

Scour variability across offshore wind farms (OWFs): Identifying site-specific scour drivers as a step towards assessing potential impacts on the marine environment

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Abstract. The development of offshore wind farms (OWFs) is critical to meeting renewable energy targets, but predicting scour around offshore wind energy structures (OWES) and the associated potential impacts on marine ecosystems remains a challenge. Using high-resolution bathymetry data, this study analyses field-measured scour depths at 460 monopiles at nine British OWFs. The analysis reveals a large spatial variability of relative scour depth (S/D) between OWF sites, but also within individual wind farms. Principal Component Analysis (PCA) is used to identify significant drivers of this variability. When the entire data set is considered, results indicate that the relative water depth (h/D), the relative median grain size (d_{50}/D), Keulegan-Carpenter number (KC_{99}), and the sediment mobility parameter MOB (θ_{99}/θ_{cr}) are the most important influencing factors for the variability of relative scour depth. Other parameters investigated, such as pile Reynolds number (Re_{99}), flow intensity (U/U_{cr}), and Froude number (Fr_{99}), were found to have a less clear influence. Further sediment-specific analysis shows that relative water depth (h/D) is a particularly relevant driver of scour at sites with fine ($63 \leq d_{50} < 200 \mu m$) and medium sands ($200 \leq d_{50} < 630 \mu m$), with larger relative scour depth occurring in shallower relative water depth.

Findings from this study provide new insights into scour behaviour across a range of spatial and environmental scales and lay a foundation for the transferability of scour prediction frameworks to new OWFs sites. In the future, findings and datasets from this study are suggested to be used to estimate scour-induced sediment transport and thereby to provide a step towards the assessment of potential impacts of OWFs expansion scenarios in the marine environment. By addressing the broader implications for regional sediment dynamics, this research contributes to the sustainable development of offshore wind energy.

Keywords: Offshore wind farms (OWFs), relative scour depth, monopile, sediment transport, Principal Component Analysis (PCA).

37 1 Introduction & Motivation

38 The expansion of renewable energy is crucial for a sustainable and independent energy supply. In order to meet
39 the European Union's targets for expanding offshore wind energy (EU, 2020), it is necessary to develop areas with
40 previously unveiled metoceanic and geophysical conditions. To this end, existing knowledge gaps about the
41 interaction of individual offshore wind energy structures (OWES) or entire offshore wind farms (OWFs) with the
42 marine environment must be closed. In general, the disturbance of the flow by an offshore structure causes scour,
43 which might not only affect the structure's stability (Saathoff et al., 2024), but the mobilized sediment may also
44 contribute to the overall regional sediment transport (Vanhellemont et al., 2014; Baeye and Fettweis, 2015; Rivier
45 et al., 2016) with potential impacts on the marine environment.

46 The scour process itself is a multivariate process, which is dependent on a combination of complex hydrodynamic
47 and geotechnical drivers. Early studies focused on the understanding of the scour process around a pile under
48 simplified isolated hydraulic conditions, such as steady flow (e.g., Sheppard et al., 2004; Zhao et al., 2012; Sarkar
49 et al., 2014; Baykal et al., 2015), unsteady and bidirectional tidal currents (e.g., Escameia and May 1999;
50 McGovern et al., 2014; Yao et al., 2016; Schendel et al., 2018) and waves (e.g., Sumer et al., 1992b; Carreiras et
51 al., 2001; Stahlmann et al., 2013). With the availability of more sophisticated experimental facilities and numerical
52 models, research is increasingly shifting toward more complex hydrodynamic loads consisting of a combination
53 of waves and currents, as in the studies of Sumer and Fredsøe (2001), Qi and Gao (2014), Schendel et al. (2020),
54 Lyu et al. (2021), and Du et al. (2022) and also towards studies addressing complex offshore structures (Welzel,
55 2021; Welzel et al., 2024; Sarmiento et al., 2024; Chen et al., 2025).

56 Despite those advances in scour research, uncertainties remain in current scour prediction methods (Chen et al.,
57 2024). Matutano et al. (2013) demonstrated the challenges of applying empirical formulas for maximum scour
58 depth by comparing different methods with data from ten European OWFs, revealing overpredictions in all but
59 two cases. The comparison highlights the fundamental challenge of accounting for complex marine flow
60 conditions, characterised by the combined effect of multiple influencing factors, such as flow velocity, sediment
61 coarseness, and wave-current interactions, in the prediction of scour processes using existing models (Gazi et al.,
62 2020; Harris et al., 2023). Compared to laboratory experiments focusing on scour processes, rather few studies are
63 based on in-situ data, which represent the actual scour development under complex flow conditions. These studies
64 assessed the scour at individual structures, such as monopiles (Walker, 1995; Noormets et al., 2003; Harris et al.,
65 2004; Rudolph et al., 2004; Louwersheimer et al., 2009) and jackets (Bolle et al., 2012; Baelus et al., 2018), or
66 dealt with larger datasets from entire offshore wind projects (DECC 2008; COWRIE 2010; Whitehouse et al.,
67 2010; Whitehouse et al., 2011; Melling (2015)), covering both spatial and temporal evolution of scour under
68 different hydrodynamic regimes and seabed types across the North Sea and British continental shelf. In general,
69 the amount and variety of field data collected has increased with the gradual installation of OWES. Focusing
70 specifically on the correlation between scour and on-site conditions, Melling (2015) analysed the relationships
71 between the variations of scour hole dimension within OWFs and both sedimentological and hydrodynamic
72 parameters of 281 OWES in the Outer Thames estuary. Melling's (2015) study, although only covering three
73 OWFs, represents one of the most comprehensive investigations of field-related scour to date, with the highest
74 number of structures examined so far. By comparing field data with physical modelling experiments and literature,
75 the study provided valuable insights into the range of observed scour and its controlling structural, hydrodynamic,
76 and sedimentological parameters.

77 In addition to local scour at individual structures, the cumulative effect of multiple structures in an OWF can alter
 78 ocean dynamics (Christiansen et al., 2022), mixing (Schultze et al., 2020), and sediment mobility, resulting in
 79 changes to suspended sediment concentrations and wave-induced turbidity plumes (Vanhellemont & Ruddick,
 80 2014). This can also lead to dynamic interactions with migrating seabed features, such as sand waves (Matthieu &
 81 Raaijmakers, 2012). Increased velocities and turbulence induced by OWFs have also the potential to affect the
 82 marine environment, potentially leading to global erosion around the structures as well as habitat loss or gain for
 83 benthic flora and fauna (Shields et al., 2011; Wilson and Elliott, 2009; Welzel et al., 2019). Concerns over the
 84 potential impacts of OWF installations on local ecosystems further include collision risks, noise pollution,
 85 electromagnetic fields, and the introduction of invasive species (Lloret et al., 2022; Bailey et al., 2014; Teilmann
 86 and Carstensen, 2012; Watson et al., 2024). As the size and scale of OWF increase, the risk of significant
 87 cumulative effects arising is also expected to increase (Brignon et al., 2022; Guşatu et al., 2021). The drivers and
 88 interdependencies of these large-scale processes are not yet well understood, and the precise impact of scour-
 89 induced sediment transport on the marine environment remains uncertain, highlighting the need for
 90 interdisciplinary research utilizing field data.

91 In order to gain a better understanding of the geophysical changes following the installation of OWFs and potential
 92 impacts on the marine environment arising from it, this study analyses the scour development at OWES as a first
 93 step. This study builds its analysis on field data, including high-resolution bathymetry scans from British OWFs,
 94 which have recently been made publicly available. This provides an opportunity to extend the understanding of
 95 scour evolution and its key drivers using a cross-regional dataset. A total of 460 monopiles were analysed to obtain
 96 local scour depth and their spatial distribution in dependence on selected hydrodynamic and geological drivers.

97 Understanding scour development is a critical first step in assessing potential environmental impacts. It will help
 98 determine whether OWES and entire OWFs contribute to regional sediment mobilization and provide a foundation
 99 for future research into the long-term morphological footprint of OWF installations and their broader ecological
 100 effects. To contribute to the overarching goal of reducing uncertainty in scour predictions at OWES, this study
 101 analyses field data from 460 monopiles across 9 OWFs, situated in diverse marine regimes with current velocities
 102 from 0.54 m/s to 1.77 m/s (99th percentile), significant wave heights from 1.5 m to 2.7 m (99th percentile), water
 103 depths from 5 to 35 m, and grain sizes ranging from cohesive sediment ($51.54 \mu\text{m}$) to medium gravel ($19872 \mu\text{m}$).
 104 The spatial distribution and variability of relative scour depth across and within these OWFs are determined and
 105 correlated with selected hydrodynamic and sedimentological parameters, using Principal Component Analysis
 106 (PCA). This analysis aims to (1) identify universal drivers of scour across all sites, (2) assess sediment-specific
 107 correlations by grain size (d_{50}) and (3) evaluate site-specific variability at the level of three selected OWFs (Robin
 108 Rigg, Lynn and Inner Dowsing, and London Array). The site-specific analysis in Section 3.5 assesses the
 109 robustness of the global correlations under local conditions and provides insight into how local conditions
 110 influence scour behaviour. Collectively, these efforts aim to decrease uncertainty in relative scour depth prediction
 111 by assessing the contribution of the main drivers of scour development from multivariable field data.

112 This paper is organized as follows: Section 2 describes the study area and methodology, in which the methods
 113 used to obtain the relative scour depth and selected on-site parameters are explained in detail (subsections 2.2 –
 114 2.5). Additionally, the application of the PCA to identify the primary correlation between these parameters and
 115 scour development is explained (subsection 2.6). The results are presented in section 3, followed by discussion
 116 (section 4) and ending with the conclusions (section 5).

117 2 Study area and methodology

118 2.1 Study area

119 The research area, located in British waters, is illustrated in Figure 1, showing the specific locations of the nine
120 studied OWFs. Figure 1A provides a general overview, while Figure 1B pinpoints the positions of the OWFs,
121 labeled 1 to 9. These OWFs correspond to Robin Rigg, Barrow, Teesside, Humber Gateway, Lincs, Lynn and
122 Inner Dowsing, Greater Gabbard, London Array, and Gunfleet Sands, respectively. Figures 1C and 1D display the
123 99th percentiles of the significant wave heights ($H_{s,99}$) and current velocity magnitudes (U_{99}) at the nine locations,
124 respectively.

125 Notably, wind farms such as Robin Rigg and Barrow are situated in the Irish Sea, while the remaining seven are
126 located in the North Sea at the east coast of the UK (Fig. 1B). Water depths (h) ranging from 5 to 35 m can be
127 found across the nine OWFs. Depth data (h) were obtained from EMODNET
128 (<https://emodnet.ec.europa.eu/en/bathymetry>). The OWF located in the shallowest water depth is Robin Rigg
129 with h ranging from 1 to 14 m (Fig. 1B). Conversely, the OWF with the deepest water depth is Greater Gabbard
130 with h ranging from 21 to 35 m (Fig. 1B).

131 The highest and lowest significant wave heights (99th percentile) can be found at Humber Gateway OWF ($H_s = 2.7$
132 m) (Fig. 1C-D) and at Gunfleet Sands OWF ($H_s = 1.5$ m), which are located at the mouths of the Humber and
133 Thames estuaries (Fig. 1C-D), respectively. Regarding current velocities, the highest value is found at Robin Rigg
134 OWF with 1.8 m/s (Fig. 1C-D), while the lowest value is found at Gunfleet Sands OWF with a value of 0.4 m/s
135 (Fig. 1C-D).

136 Depending on the locations of the OWFs, the seabed conditions vary from sandbanks featuring a variety of
137 bedforms to intertidal mudflats. Accordingly, the sediment also varies from silt to coarse and very coarse gravel,
138 with the sediment at Teesside OWF consisting of fine and silty sands and that at Humber Gateway consisting of
139 sandy gravel and boulders. In contrast, OWFs such as London Array and Greater Gabbard are located in the Outer
140 Thames Estuary with sandbanks and channels, while others such as Barrow and Robin Rigg have distinct
141 geological features such as megaripples, mudflats, and deposits from different geological eras.

142 2.2 Data description

143 Bathymetric datasets from the nine OWFs considered in this study were collected via multibeam echosounder
144 (MBES) before, during, and after the construction of the OWFs and were afterwards made available by their
145 operators via the Marine Data Exchange (MDE).

