scour pits
708 ($x\sim 188$), and weakens the horizontally elongated current cell ($x\sim 207$).

709

710 Figure 13. Steady current generated by nonlinear effects induced by waves. Left panel shows numerical experiments for LEP conditions.

711 Right panel shows numerical experiment for HEP conditions. Cold colours indicate higher velocities and warm colours indicate lower

712 velocities.

713 In the E5_HEP simulation, the offshore breaking wave increases SCw
714 current velocity to $0.3 \text{ m}\cdot\text{s}^{-1}$, while the inshore current cell reduces in size
715 and velocity (Figure 13j).

716 **4.6 Bed shear stress**

717 Live-bed scouring dominates the entire site since the bed shear stress is
718 larger than critical bed shear stress for sediment motion in all wave
719 conditions tested. Figure 14 (a-e) depicts the spatial distribution of the ratio
720 between bed shear stress (τ) and critical bed shear stress for the sloping
721 bed (τ_c), with the bathymetric profiles corresponding to HEP and LEP plotted
722 below (Figure 14f). Note that different scales used for ease of interpretation
723 of the τ/τ_c features. For all simulations, larger values of τ/τ_c are obtained at
724 and downwave from the wreck. The maximum τ/τ_c occurs downwave of the
725 wreck ($x\sim 200\text{m}$), it is more evident in the HEP simulations. The τ/τ_c
726 variations induced by bathymetric changes are clear in the larger values of
727 τ/τ_c in the LEP simulations at the sand accumulation upwave of the wreck
728 ($x=185\text{m}-190\text{m}$). In addition, the LEP τ/τ_c maximum occurs around $x=195$
729 at the top of the wreck (Figure 14f), where after a gradual increase the bed
730 shear stress peaks before flow separation. In the HEP simulations
731 bathymetric peaks of τ/τ_c occur on the offshore scour crest ($x=185\text{m}$), near
732 the centre of the wreck site ($x\sim 192\text{m}$), just downwave of the top of the
733 wreck ($x\sim 194.5\text{m}$), and at the inshore scour crest ($x\sim 202.5\text{m}$). Notable
734 also are maxima of τ/τ_c beyond the inshore scour crest ($x=203\text{m}-210\text{m}$).
735 The increase in wave height and period increases the τ/τ_c ratio significantly.
736 Figure 14d shows the τ/τ_c maximum values for longer and higher waves just
737 before breaking ($x=205$), and corresponding to the maximum differences

738 between LEP and HEP experiments. Finally, for simulations E5_LEP and
 739 E5_HEP (Figure 14e), τ/τ_c is reduced due to the drastic reduction of wave
 740 height caused by the offshore wave breaking ($x=89\text{m}$).

741

742 Figure 14. Spatial distribution of the ratios between bed shear stress calculated and
 743 critical bed shear stress for the sloping bed for the two morphological statuses
 744 analyzed. (a) Experiments E1_HEP and E1_LEP. (b) Experiments E2_HEP and

745 E2_LEP. (c) Experiments E3_HEP and E3_LEP. (d) Experiments E4_HEP and
746 E4_LEP. (e) Experiments E5_HEP E5_LEP. (f) Bathymetric profiles corresponding to
747 HEP and LEP.

748 **5 Discussion**

749 Wreck-wave interaction and its seasonal variation was analyzed using
750 computational fluid dynamic simulations at the *Fougueux* site. This method
751 allowed us to evaluate the relative importance of the different processes
752 involved in scouring at a fully-submerged, wave-dominated historic
753 shipwreck site, under the influence of seasonal forcing. Our analysis reveals
754 characteristics of the mean oscillatory flow, flow velocity increase,
755 coherency of structures, recirculation cells and residual turbulence.

756 Although the two bathymetric profiles (LEP and HEP) used in the study were
757 obtained from different sources (multibeam and single beam) and are of
758 different resolution, the variations introduced in the shipwreck shape
759 representation are minor in comparison to the flow pattern variations
760 induced by morphological changes (Figure 1c).