146 In total, 460 OWES (of 680 available) with monopile foundations were analysed in this study. For the correlation
147 between scour and hydrodynamic conditions at the nine studied OWFs, metocean hindcast datasets (i.e., significant
148 wave height (H_s) and velocity magnitude (U)) by the Copernicus Marine Service (CMEMS)
149 (<https://marine.copernicus.eu/>) were used (CMEMS, 2023a, 2023b).

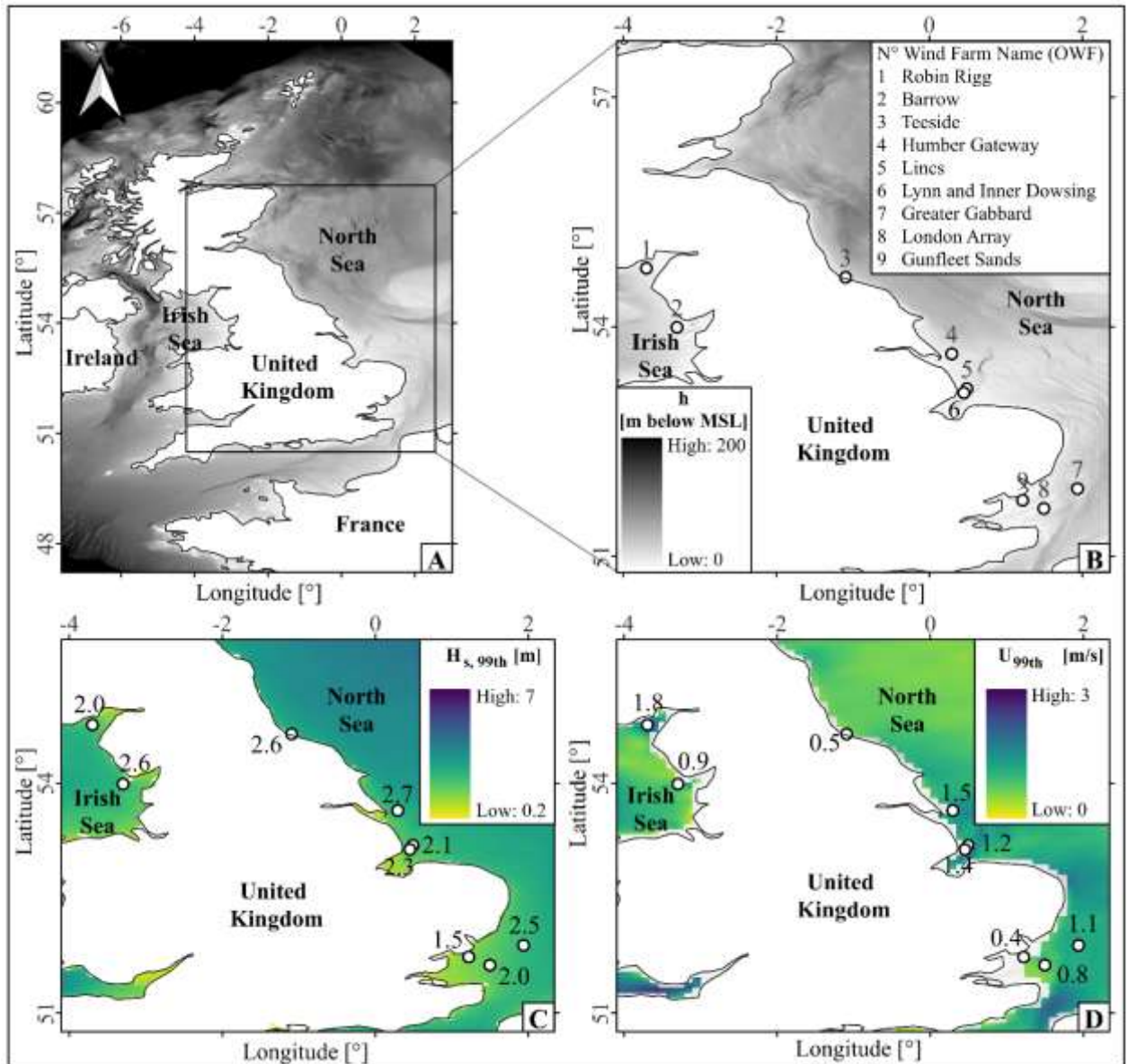


Figure 1: A) Study area. B) Location of the nine studied OWFs. Shown bathymetry data originates from EMODNET (<https://emodnet.ec.europa.eu/en/bathymetry>). C) 99th percentile of significant wave heights (H_s) based on data for the year 2012. D) 99th percentile of current velocity magnitudes (U) based on data for the year 2012.

Table 1 shows the OWFs considered in this study and provides an overview of their structural characteristics as well as the hydrodynamic and geotechnical site conditions. Pile diameters (D) were obtained from Negro et al. (2017), water depths (h) are based on EMODNET (2020), d_{50} represents the median grain diameter of the sediment. The sediment data shown in Table 1 were obtained in Phi units from each OWF's benthic reports, then converted to d_{50} values in micrometers (μm) according to Bunte et al. (2001). The scour depth S represents the deepest scour at an individual OWES. The number of OWES varies from 26 OWES installed at Teesside OWF to 174 OWES installed at London Array OWF, indicating the different operational scales. For some OWFs, including Lynn and Inner Dowsing, extensive bathymetric data spanning over ten years was available. In contrast, others, such as Humber Gateway, had more limited bathymetric data with a coverage duration of four years. The highest grid resolutions of the bathymetric datasets found at each OWF varied from 0.2 to 0.5 m, with the highest resolution

165 of the bathymetries found at each OWF being used. The earliest bathymetry was collected at Barrow OWF in
 166 2005, and the most recent was collected at Lynn and Inner Dowsing in 2017, highlighting the long-term monitoring
 167 efforts at the wind farms. However, in this study only scour depth obtained from the pre- and the first post-
 168 construction bathymetries were considered. The shortest period between pre- and post- bathymetries was found at
 169 Lincs OWF, with 377 days between August 2010 and August 2011, while the longest period between scans was
 170 detected at Greater Gabbard OWF, with 2902 days (~8 yrs) between June 2005 and May 2013.

171 Furthermore, environmental and hydrodynamic conditions associated with each OWF are also shown in Table 1,
 172 which are essential for understanding how different variables contribute to scour around monopiles. These
 173 variables include the 99th percentile significant wave height ($H_{s,99}$), representing the average height of the highest
 174 third of waves. The wave height has a direct influence on the wave-induced current velocity near the seabed and
 175 thus strongly determines the bed shear stresses and the formation of the vortex system around the OWES (Sumer
 176 & Fredsøe, 2002; Schendel et al., 2018). The 99th percentile current velocity magnitude (U_{99}) indicates the resultant
 177 of eastward (u_0) and northward (v_0) tidal flow components; those represent the depth-averaged velocity
 178 magnitude, whereas U_{cr} depicts the critical flow velocity for sediment entrainment. Their ratio, the flow intensity
 179 (U/U_{cr})₉₉ is a key parameter in describing the general sediment mobility and has a large impact (h/D) influences
 180 on the formation of the horseshoe vortex in such a way that the size of the horseshoe vortex is reduced as the flow
 181 depth decreases, resulting in a reduction in the relative scour depth. At greater relative water depth $h/D \geq 5$ the
 182 relative scour depth becomes almost independent of relative water depth (Sumer and Fredsøe, 2002).

183 The Froude number (Fr_{99}) and pile Reynolds number (Re_{99}) are used to characterize the flow conditions around
 184 the pile, and their calculations are shown in Table 2, Equations 2 and 3. The Froude number indicates whether the
 185 flow is dominated by gravitational or inertial forces. With increasing Froude number, stronger inertial forces
 186 produce more pronounced pressure gradients at the upstream face of the monopile. Promoting early boundary layer
 187 separation and enhances the strength of the horseshoe vortex system near the seabed, which increases local bed
 188 shear stress and accelerates sediment erosion. As shown by Hu (2021), these dynamics are key in amplifying scour.
 189 Similarly, Corvaro et al. (2015) found that higher Froude numbers lead to larger vortex structures and increased
 190 bed shear stress, resulting in deeper equilibrium scour depth. On the other hand, the Reynolds number provides
 191 information on whether the flow is laminar or turbulent, and determines the characteristics of the vortex system
 192 around the pile.

193 Additionally, the Keulegan–Carpenter number (KC_{99}), which is used to determine the relative influence of drag
 194 and inertia forces, the formation of vortices, and the potential for sediment transport (Sumer & Fredsøe, 2002).
 195 The mobility parameter (θ_{99}/θ_{cr}) is considered a key controlling factor for scour, as it represents the degree to
 196 which the bed shear stress exceeds the critical threshold for sediment motion under given flow conditions (Soulsby,
 197 1997; Whitehouse et al., 2000). The calculations of those two parameters are shown in Table 2, Equations 9 and
 198 20. The datasets were obtained between pre- and post- construction bathymetries. The data was collected over a
 199 one-year period, prior to the post-construction bathymetry.

200 Dimensionless parameters as given in Table 1 were calculated based on the equations summarized in Table 2.

OWF name	N° of OWES	Pile diameter D (m)		Scour depth S (m)	Water depth h (m)	D_{50} (μm)	Wave height $H_{s,99}$ (m)	Current Velocity U_{99} (m/s)	Relative scour depth S/D	Relative water depth h/D	Froude number Fr_{99}	Reynolds number Re_{99}	Keulegan Carpenter number KC_{99}	Mobility parameter θ_{99}/θ_{cr}	Flow intensity $(U/U_{cr})_{99}$
Robin Rigg Barrow	60	4.3	Min	1.3	5	167	2.36	1.55	0.30	1.03	0.13	5.14×10^6	0.99	15.3	3.51
			Max	10	14	267	2.59	1.77	2.32	3.07	0.23	5.86×10^6	1.9	25.4	4.43
	30	4.75	Min	0.98	15	138	2.43	0.91	0.20	3.67	0.06	3.50×10^6	0.34	4.4	1.89
			Max	6	23	445	2.52	1.11	1.20	4.71	0.08	4.26×10^6	0.48	7.2	2.40
Teesside	26	5	Min	0.65	8	51	2.52	0.54	0.13	2.08	0.04	2.10×10^6	1.2	6.1	1.19
			Max	1.62	20	166	2.76	0.54	0.32	3.49	0.05	2.10×10^6	1.6	9.6	1.29
Humber Gateway	72	4.2	Min	0.5	15	5918	2.24	1.51	0.11	3.65	0.11	4.87×10^6	0.92	0.4	0.58
			Max	2.51	20	1900 0	2.37	1.56	0.59	4.65	0.12	5.06×10^6	1.11	1.2	0.99
Lincs	75	5.2	Min	0.54	12	505	2.47	1.07	0.10	2.41	0.08	4.29×10^6	0.64	2.6	1.31
			Max	1.92	21	1982	2.71	1.67	0.38	3.88	0.13	6.71×10^6	1.01	11.1	3.12
Lynn and Inner Dowsing	60	4.74	Min	0.5	9	684	2.11	1.30	0.10	2.10	0.11	4.76×10^6	0.84	3.2	1.63
			Max	2.35	17	1950	2.36	1.45	0.49	3.47	0.13	5.29×10^6	1.3	7.3	2.53
Greater Gabbard	139	6	Min	0.5	23	394	2.41	1.02	0.08	3.50	0.05	4.72×10^6	0.18	1.3	1.14
			Max	4.54	35	2296	2.67	1.22	0.75	5.83	0.07	5.64×10^6	0.33	6.1	2.25
London Array	174	7	Min	1.2	1	120	1.89	0.71	0.21	0.31	0.04	2.56×10^6	0.1	1.5	1.14
			Max	9.5	27	930	2.36	0.81	2.02	4.67	0.19	3.56×10^6	2.3	32.6	2.33
Gunfleet Sands	49	4.7	Min	0.88	2	146	1.52	0.48	0.18	0.54	0.03	1.74×10^6	0.45	2.1	1.05
			Max	7.73	16	253	1.72	0.86	1.64	3.34	0.09	3.12×10^6	1.68	17.6	2.07

Table 1. Overview of studied OWFs with hydrodynamic and sedimentological site conditions.