761 The analysis of oscillatory flow for the different wave conditions reveals that
762 seasonal morphological changes largely modify the oscillatory flow velocity
763 pattern around the shipwreck. The inshore and offshore scour observed in
764 HEP simulations promotes the reduction of maximum and minimum near
765 bottom velocity values as a direct consequence of depth increase in both
766 areas (Figures 3 and 4). These modifications occur for all wave conditions,
767 although they are more evident in those experiments with higher Re . In
768 addition, the differences in near bed velocity are larger upwave of the hull
769 remains than downwave. This can be attributed to the larger changes in

depth in this location (Figure 1c), and also to the amplification of flow velocity resulting from the erosion of the offshore sand accumulation in HEP, particularly during mean storm conditions (20%) (Table 2).

Location	$\frac{\langle U_{mo} \rangle_{E1_HEP}}{\langle U_{mo} \rangle_{E1_LEP}}$	$\frac{\langle U_{mo} \rangle_{E2_HEP}}{\langle U_{mo} \rangle_{E2_LEP}}$	$\frac{\langle U_{mo} \rangle_{E3_HEP}}{\langle U_{mo} \rangle_{E3_LEP}}$	$\frac{\langle U_{mo} \rangle_{E4_HEP}}{\langle U_{mo} \rangle_{E4_LEP}}$	$\frac{\langle U_{mo} \rangle_{E5_HEP}}{\langle U_{mo} \rangle_{E5_LEP}}$
X=194.5	20%	12%	14%	14%	10%

Table 2. Flow velocity increase percentage at hull remains x=194.5

The modification of velocity profiles is promoted by the vortex dynamics. It is observed in the LEP simulations (see for example Figure 3b upwave x=191, at $t^* = 6/9$ and $7/9$ and downwave x=198, at $t^* = 2/9$ and $t^* = 4/9$). This process is more obvious in HEP simulations, for instance in H2_HEP (see Figures 4b and Figure 8). At the toe of hull remains (x=198) the velocity profile is modified by the counter clockwise vortex ($t^* = 4/9$ - $t^* = 7/9$), increasing the near bottom velocity. Likewise, the shedding of the vortex shoreward changes the horizontal velocity profiles at x=205 ($t^* = 4/9$) and at x=208.5 ($t^* = 6/9$ - $7/9$).

The dynamics of large coherent structures (LCS) is controlled by the Keulegan-Carpenter (KC) number (Summer, 1991). LCS clearly dominate the HEP simulations due to the presence of inshore and offshore scour-crest systems, which introduce two additional areas of vortex generation. Table 3 lists the KC values for the different locations prone to flow separation and vortex generation: the upwave and downwave scour-crest systems, and the hull remains. For the KC calculation, the diameter (D) was assumed as the width of the scour-crest, and the distance from the centre of the wreck site to the toe of wreck (x~197) for the hull remains.

	X(m)	D(m)	E1_LEP	E2_LEP	E3_LEP	E4_LEP	E5_LEP
Hull remains	195	4.1	2	6	12	15	5
	X(m)	D(m)	E1_HEP	E2_HEP	E3_HEP	E4_HEP	E5_HEP
Hull remains	195	3.7	2	5	12	16	5
Offshore scour-crest	185.2	2.3	3	9	21	26	7
Inshore scour-crest	202.7	1.2	6	7	29	40	16

Table 3. KC calculated from numerical experiment of the wave condition

tested with LEP and HEP bathymetry.

Flow separation does not occur at the wreck or at the offshore scour-crest in simulations E1_LEP and E1_HEP, as was expected for values of $KC < 4$ according to Sumer (1991). K and L vortices are only observed at the inshore scour crest ($KC=6$), along with the coherent structures (RC^+ and RC^-), whose position and rotation match with the recirculation cell identified in Figure 13a.