Table 2. Calculation of the variables included in the analysis

Variable	Equation	
Velocity magnitude	$U_{99} = (\sqrt{u_0^2 + v_0^2})_{99}$	(1)
Froude number	$Fr_{99} = \left(\frac{U}{\sqrt{gh}} \right)_{99}$	(2)
Pile Reynolds number	$Re_{99} = \left(\frac{UD}{\nu} \right)_{99}$	(3)
Dimensionless grain size	$D_* = \left(\frac{\rho g}{\nu^2} \right)^{\frac{1}{3}} d_{50}$	(4)
Critical Shields	$\theta_{cr} = \frac{0.3}{1 + 1.2D_*} + 0.55(1 - \exp(-0.02D_*))$	(5)
U_{cr}	$U_{cr} = 7 * \left(\frac{h}{d_{50}} \right)^{\frac{1}{7}} (g(s-1)d_{50}\theta_{cr})^{0.5}$	(6)
Flow intensity	$\left(\frac{U}{U_{cr}} \right)_{99}$	(7)
Zero crossing period (T_z)	$\frac{T_p}{1.28}$	(8a)
Natural period (T_n)	$T_n = \sqrt{\frac{h}{g}}$	(8b)
A_t	$A_t = (6500 + \left(0.56 + 15.54 \frac{T_n}{T_z} \right)^6)^{1/6}$	(8c)
RMS velocity (U_{rms})	$U_{rms} = 0.25 \frac{H}{T_n (1 + \left(A_t \frac{T_n^2}{T_z} \right)^3)}$	(8d)
Wave-induced velocity (U_m)	$U_m = \sqrt{2} U_{rms}$	(8e)
Keulegan-Carpenter number (KC)	$KC_{99} = \left(\frac{U_m T_p}{D} \right)_{99}$	(9)
Roughness related to d_{50} (ks)	$ks = 2.5d_{50}$	(10)
Amplitude of wave orbital motion at the bed (A)	$A = \frac{U_m T_p}{2\pi}$	(11)
shear velocity (U_f)	$U_f = \frac{U}{6.0 + 2.5 \ln \left(\frac{h}{ks} \right)}$	(12)

wave friction factor (f_w)	$f_w = \begin{cases} 0.32 \left(\frac{A}{k_s} \right)^{-0.8}, & \frac{A}{k_s} < 2.92 \\ 0.237 \left(\frac{A}{k_s} \right)^{-0.52}, & 2.92 \leq \frac{A}{k_s} < 727 \\ 0.04 \left(\frac{A}{k_s} \right)^{-0.25}, & \frac{A}{k_s} \geq 727 \end{cases} \quad (13)$
Angle between the direction of the wave and the current (α)	$\alpha = \text{atan2}(u_0, v_0) - D_w \quad (14)$
current induced bed shear stress (τ_c)	$\tau_c = \rho_w U_f^2 \quad (15)$
wave induced bed shear stress (τ_w)	$\tau_w = 0.5 \rho_w f_w U_m^2 \quad (16)$
cycle-mean shear stress (τ_m) due to a combined wave-current load	$\tau_m = \tau_c \left[1 + 1.2 \left(\frac{\tau_w}{\tau_c + \tau_w} \right)^{3.2} \right] \quad (17)$
maximum shear stress value under combined wave-current load (τ_b)	$\tau_{max} = [(\tau_m + \tau_w \cos \alpha)^2 + (\tau_w \sin \alpha)^2]^{0.5} \quad (18)$
Shields parameter (θ)	$\theta_{99} = \left(\frac{\tau_{max}}{(\rho_s - \rho_w) g d_{50}} \right)_{99} \quad (19)$
Mobility parameter	$\theta_{99} / \theta_{cr} \quad (20)$

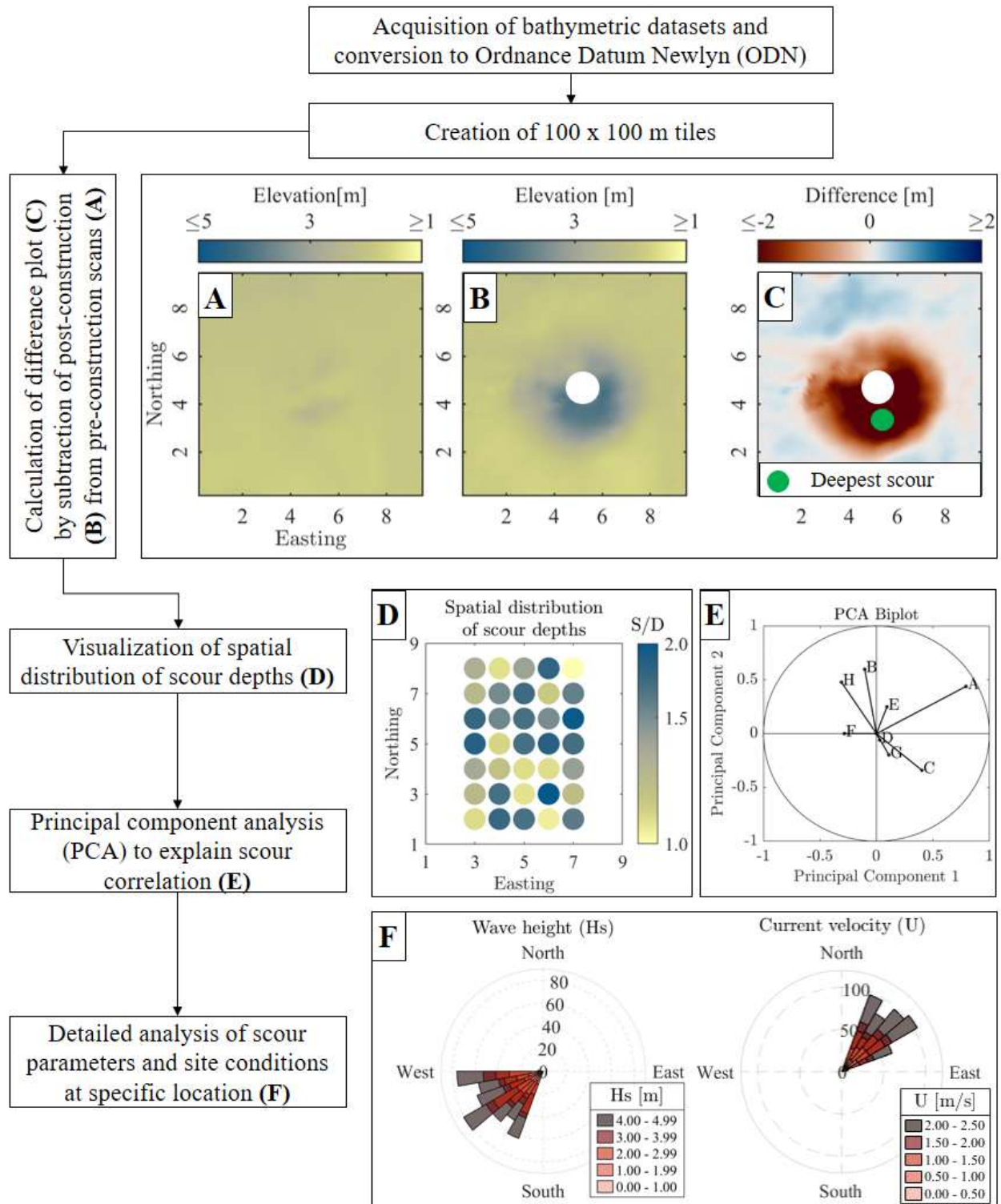
204 The values assumed for all OWFs sites are: $\rho_s = 2650 \text{ kg/m}^3$ (sediment density, based on Soulsby, 1997), $\rho_w =$
 205 1027 kg/m^3 (water density), $\nu = 1.3 \times 10^{-6} \text{ m}^2/\text{s}$ (kinematic viscosity), $g = 9.8 \text{ m/s}^2$ (gravitational
 206 acceleration). Equation 4 was calculated based on van Rijn (1984), where D_* is the non-dimensional grain diameter
 207 that is used to calculate the critical Shields parameter (θ_{cr}), which represents the threshold for initiation of motion
 208 at the bed, as proposed by Soulsby (1997). Equation 5 is taken from Soulsby and Whitehouse (1997), where s
 209 ($s = \rho_s / \rho_w$) represents the specific gravity of sediment grains. The d_{50} represents the median sediment grain size.
 210 In equation 18, the maximum bed shear stress value (τ_{max}) was calculated following Roulund et al. (2016), which
 211 builds upon Soulsby (1997) by combining current- and wave-induced shear stress through a directional correction.
 212 Shields parameter (θ_{99}) is derived using equation 19, based on the maximum bed shear stress (τ_{max}) under
 213 combined wave and current conditions. The Keulegan–Carpenter number is defined in equation 10, where T_p is
 214 the peak wave period and D the monopile diameter.
 215 Equation 20 provides the calculation of the mobility parameter to assess sediment mobility, providing a
 216 dimensionless indicator of whether the hydrodynamic forcing was sufficient to initiate sediment motion. All
 217 relevant equations are summarized in Table 2.

218 2.3 Pre-processing of bathymetric data

219 Figure 2 shows the workflow used in this study, starting with the acquisition of bathymetric datasets, originally
 220 obtained from the Marine Data Exchange, and their conversion to Ordnance Datum Newlyn (ODN). This was
 221 followed by the generation of 100 m x 100 m tiles for each available bathymetric dataset, centered on each turbine
 222 location. If bathymetric scans with different spatial resolutions were available for the same date, only the one with
 223 the highest resolution was used. In addition, some turbine locations could not be further analysed due to missing
 224 pre-construction scans or poor data quality. Tiles with more than 50% empty cells were discarded because a high
 225 percentage of missing data increases the likelihood that important areas, such as the scour region, are poorly

226 captured. Tests were conducted with lower missing cell thresholds (10% and 25%), but even with 50% missing
227 data, valuable information for scour analysis was retained. Using a stricter 25% threshold, too many tiles were
228 lost, including those that still contained useful data. As a result, 460 OWES across the nine OWFs were analysed
229 in this study.

230 The difference in bed elevation at turbine sites between the pre-construction (Fig 2.A) and post-construction
231 surveys (Fig 2.B), was used for extracting scour information. The deepest scour at each turbine site was then
232 extracted from the difference plot (Figure 2.C). A detailed description of this part of the workflow is provided in
233 section 2.4.



234

235 **Figure 2: General workflow and methodology used to assess the scour distribution and evolution as well as**
 236 **the correlation between scour parameters and site conditions. A) Pre-installation scan. B) Post-installation**
 237 **scan. C) Difference plot after subtraction of B from –A. D) Map of spatial distribution of relative scour**
 238 **depth. E) Principal Component Analysis (PCA). F) Site conditions of wave heights and current velocities.**

239 2.4 Calculation of scour parameters

240 First, to eliminate outliers, a threshold based on the 99th percentile was used to filter out extreme values, ensuring
 241 that outliers did not skew subsequent analyses or visualizations. Subsequently, to address potential offsets between

pre- and post-construction, a median filter was applied to both datasets. The difference in medians, excluding the presumed scour area, was considered the offset. This offset was then applied while calculating the difference plot between the pre- and post-construction bathymetries (Fig. 2A-C). To remove additional outliers close to the turbine, an area equivalent to 110% of the pile's footprint area was excluded from the center of the difference plot. The deepest scour depth (see green dot in Fig. 2C) was then extracted from the difference plot (Fig. 2C). The calculated relative scour depth were then visualized to show the spatial distribution across the nine OWFs (Fig. 2D).

2.5 Principal Component Analysis (PCA)

In the case of field data, the correlation of the scour process with hydrodynamic and geotechnical variables is complicated by the simultaneous change of several of these variables. In order to reduce the complexity and simplify this multivariate problem, PCA was used in a next step (Fig. 2.E). PCA works by transforming the data into a set of new variables called principal components, which are linear combinations of the original variables (Jolliffe & Cadima, 2016). These components are ordered based on how much variance they explain, with the first principal component (PC1) explaining the maximum variance in the data, followed by the second principal component (PC2). Each component also has an eigenvalue, which shows the amount of variation it captures. Generally, the PCA is able to handle lots of independent variables and helps to simplify the data without losing important information (Harasti, 2022).

In this study, the PCA was applied to a dataset of 692 OWES, including 460 from our analysis and an additional 232 OWES from London Array and Thanet OWF, based on Melling's (2015) data. The PCA was then performed using eight independent variables that contributed to the principal components. Those dimensionless variables were the relative water depth (h/D), Keulegan-Carpenter number (KC_{99}), mobility parameter (θ_{99}/θ_{cr}), Reynolds number (Re_{99}), Froude number (Fr_{99}), relative sediment size (d_{50}/D), flow intensity ($(U/U_{cr})_{99}$), and the relative scour depth (S/D). Following this, the data was organized into a matrix, with each row representing a specific OWES and each column representing a selected dimensionless variable. All the variables were extracted as representative values specific to the OWES, with the focus on the 99th percentile to capture extreme hydrodynamic conditions. Scour processes are more likely to occur in these extreme conditions because maximum scour depth usually develops during storm-induced events, rather than under mean or median values. Subsequently, the variables were standardised to ensure the comparability of the results.