In E2_LEP, flow velocity increases at the wreck ($KC= 6$). As a result type K and L' vortices are observed for E2_LEP, and the coherent structure (RC^+) is identified as a recirculation cell (Figure 13c). In the E2_HEP simulation, a type K' vortex is formed at the wreck ($KC= 5$) and remains attached. Vortex shedding does not occur at values of $4 < KC < 7$, in agreement with Sumer (1991). At the inshore scour-crest ($KC=7$), the vortex dynamics are accelerated and the vortex shedding takes place as two vortex pairs; K-L downwave and M- K_2 upwave. The M- K_2 pair is segregated, and the K-L pair is transported initially shoreward by the counter clockwise current cell (Figure 13d).

Although the KC increase at the wreck there is no significant variation in the other LEP simulations.

In contrast, in E3_HEP even with the same value of KC for the wreck, the absence of the offshore sand accumulation promotes the generation of a type L'' vortex at the centre of the wreck site. The growth of $KC = 29$ at the inshore scour-crest does not generate changes in vortex dynamics, solely producing modification in the trajectory of the M vortex that is constrained by the larger clockwise current cell formed above the inshore scour pit (Figure 13f).

In the case of the inshore breaking wave E4_HEP, a KC value of 16 is calculated at the wreck, indicating a more complex dynamic as revealed by the presence of a N vortex developed at the inshore scour pit, the L' vortex split into smaller eddies, and the L'' vortex at the centre of the wreck site. The vortex L' partition could be associated with larger turbulent shear after the wave breaking process (Figure 12d). In addition the clockwise current cell (Figure 13h) marks the trajectory of the M vortex and vortex shedding also takes place at the offshore scour-crest system ($KC=26$).

In simulation E5_HEP, vortices are developed only at the scour-crest system. The two vortex pairs at the inshore scour crest remain attached to the crest, in spite of the fact that the value $KC=16$ is larger than the supposed threshold for vortex shedding ($KC=7$) (Sumer, 1991).

It is important to note how vortex dynamics modifies the velocity profiles and increases the turbulent shear. This is observed when mean streamwise velocity (Figure 3 and Figure 4) and turbulent shear profiles (Figure 11 and 12) in different wave phases are compared with the position of vortices at those phases (Figures 6-10). This promotes an increase in boundary layer

838 thickness (Figure 5), similar to the one that forms in the presence of sand
839 ripples when they originate from rhythmic vortices (Nielsen, 1992).

840 On the subject of turbulent shear stress, results show an important
841 increment in turbulence for the HEP morphological setting. This behaviour is
842 observed in all simulations, especially downwave of the wreck, with flow
843 velocity increase, LCS, and recirculation cells developed downwave.

844 The recirculation cells generated by the SCw are only present in the LEP
845 simulations at the toe of the wreck, with velocities lower than 0.10 m.s^{-1} .
846 Higher velocities of steady current are associated with undertow, which is
847 markedly significant in the cases of breaking wave E4_LEP and E5_LEP
848 (Figure 13). The recirculation cells are observed in all HEP simulations,
849 particularly downwave and with larger velocities ($0.3\text{-}0.7 \text{ m.s}^{-1}$) than in LEP.

850 The mean oscillatory flow brings sediment into suspension and as the
851 results have shown controls the trajectory of LCS increasing its effect in the
852 sediment transport.

853 It is remarkable the contribution of the LCS to the SCw. It can be observed
854 in the cases of E2_HEP, E3_HEP and E4_HEP (Figures 8, 9 and 10), where
855 the major LCS located in the inshore scour contributes to the residual
856 velocity as point the recirculation cell located in that area. (Figures 13d, 13f
857 and 13h). In addition, when the LCS are weak i.e. E1_HEP (Figure 6), the
858 recirculation cells can be identified by the Okubo-Weiss criteria. In that
859 case, at difference of the vortex, the RC remains during the entire wave
860 period with slight variations in its position (Figure 13a).