In some studies, the PCA is used for reducing the number of dimensions (Harasti, 2022), or to help develop predictive models grouped by soil classes (Annad, 2023). However, the aim of this study was to keep all the principal components. This approach enabled the full exploration of the interdependence between physical drivers and scour response across sites. To interpret the relationships among the variables, a principal component analysis biplot was generated (Gabriel et al., 1971). In the biplot, variables are represented as vectors, and the angle between vectors indicates the degree of correlation. The strength of the correlation was quantified using the cosine of the angle (Jolliffe & Cadima, 2016), enabling us to assess the strength of association between each variable and scour variability across different OWFs sites. Similar to previous studies that applied PCA for parameter selection in bridge pier or scour formula development (Harasti, 2022; Annad, 2023), this multivariate analysis provides a clearer understanding of which parameters dominate the scour process under real offshore conditions

280 An additional approach to reducing the complexity of multivariate datasets is to initially group the data based on
281 a selected key variable. Accordingly, the PCA was also applied to the dataset after it had been grouped by grain
282 size (d_{50} diameter) classes (Annad et al., 2021), given that the sediment characteristics of the seabed play a
283 significant role in local scour (Qi et al., 2016). This approach facilitated a more precise estimation of local scour,
284 thereby reducing uncertainties related to sediment.

285 3 Results

286 3.1 Spatial distribution of relative scour depth

287 To illustrate the variability in relative scour depth between the nine studied OWFs and within single OWFs, Figure
288 3 shows the spatial distribution of relative scour depth. There are clear differences between OWFs in both the
289 magnitude and variability of relative scour depth. For example, at OWF Robin Rigg (Figure 3.A), the highest
290 relative scour depth were identified, the values range from $S/D=0.29$ to $S/D=2.49$. This OWF is characterised by
291 fine and medium sands. In contrast, the smallest relative scour depth occurred at the OWF of Lynn and Inner
292 Dowsing (Figure 3.F), with values from $S/D=0.12$ to $S/D=0.92$, which is possibly linked to coarse sands presented
293 at this site. Furthermore, the highest variability ($\sigma = 0.44$) in relative scour depth were detected at OWF London
294 Array (Figure 3.H) and Barrow (Figure 3.B), likely influenced by the complex seabed morphologies and sediment
295 compositions in these areas. On the other hand, the significant variability at London Array may be explained by
296 the presence of the Long Sand and Kentish Knock sandbank. This illustrates how different site characteristics can
297 result in various scour distributions, even within a single OWF.
298 The remaining OWFs showed relatively low relative scour depth and little spatial variability, even though site
299 conditions were significantly different, as indicated by their seabed conditions from very fine sand for Teesside
300 (Figure 3.C) to coarse and very coarse gravel for Humber Gateway (Figure 3. D).

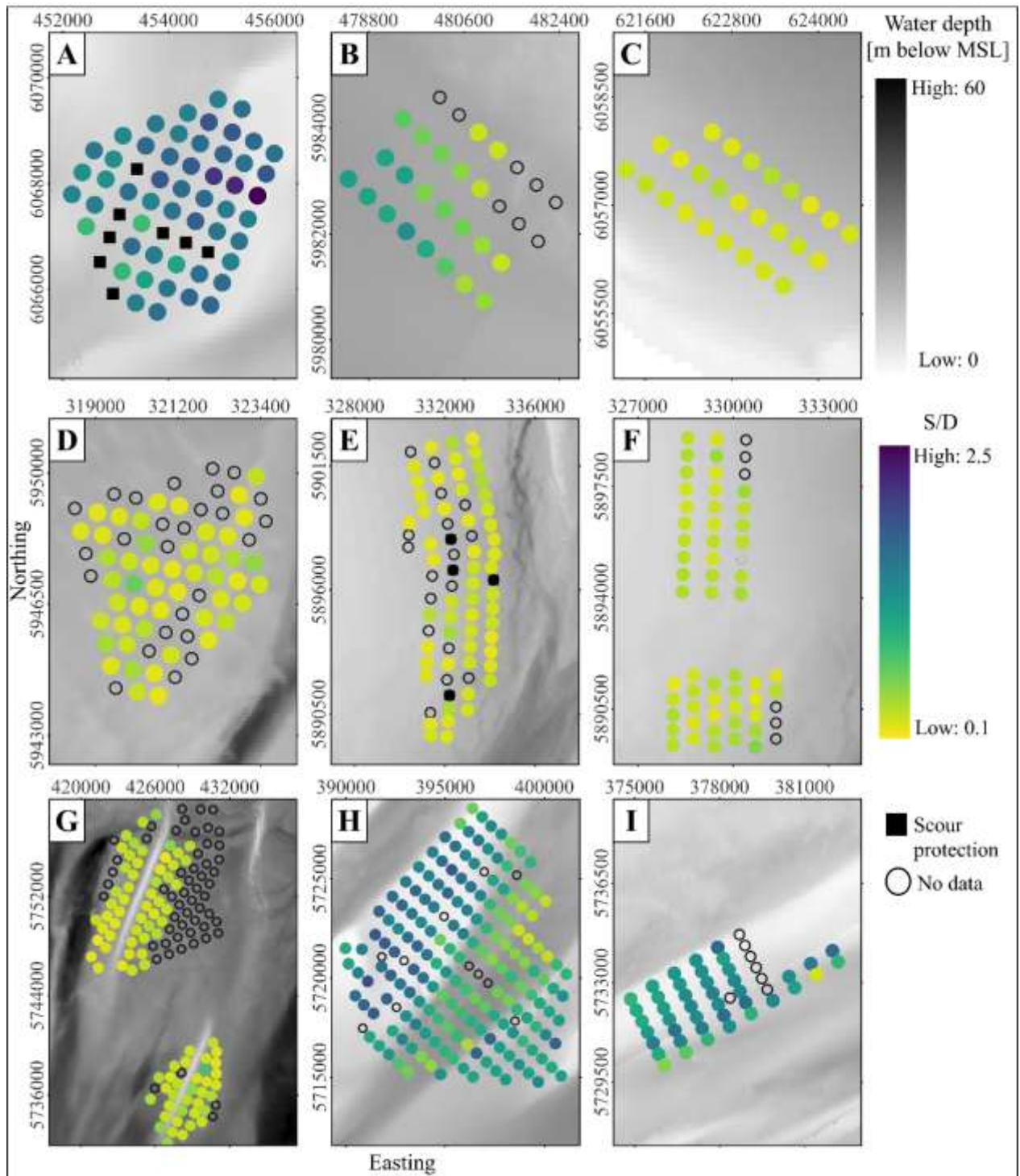
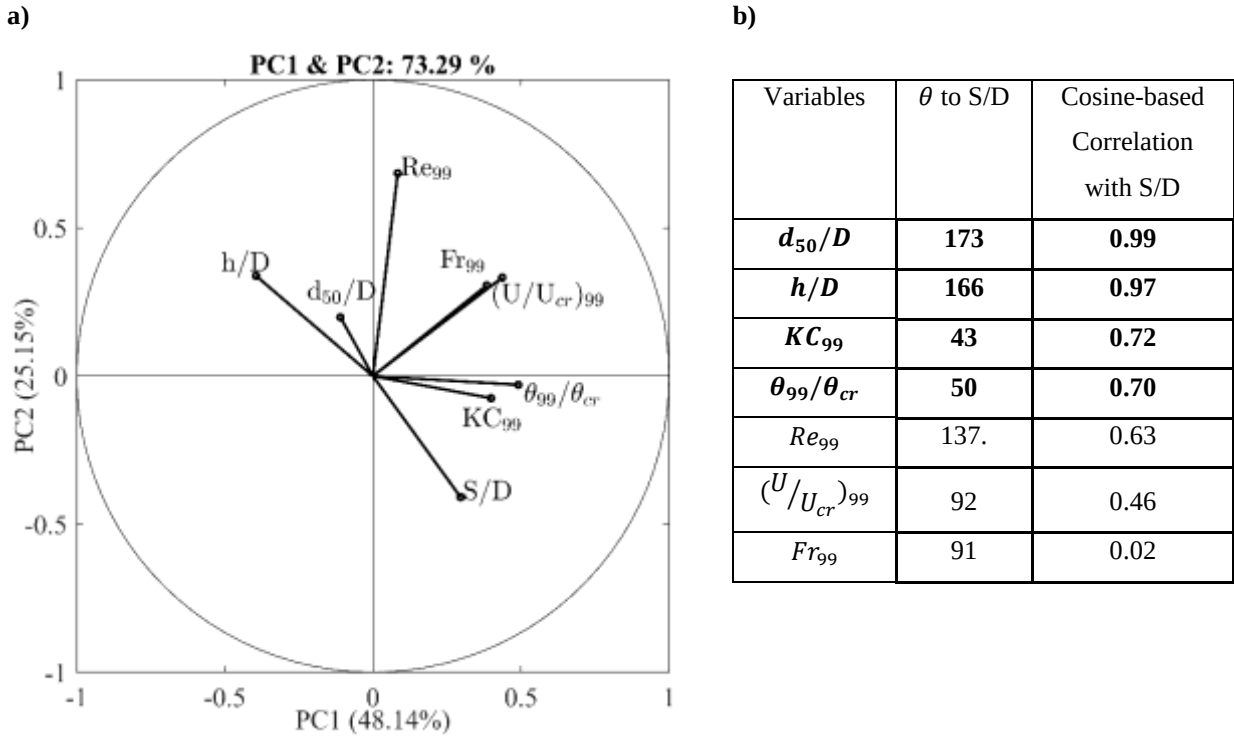


Figure 3: Spatial distribution of relative scour depth at the nine studied OWFs. Letters (A-I) denote the locations of Robin Rigg, Barrow, Teesside, Humber Gateway, Lincs, Lynn and Inner Dowsing, Greater Gabbard, London Array, and Gunfleet Sands OWFs, respectively. The upper colourmap represents water depth, with darker shades indicating deeper water. The lower colourmap indicates relative scour depth, with darker blue colour indicating the largest scour. Black filled squares represent OWES with scour protection, while empty circles denote missing data. Shown bathymetry data originates from EMODNET (<https://emodnet.ec.europa.eu/en/bathymetry>).

3.2 Principal Component Analysis (PCA)

310 The analysis of Figure 3 reveals notable variations in relative scour depth across individual OWFs. This variance
311 underscores the need for a more detailed examination of specific wind farm characteristics to identify the drivers
312 of scour. To this end, a PCA was conducted to correlate relative scour depth and selected parameters by identifying
313 and quantifying their relationships. The PCA biplot presented in Figure 4 illustrates these correlations between
314 relative scour depth and the studied variables and provides a comprehensive view of how different factors interact
315 and influence relative scour depth.



316 **Figure 4: a) PCA biplot, illustrating the correlation between variables and relative scour depth. b) The table**
317 **detailing the angles between the relative scour depth and the other variables (in degrees), along with the**
318 **magnitude cosine-based correlation (values from 0 to 1), where values closer to 1 indicates stronger**
319 **correlation. Boldface highlights the variables with the strongest correlation with relative scour depth.**

320 As shown in the biplot, PC1 and PC2 account for 73.29% of the variation in the data set. This high percentage
321 indicates that these two components capture most of the significant patterns in the data, allowing for a meaningful
322 interpretation of the relationships among the variables. In the biplot, each vector stands for a variable, with the
323 direction and magnitude of the vector reflecting its contribution to the principal components. The variables that
324 contribute the most to the variance in PC1 are the mobility parameter, the Froude number, and Keulegan Carpenter
325 number, with shares of 0.49, 0.43, and 0.39, respectively. In contrast, the variance in PC2 is primarily explained
326 by the pile Reynolds number, the relative water depth and the Froude number, with shares of 0.68, -0.34, and 0.33,
327 respectively. This significant contribution of the mobility parameter, the Froude number, and the Keulegan
328 Carpenter number to PC1 suggests that variations in these hydrodynamic parameters are critical in shaping the
329 principal dynamics of the dataset. The table (Fig. 4b) next to the biplot provides further insight by showing the
330 angular distances between the S/D vector and each of the other variables, as well as their respective correlation
331 coefficients. One of the key observations is that the relative scour depth has the strongest negative correlation of
332 0.99 with the relative grain size. This highlights the critical influence of sediment size on scouring processes, even
333 though it does not account for much of the variance captured by the first two principal components. This

observation can be explained by the underlying physical processes that affect scour depths. As noted by Whitehouse (2010) for non-cohesive sediments, larger sediment sizes are more resistant to erosion, resulting in reduced scour depths. Therefore, while relative grain size is strongly correlated with scour depths, it does not explain the broader variability in the data that is influenced by other factors. The next strongest correlation is with the relative water depth with a correlation factor of 0.97, which underscores the critical role of water depth in governing scour intensity. Shallower relative depths concentrate flow energy at the bed, intensifying near-bed velocities and shear stresses that promote deeper scour holes (Smith & McLean, 1977; Whitehouse, 2010). Furthermore, a significant positive correlation was found with the Keulegan-Carpenter number with a correlation factor of 0.72, indicating the importance of oscillatory flow conditions in scour development. Higher Keulegan Carpenter number directly leads to higher relative scour depth (Sumer and Fredsoe, 2002). This is driven by the onset of the horseshoe vortex and lee-wake eddy shedding (Sumer et al., 1992b; Zanke et al., 2011), with increased permanence of the horseshoe vortex and amplification of bed shear stresses at higher KC values (Sumer et al., 1997). In addition, the mobility parameter exhibits a strong positive correlation (0.70) with the relative scour depth. The mobility parameter quantifies the instantaneous capacity of the flow to exceed the entrainment threshold, driving rapid sediment entrainment when significantly above unity (Soulsby, 1997; van Rijn, 1993). Variables such as the pile Reynolds number, the flow intensity, and the Froude number, although less correlated with relative scour depth, contribute more to the total variance. This suggests that these flow-related variables influence relative scour depth through more complex or non-linear interactions with other hydrodynamic conditions and sediment characteristics.

Given that the initial PCA analysis indicates the strongest negative correlation between the relative grain size and relative scour depth, and since seabed sediment characteristics play a significant role to local scour (Qi et al., 2016), the PCA was applied again to the same dataset but pre-clustered into different soil classes (Annad et al. 2021). By reducing the uncertainties related to grain size (d_{50}), this analysis should provide a better estimation of the local scour. This classification also facilitates the identification of parameters that are more influential in estimating scour for specific soil classes, rather than uniformly across different types. After the clustering, six soil classes were obtained: cohesive sediment ($d_{50} \leq 63 \mu m$) with 5 data points, fine sand ($63 \leq d_{50} < 200 \mu m$) with 203 data points, medium sand ($200 \leq d_{50} < 630 \mu m$) with 249 data points, coarse sand ($630 \leq d_{50} < 2000 \mu m$) with 170 data points, fine gravel ($2000 \leq d_{50} < 6300 \mu m$) with 18 data points, and medium gravel ($d_{50} \geq 6300 \mu m$) with 49 data points.

3.3 Principal Component Analysis (PCA) by clustered soil classes

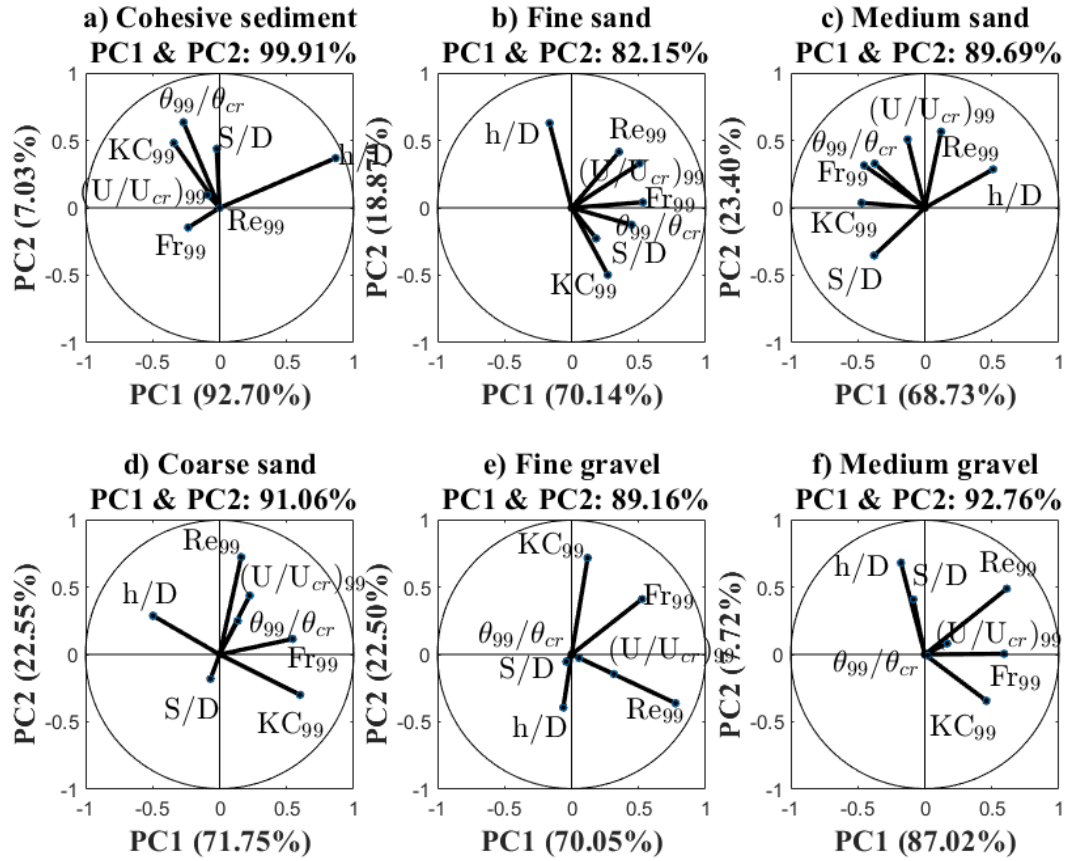


Figure 5: PCA correlation by clustered soil classes based in the grain size (d_{50}), remaining parameters that are shown in the biplots are explained in data description (section 2.2). a) Cohesive sediment ($d_{50} \leq 63 \mu m$). b) Fine sand ($63 \leq d_{50} < 200 \mu m$). c) Medium sand ($200 \leq d_{50} < 630 \mu m$). d) Coarse sand ($630 \leq d_{50} < 2000 \mu m$). e) Fine gravel ($2000 \leq d_{50} < 6300 \mu m$). f) Medium gravel ($d_{50} \geq 6300 \mu m$). Clustering of the grain size (d_{50}) was based on Annad et al. (2021).

Building on the initial PCA analysis, which emphasized the significant influence of grain size on relative scour depth, a more detailed investigation was conducted by categorizing the dataset into six soil classes: cohesive sediment ($d_{50} \leq 63 \mu m$) with 5 data points, fine sand ($63 \leq d_{50} < 200 \mu m$) with 203 data points, medium sand ($200 \leq d_{50} < 630 \mu m$) with 249 data points, coarse sand ($630 \leq d_{50} < 2000 \mu m$) with 170 data points, fine gravel ($2000 \leq d_{50} < 6300 \mu m$) with 18 data points, and medium gravel ($d_{50} \geq 6300 \mu m$) with 49 data points.

Figure 5 shows PCA biplots for each soil class illustrating the relationships between relative scour depth the relative water depth, the Keulegan-Carpenter number, the mobility parameter, the pile Reynolds number, the flow intensity and the Froude number. The first two principal components (PC1 and PC2) explain between 82 % and 99% of the variance within each class, thus describing more of the variance in comparison to when the PCA was applied to all data. Data complexity seems to be greatly reduced by just removing the effect of sediment. In the cohesive sediment soil class (Figure 5a), relative scour depth is positively correlated with the mobility parameter. However, the calculation of the mobility parameter might contain larger uncertainties for cohesive soils (Soulsby, 1997), so the results should be treated with caution.

In contrast, relative water depth has a strong negative correlation with relative scour depth in fine sand (Figure 5b) and medium sand (Figure 5c). This indicates that as relative water depth increases, relative scour depth tends to

decrease in these finer soil classes. From a physical view, Melling (2015) found out that in similar substrates, relative scour depth agree well between different geographic locations and showed that OWES located in sandy sediments exhibit a strong influence of relative water depth on scour, suggesting geotechnical factors are less influential in coarser sediments. Although the observation that relative scour depth decreases as relative water depth increases might initially seem counterintuitive. This behaviour is best explained through the transition between shallow-water and deep-water flow regimes. As flow approaches a pile, stagnation pressure develops on its upstream face, causing the flow to separate into an up-flow and a down-flow component. The down-flow is directed toward the bed and promotes the formation of a horseshoe vortex. Flow separation occurs at the stagnation point, defined as the location of maximum energy from the approaching flow at the pile face. The energy of the approach flow consists of hydrostatic and kinetic components, whose vertical distribution is governed by the boundary layer. In shallow water, the kinetic component dominates over hydrostatic pressure, resulting in a stagnation point located higher up the pile, near the water surface. This enhances down-flow and vortex activity, intensifying scour processes (Melville, 2008). Additionally, shallower water often features thinner boundary layers with higher velocity gradients near the seabed, potentially leading to greater bed shear stresses and increased sediment mobility. In contrast, in deeper water, hydrostatic pressure becomes more influential, leading to a more uniform pressure field across the pile face and shifting the stagnation point closer to the bed. This results in weaker down-flow and reduced vortex strength, thereby diminishing the scour depth (FHWA, 2012; Harris & Whitehouse, 2014). Furthermore, Link and Zanke (2004) observed that maximum relative scour depth tends to develop more slowly and reach lower values in deeper water depth, even under constant average flow velocity, due to reduced shear velocity over the undisturbed bed. This highlights that the relationship between relative water depth and scour is not necessarily linear.

The dynamics observed in coarse sand (Figure 5d) and fine gravel (Figure 5e) are different from the finer sediments. In these classes, the flow intensity and the Froude number show significant negative correlations with relative scour depth, indicating that higher values of these parameters correspond to reduced relative scour depth. However, these soil classes are also characterised by comparatively small relative scour depth, which makes the relationship less prominent.

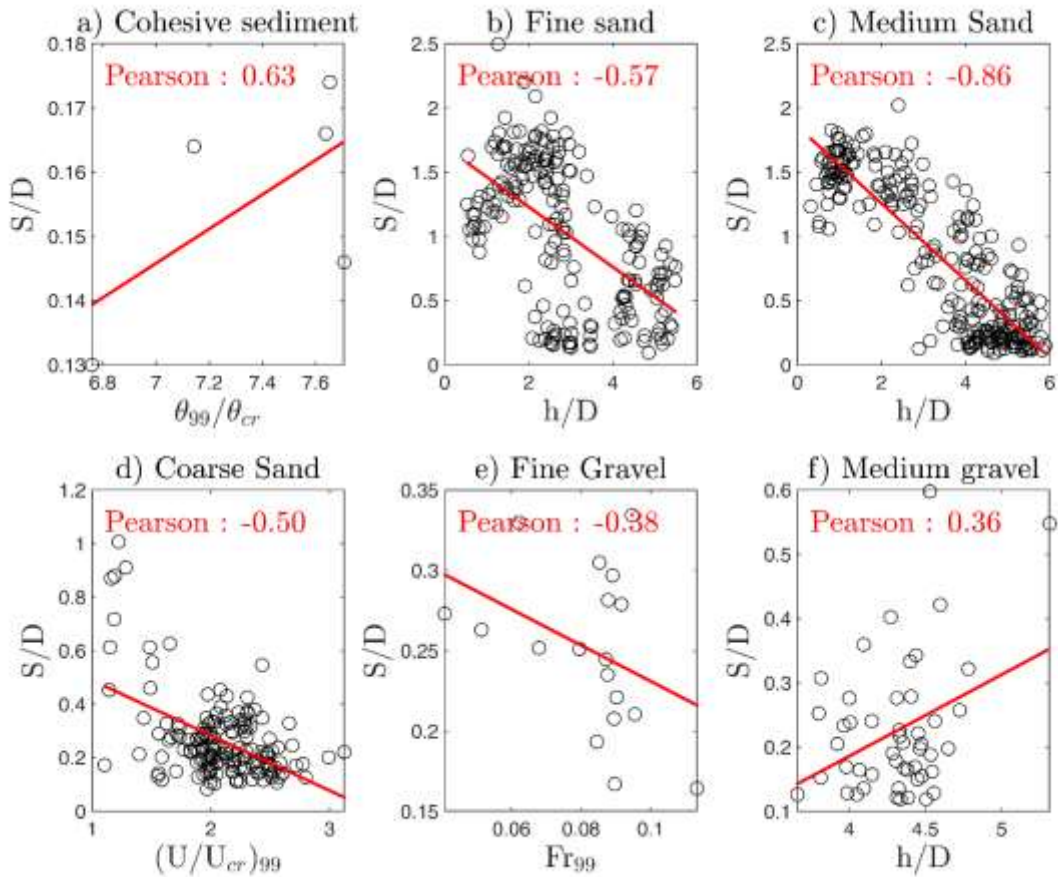
For medium gravel (Figure 5f), relative water depth has a positive correlation with relative scour depth, meaning that greater relative water depth is associated with greater relative scour depth in coarser sediments. The data points in the cluster can be attributed to the Humber Gateway OWF, which is the only OWF that features clear-water conditions. Given the large grain sizes, a smaller influence of flow parameters on the variability of relative scour depth should be expected.