861 These processes modify the spatial distribution of bed shear stress on the
862 wreck and the surrounding seabed. Thus the speed up and vortex shedding

863 and its associated turbulence produce a maximum in τ/τ_c downwave of the
864 wreck, more evident in HEP simulations (Figure 14, $x \sim 200$). The increase in
865 bed shear stress caused by the vortex and the shear stress underneath the
866 vortex is clearly observable for the HEP simulation shoreward of the inshore
867 scour ($x > 202$), and at the toe of the wreck (Figure 14b). For more energetic
868 conditions (Figure 14c and Figure 14d) higher values of τ/τ_c are found in
869 LEP simulations, revealing that the influence of frictional velocity
870 amplification due to depth reduction in LEP is larger than the influence
871 caused by the effect of turbulence underneath the vortex in the HEP
872 simulations. This effect is more conspicuous upwave of the wreck, at the
873 offshore sand accumulation in LEP. Furthermore, the increase in the grid
874 size of the first computational cell above the seabed outside of region two in
875 the computational mesh (R2) (Figure 2) induces an error in the bed shear
876 stress calculation. This is observed in HEP experiments (Figure 14), where
877 τ/τ_c changes in the limit of the R2 region. However, the results are valid for
878 HEP because the relative changes induced by the increase in the grid size of
879 the first computational cell above the seabed outside of region two (R2), are
880 smaller than the changes caused by the hydrodynamic and vortex pattern.
881 On the contrary, in the case of LEP the changes promoted by the
882 hydrodynamics and the vortex pattern are not meaningful in comparison
883 with those induced by the variation in mesh size. Therefore, in the case of
884 LEP bathymetry the relative magnitude of this error with respect to the
885 spatial variation of τ/τ_c invalidates the τ/τ_c results outside the region R2.
886 Previous investigations at the wreck site (Fernández-Montblanc et al.,
887 2016), based on time-lapse bathymetric surveys and conventional
888 hydrodynamic modelling, concluded that sediment is alternatively deposited

and eroded at the *Fougueux* site in response to seasonal wave climate variation. Thus the morphological changes observed in HEP and LEP are intrinsically linked to the seasonal wave climate variation in an inter-annual interactive cycle. Furthermore, a feedback mechanism occurs where the geomorphological changes induce changes in the oscillatory flow velocity patterns around the shipwreck. This iterative cycle can be described as follows. During the mean storm after a prolonged low energy period (from May to September) (H1_LEP) the friction velocity and speed of flow produces the erosion of the offshore sand accumulation and the initial development of the onshore scour mark. The development of the inshore and offshore scour marks increases the speed of flow on the hull remains (see Table 2), accelerates the vortex dynamics and the intensification of the current cell, resulting in amplification of the shear stress. It occurs most notably during the extreme events (H2_HEP, H3_HEP, H4_HEP and H5_HEP), leading to the enhancement of sediment transport by shoreward vortex shedding. Finally, during the swell-wave period (low-energy conditions from May to September) asymmetry between the orbital velocities beneath crests and troughs tend to drive sediment from the offshore direction towards the coast producing the offshore sand accumulation, partially filling partially the inshore scour mark with the surrounding sediment.

914

915 **6 Conclusions**

916 The CFD simulations from the *Fougueux* site indicate that the friction
917 velocity due to oscillatory flow and flow velocity amplification are the
918 dominant physical processes in operation during the low energy period, and
919 the large coherent structure formed at the toe of the wreck initiates scour at
920 that location. During the high energy period, the relevance of turbulent
921 shear and the large coherent structure are markedly greater, and flow
922 increases at the wreck site. In addition, the recirculation cells originated by
923 steady streaming and undertow are more important in high energy periods.
924 The velocity increase of the current cell in high energy settings modifies the
925 trajectory of the shed vortex increasing its capacity of sediment transport.

926 The results confirm CFD as a valuable tool to understand the mechanisms
927 promoting scouring at shipwreck sites and other submerged structures
928 under the influence of waves. Beyond the aim of this study, the successful
929 application of a full scale CFD study in the simulation of waves and structure
930 interactions allows the behaviour of these structures in full scale and
931 realistic morphological conditions to be tested. In addition, the full scale
932 CFD application will allow the parameterization of different physical process
933 related to waves, thus avoiding the many restrictions of physical lab
934 experiments and field-based deployments during extreme conditions.

935 In summary, the full scale CFD modelling presented in this study allows
936 detailed analysis of key physical processes in coastal engineering,
937 addressing limitations inherent in traditional physical models and field
938 deployments.

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