3.4 Correlation of scour depth with main drivers

Following the PCA (Figure 5), which identified the primary variables influencing relative scour depth across soil classes, a Pearson correlation analysis was performed to quantify the strength and direction of these relationships. Figure 6 shows the Pearson correlation results for each cluster and the variable with the strongest correlation, with the red lines representing the linear regression fit and the correlation coefficients shown in red text. The Pearson correlation was calculated by the following equation:

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \dots\dots\dots (9)$$

422 Considering the small number of data points in this sediment cluster, relative scour depth at locations with cohesive
 423 sediments (Fig. 6a) shows a moderate correlation between scour with the mobility parameter. For the fine and
 424 medium sand clusters, the PCA revealed a similarly strong dependence of relative scour depth on relative water
 425 depth. Plotting relative scour depth against relative water depth now shows a clearer correlation and hence
 426 dependence for the medium sand sites (Fig. 6c) than for the fine sand sites (Fig. 6b). The Pearson coefficients of -
 427 0.57 and -0.86 confirm this difference in the dependence of relative scour depth on relative water depth. The
 428 correlations of the fine and medium sand clusters are supported by a larger number of data points, increasing the
 429 reliability of the findings.



430

431 **Figure 6: Pearson correlation of representative variables obtained by PCA analysis with relative scour**
 432 **depth across different soil classes. a) Cohesive sediment ($d_{50} \leq 63 \mu m$). b) Fine sand ($63 \leq d_{50} < 200 \mu m$).**
 433 **c) Medium sand ($200 \leq d_{50} < 630 \mu m$). d) Coarse sand ($630 \leq d_{50} < 2000 \mu m$). e) Fine gravel ($2000 \leq$**
 434 **$d_{50} < 6300 \mu m$). f) Medium gravel ($d_{50} \geq 6300 \mu m$).**

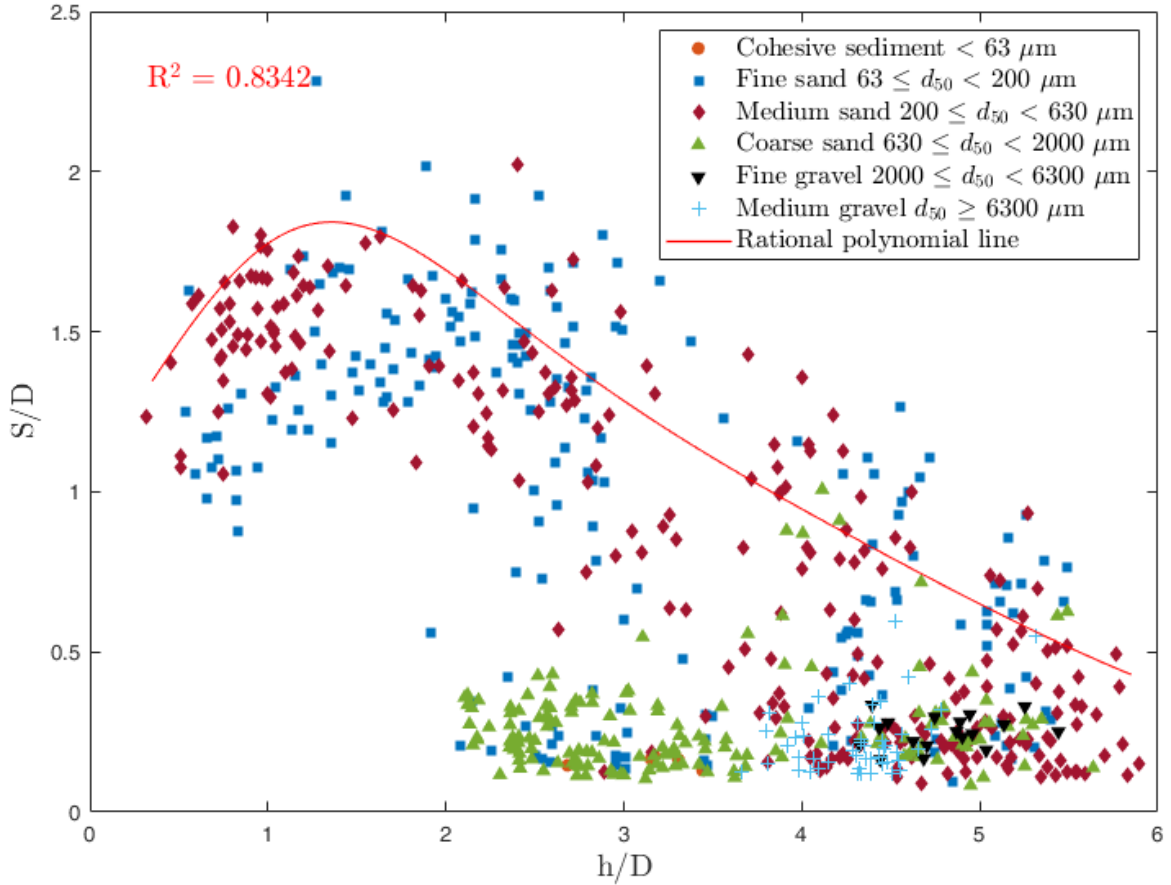
435 For the coarse sand (Figure 6d), the PCA analysis revealed a negative correlation between relative scour depth and
 436 flow intensity. This result directly aligns with the established understanding of live-bed scour behaviour in coarse-
 437 grained sediments. Once flow intensity surpasses the critical threshold ($(U/U_{cr})_{99} > 1$), the sediment mobilizes,
 438 establishing live-bed conditions. In such scenarios, the development of large, well-defined scour holes is
 439 consistently observed to be suppressed. This suppression occurs because the continuous transport and
 440 replenishment of sediment into the scour region actively works against deep erosion. This dynamic equilibrium of
 441 the seabed results in shallower, or inherently more unstable, scour holes when compared to clear-water conditions.

442 In clear-water, where sediment remains immobile, scouring is driven purely by flow-induced vortex action around
 443 the structure (Sumer & Fredsøe, 2002; Whitehouse et al., 2011). Consequently, the negative correlation observed
 444 in this soil class accurately reflects the inherent limitation of scour growth under the highly mobile conditions
 445 characteristic of coarse sandy beds.

446 For fine gravel (Figure 6e), the PCA suggests a correlation between relative scour depth and the Froude number,
 447 but this is difficult to confirm visually due to the small sample size and narrow Froude number range. Since relative
 448 scour depth is comparatively small in this class, relationships are less clear, and parameters like Froude number
 449 come to the foreground that were not as prominent in finer sediments. A broader distribution of Froude
 450 number values would be necessary to confirm this more conclusively.

451 Finally, medium gravel (Figure 6f) displays a positive correlation between relative scour depth and relative water
 452 depth, with a Pearson coefficient of 0.36. This indicates that larger relative water depth correspond to increased
 453 scour depth, although the range of this increment remains small (between $S/D = 0.1$ and $S/D = 0.4$). This variation
 454 in scour depth is small compared to the correlations observed in fine and medium sands, where changes in relative
 455 water depth yield more pronounced differences in relative scour depth. The smaller impact in medium gravel may
 456 be attributed to the generally greater resistance of larger sediments to scour, even with increasing relative water
 457 depth.

458 The most significant correlations emerge from the fine sand (Figure 6b) and medium sand (Figure 6c), where
 459 strong negative correlations between relative scour depth and relative water depth are observed. This suggests that
 460 significant scour occurs in shallower waters with finer sediments. Such findings highlight the importance of
 461 relative water depth as a key factor influencing scour processes in specific sediment types, emphasizing that scour
 462 management and predictions for offshore structures should take sediment characteristics and relative water depth
 463 into account. These results are consistent with the studies from Melling (2015) and Harris and Whitehouse (2014),
 464 which also show a decrease in relative scour depth in finer sediments as relative water depth increase. This negative
 465 correlation can be explained by the reduction in bed shear stress with increasing relative water depth, which limits
 466 sediment mobilization, particularly in fine and medium sands (Sumer & Fredsøe, 2002; Fredsøe & Sumer, 2014).
 467 However, those results disagree with experimental work where scour around a monopile weakens with reducing
 468 relative water depth (e.g. May and Willoughby, 1990; Whitehouse, 1998). Consequently, relative water depth is
 469 included as a parameter in many empirical formulas, especially in for scour around bridge piles with limited water
 470 depth (eg., Laursen, 1963; Hancu, 1971; Breusers et al., 1977; May and Willoughby, 1990; Richardson et al.,
 471 2001). Besides that, these insights from field data are critical for the accurate assessment and planning of offshore
 472 infrastructure installations, particularly in regions with varying sediment characteristics.



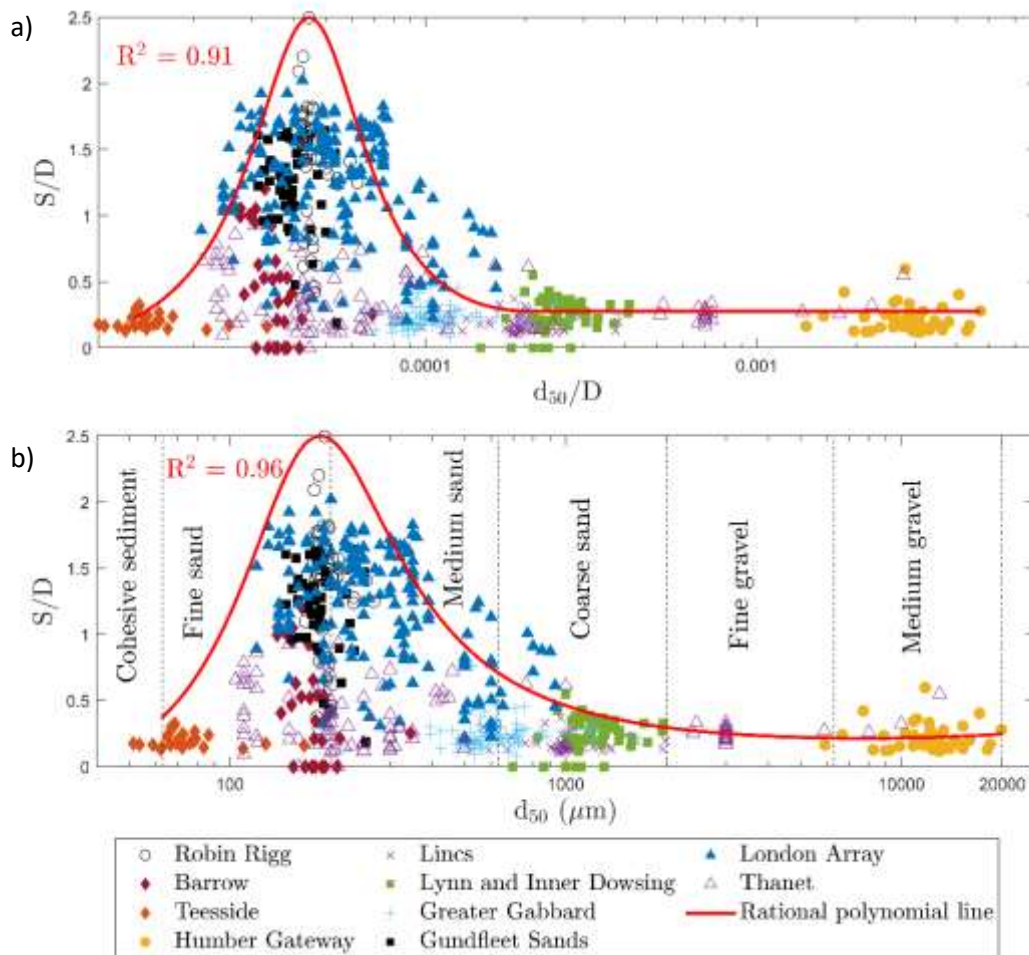
473

474 **Figure 7: Relative scour depth vs relative water depth, and soil classes. The solid red curve represents a**
 475 **rational polynomial fit to the 99th percentile of relative scour depth. Data points for London Array and**
 476 **Thanet OWFs are included from Melling (2015).**

477 Figure 7 summarizes the findings from the PCA analysis (Figure 4) by plotting the relationship between the relative
 478 scour depth and the relative water depth. Relative water depth has shown to be the one of the parameters with the
 479 largest correlation influencing relative scour depth. However, it should be noted that relative water depth has a
 480 direct effect on other hydrodynamic parameters. For example, not only is the Froude number formed with the
 481 water depth, but relative water depth also significantly determines the potential influence of waves on the
 482 development of scour, which in this study has also been considered by the Keulegan–Carpenter number. Therefore,
 483 it remains unclear whether the influence of relative water depth on relative scour depth is a direct causal factor or
 484 an indicator of broader changes in hydrodynamic conditions. Nevertheless, Figure 7 illustrates the comprehensive
 485 correlation between the relative scour depth and the relative water depth with different markers (colour and shape)
 486 representing the studied soils classes. The solid red curve shows a correlation between relative scour depths across
 487 all relative water depths, independent of sediment class. This curve was systematically developed by fitting a
 488 rational polynomial function to the 99th percentile values of relative scour depth, computed within uniform relative
 489 water depth intervals (e.g., 0.1).

490 The correlation observed in Figures 6b and 6c is reaffirmed in Figure 7. A distinct relationship exists between the
 491 relative scour depth and relative water depth in these two sediment types, i.e. both fine sand ($63 \leq d_{50} < 200 \mu m$)
 492 and medium sand ($200 \leq d_{50} < 630 \mu m$) show that the relative scour depth decreases with increasing relative
 493 water depth. This correlation appearing throughout the bigger dataset emphasizes a strong negative correlation

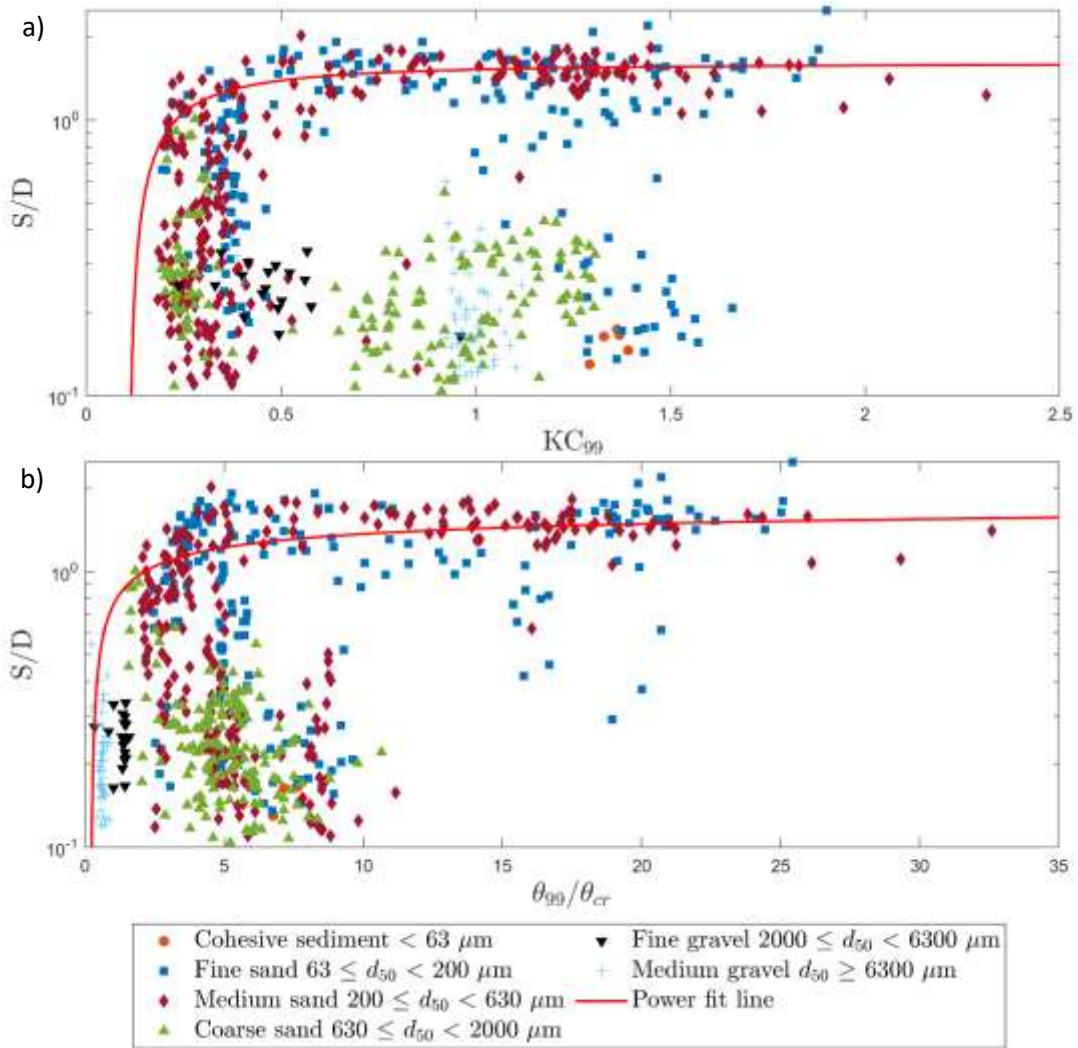
494 between relative water depth and relative scour depth for those soil classes. This behaviour is consistent with
 495 findings from previous analyses that identified relative water depth as a critical factor in shaping scour dynamics
 496 (Whitehouse et al., 2010 and Melling, 2015).
 497 In contrast, for sediments with median grain diameters above coarse sands ($d_{50} \geq 630 \mu\text{m}$) the relative scour depth
 498 remains relatively constant and shows little variability. Figure 7 suggests a generally stable relationship between
 499 relative scour depth and relative water depth for these soil classes, where changes in relative water depth do not
 500 significantly alter relative scour depth. However, there are a few exceptions. For example, some locations with
 501 coarse sand located in deeper water exhibit unexpectedly large relative scour depth. These outliers might stem
 502 from site-specific conditions such as dynamic sandbanks and highly variable bathymetry, as seen at the London
 503 Array OWF (Sturt et al., 2009). These unique environments, characterised by flow recirculation and sediment
 504 mobility, can lead to deviations from expected scour behaviour (Melling, 2015). The results for fine and medium
 505 sands suggest a potential influence of relative water depth in reducing relative scour depth. Although these results
 506 are preliminary, they provide a first step in understanding how offshore wind OWES could affect sediment
 507 redistribution in regions dominated by these sediment types and small relative water depth.



508
 509 **Figure 8: Relative scour depth against (a) the relative grain size, and (b) grain size. The solid red curves**
 510 **represent the rational polynomial line fits to the 99th percentile of relative scour depth, for various relative**
 511 **grain size and grain size .Data points for London Array and Thanet OWFs are included from Melling**
 512 **(2015).**

513 Figure 8a summarizes the findings from the PCA analysis (Figure 4) by plotting the relationship between the
 514 relative scour depth and relative grain size across all the sampled locations. Figure 8b is also shown here to support

515 figure 8a by representing the data in terms of the grain size, allowing the comparison of dimensional and non-
 516 dimensional relative grain size. Figures 8a and 8b illustrate a discernible correlation where the largest relative
 517 scour depth occurs predominantly in fine to medium sands, as indicated by the rational polynomial line which
 518 approximates the upper limit of relative scour depth for various relative grain size (Figure 8a) and grain size (Figure
 519 8b). Similar to the correlation presented in Figure 7, this curve approximate upper limit of S/D and it was derived
 520 by fitting a rational polynomial function to the 99th percentile values of relative scour depth, computed within
 521 uniform interval of relative grain size (e.g., 0.00001) and grain size (e.g., $25 \mu\text{m}$). The correlation shown in figures
 522 8a and 8b are well explained. In general, the mobility potential of the sediments decreases with increasing grain
 523 size, which leads to lower relative scour depth for coarser sediments. Very fine sediments, on the other hand, are
 524 subject to the influence of cohesion forces that reduce their erodibility, which also leads to lower relative scour
 525 depth. Therefore, fine and medium sandy sediments have the largest scour potential, which is reflected in the data
 526 of Fig. 8b. The different symbols represent the OWF, highlighting the geographic spread and variability within the
 527 dataset. However, it is important to note that most of the data points fall within the range of fine to medium sands,
 528 potentially skewing the interpretation.



529

530 **Figure 9: Relative scour depth against the a) Keulegan-Carpenter number and b) the mobility parameter.**

531 **The red line gives the power fit line based on the 99th percentile of the data of relative scour depth for**
532 **various grain size. Data points for London Array and Thanet OWFs are included from Melling (2015).**

533 The third and fourth parameters, that correlate with the relative scour depth, are the Keulegan-Carpenter number
534 and the mobility parameter as identified by the PCA. Figure 9a shows the correlation between the relative scour
535 depth and the Keulegan-Carpenter number, revealing a distinct increase of relative scour depth with increasing
536 Keulegan-Carpenter number up to $KC_{99} = 0.5$. Above this value, relative scour depth shows little variation with
537 further increase of the Keulegan-Carpenter number, which reaches a maximum value of 2.5 in this field dataset.
538 Those results are generally consistent with findings from previous studies (e.g., Qu et al., 2024; Sumer & Fredsøe,
539 2002), which indicate that scour development is strongly dependent on KC_{99} at lower values, but becomes less
540 sensitive as KC_{99} increases. However, experimental studies often focus on wave regimes with KC numbers greater
541 than 6, since it has been established that this is the threshold for generating a horseshoe vortex. Despite considering
542 the 99th percentile of KC numbers over the time period in question, the KC numbers are much smaller for the field
543 conditions presented herein. This strengthens the argument for further scour research to focus on boundary
544 conditions with low KC values.

545 Figure 9b shows the correlation between relative scour depth and mobility parameter, comparing the Shields
546 parameter with its critical threshold for sediment motion, and revealing a distinct increase of relative scour depth
547 with increasing mobility parameter up to approximately $\theta_{99}/\theta_{cr} = 5$. At higher mobility values (typically above 5–
548 10), the increase in scour depth tends to stabilize. This correlation aligns with experimental observations from
549 Sumer et al. (2013), Chiew (1984), and others, which describe similar stabilization of scour depth under fully
550 mobile conditions. Notably, the response also varies with sediment type: coarser sediments exhibit low relative
551 scour depth values even at high mobility ratios, likely due to their higher resistance to entrainment and potential
552 armoring effects. In contrast, finer sediments (e.g., $d_{50} < 200 \mu m$) show a steeper increase in scour depth,
553 reflecting their greater susceptibility to hydrodynamic conditions.

554 Overall, Figure 9a and 9b emphasize the nonlinear and sediment-dependent nature of scour formation. The
555 separation of correlations by soil class supports the need for sediment-specific scour prediction models, as also
556 suggested in previous studies (e.g., Whitehouse et al., 2011; Sumer & Fredsøe, 2002). The results provide empirical
557 evidence of this dependency using field-scale data, bridging a critical gap between controlled experiments and
558 real-world conditions.

559 **3.5 Detailed analysis of scour patterns for selected OWFs**

560 Following the observed overall correlation shown in Figure 7, this section moves on to examine scour patterns
561 within individual OWFs, such as Robin Rigg, Lynn and Inner Dowsing, and London Array. This specific analysis
562 will assess whether the global relationship between relative scour depth d_{50} , and relative water depth holds under
563 the unique environmental conditions of each site. This section aims to further our understanding of the dynamics
564 between sediment characteristics and scour processes by a detailed analysis of the variation within each wind farm
565 to determine if these global correlations are consistent at the local scale or if there are deviations due to site-specific
566 factors.

567 **3.5.1 Robin Rigg OWF**

568 Robin Rigg is presented and discussed in this section, as this OWF has the largest overall relative scour depth of
569 all the OWFs. This detailed analysis will help to investigate whether the negative correlation between relative

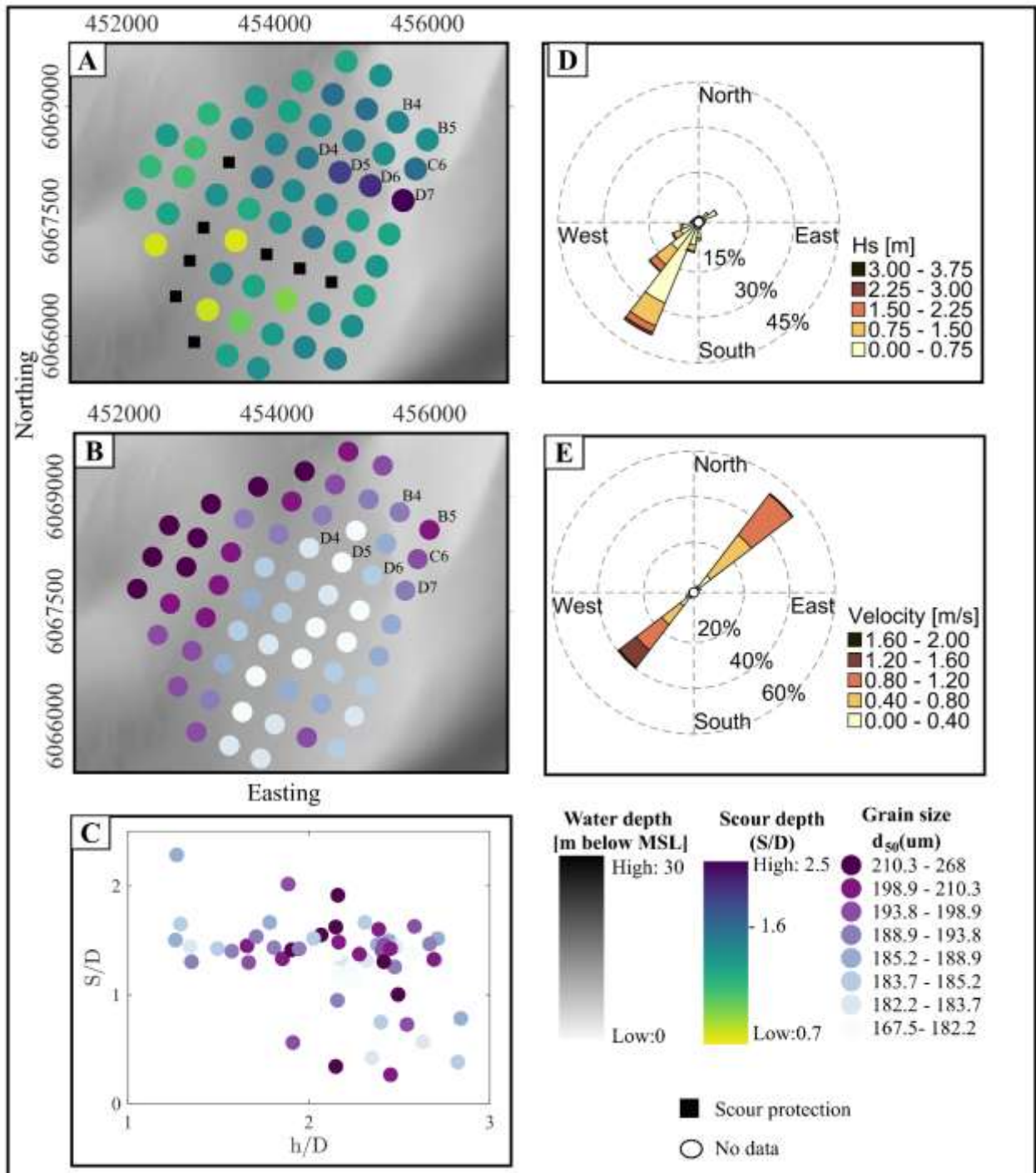
570 scour depth and relative water depth observed globally in Figure 7 holds true under variable geotechnical
 571 conditions, taking into account that sediment grain sizes range from fine to medium sands.

572 Figure 10 shows the distribution of relative scour depth at Robin Rigg in relation to the variable geotechnical and
 573 hydrodynamic site conditions. This sequence begins with Figure 9A, showing the spatial distribution of scours
 574 measured one year after turbine installation. A significant variation in relative scour depth in different areas of the
 575 OWF can be observed, with the deeper relative scour depth mainly located in the north-eastern part, particularly
 576 around OWES D7, C6, B5 and B4, which are located in the shallowest waters. Figure 10B shows the spatial
 577 distribution of the median grain diameter d_{50} in the uppermost sediment layer in 2005, with sediment sizes
 578 predominantly in the range of fine to middle sand (182 μm to 268 μm). OWES in areas with finer sands, such as
 579 D4, D5, and D6, are observed to generally experience the large scour, consistent with previous observations by
 580 Whitehouse (2006) that finer sand substrates are more susceptible to scour.

581 Figure 10C shows the correlation of relative scour depth and relative water depth, classified by coloured points
 582 which represent sediment grain size from figure 9B. Contrary to the clear negative correlation between relative
 583 scour depth and relative water depth observed globally in Figure 8, Figure 10C shows a wide distribution of data
 584 points with no clear correlation, suggesting that local factors in addition to relative water depth and sediment type
 585 have an influence on scour at this site.

586 For additional insight, Figures 10D and 10E show the distribution of the directions of significant wave heights, as
 587 well as the directions of current velocity magnitudes one-year period, prior the post scan. The highest wave heights
 588 came predominantly from the southwest, which should influence sediment mobility and thus scour structures along
 589 this direction and especially in shallow relative water depth where wave-induced shear stresses should be higher.

590 Similarly, the tidal current, with its main directions of south-west and north-east, should result in a change in
 591 relative scour depth along this main axis. However, a clear correlation of relative scour depth changing in this
 592 direction is not given for Robin Rigg.



593

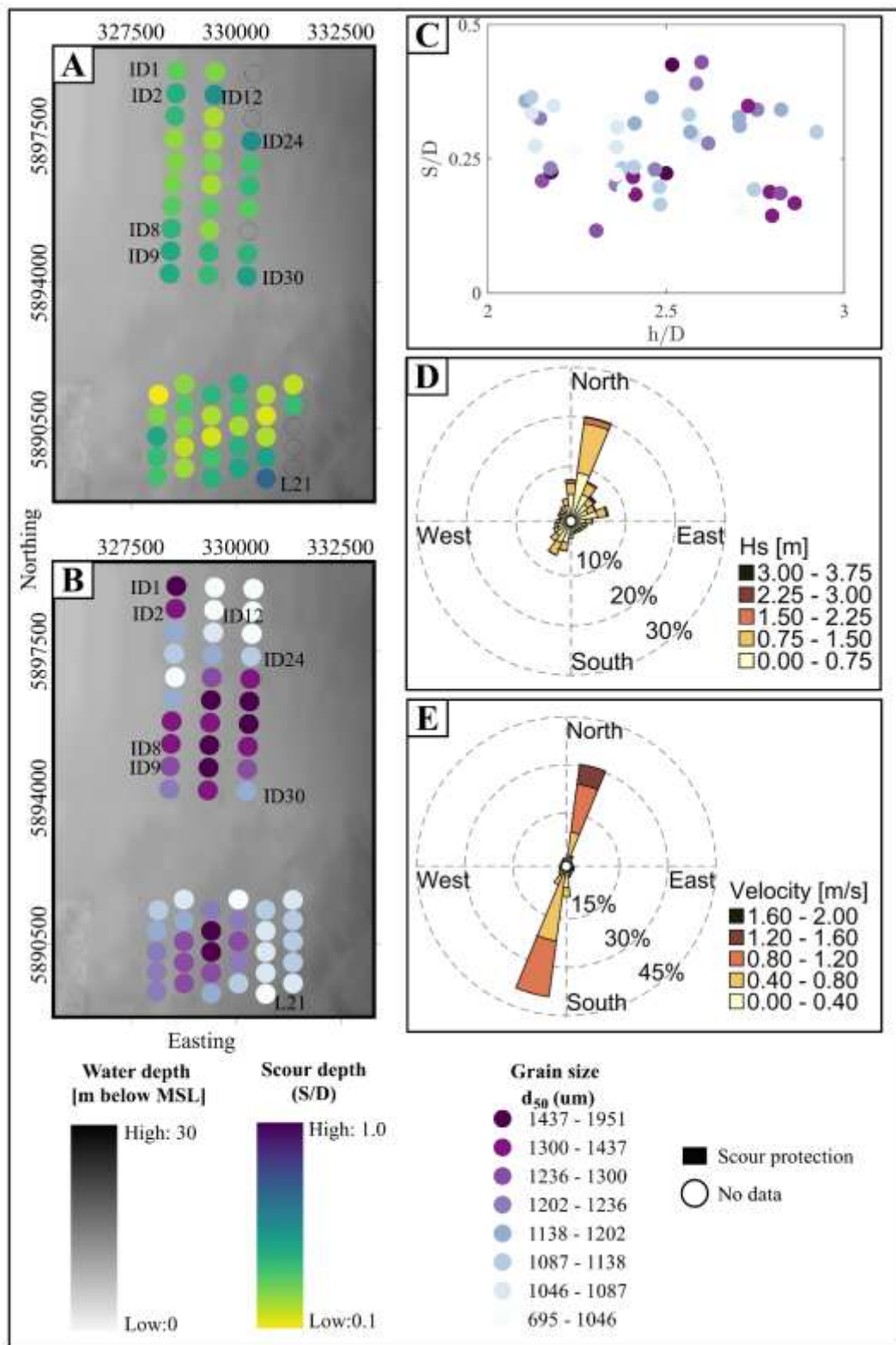
594 **Figure 10: A) Spatial distribution of relative scour depth from 2008-2009 at Robin Rigg OWF. B) Grain-**
 595 **size distribution. C) Relative scour depth vs relative water depth, and grain size classification. D) Significant**
 596 **wave heights and E) Current velocities.**

597 This comprehensive analysis using Figures 10A to 10E shows that while correlations obtained from global findings
 598 provide a useful baseline for understanding scour, the actual scour observed at Robin Rigg does not necessarily
 599 follow those correlations. While the distribution of relative scour depth appears to be strongly influenced by local
 600 environmental conditions such as sediment type, waves and currents, the dominant influence among these cannot
 601 be clearly identified, rather the distribution of relative scour depth appears to be due to the interaction of all
 602 influences.

603 The discrepancies between the local scour behaviour at Robin Rigg and the broader correlations observed in Figure
604 7 underscore the need for site-specific assessments. Such detailed analyses are critical to the development of
605 effective scour management and mitigation strategies tailored to the unique conditions of each offshore wind farm.

606 3.5.2 Lynn and Inner Dowsing OWF

607 Lynn and Inner Dowsing was chosen as a further example as this OWF had the lowest relative scour depth of all
608 the OWFs investigated and is also characterised by coarse to very coarse sands. Figure 11 provides the same
609 analysis as Figure 10 by providing insight into how local conditions compare to the global correlation seen in
610 Figure 7. Figure 10A shows the spatial distribution of relative scour depth measured from 2007 to 2010. Figure
611 11A shows that the largest relative scour depth are mainly concentrated in the Inner Dowsing area, especially
612 around OWES ID1, ID2, ID8, ID9, ID12, ID24, and ID30. Except for turbine L21, which has the deepest relative
613 scour depth in the entire wind farm and which is located at the south-eastern end. The significant relative scour
614 depth observed at certain locations (e.g., D30, L21) are related to cable exposure (EGS Ltd, 2012; EGS Ltd, 2013),
615 while smaller relative scour depth are more common in the southern region. Overall, the spatial distribution shows
616 a slight correlation of increasing relative scour depth from south to north.



617

618 **Figure 11: A) Spatial distribution of relative scour depth at Lynn and Inner Dowsing OWF from 2007-2010.**
 619 **B) Grain-size distribution. C) Relative scour depth vs relative water depth, and grain size classification. D)**
 620 **Significant wave heights and E) Current velocities.**

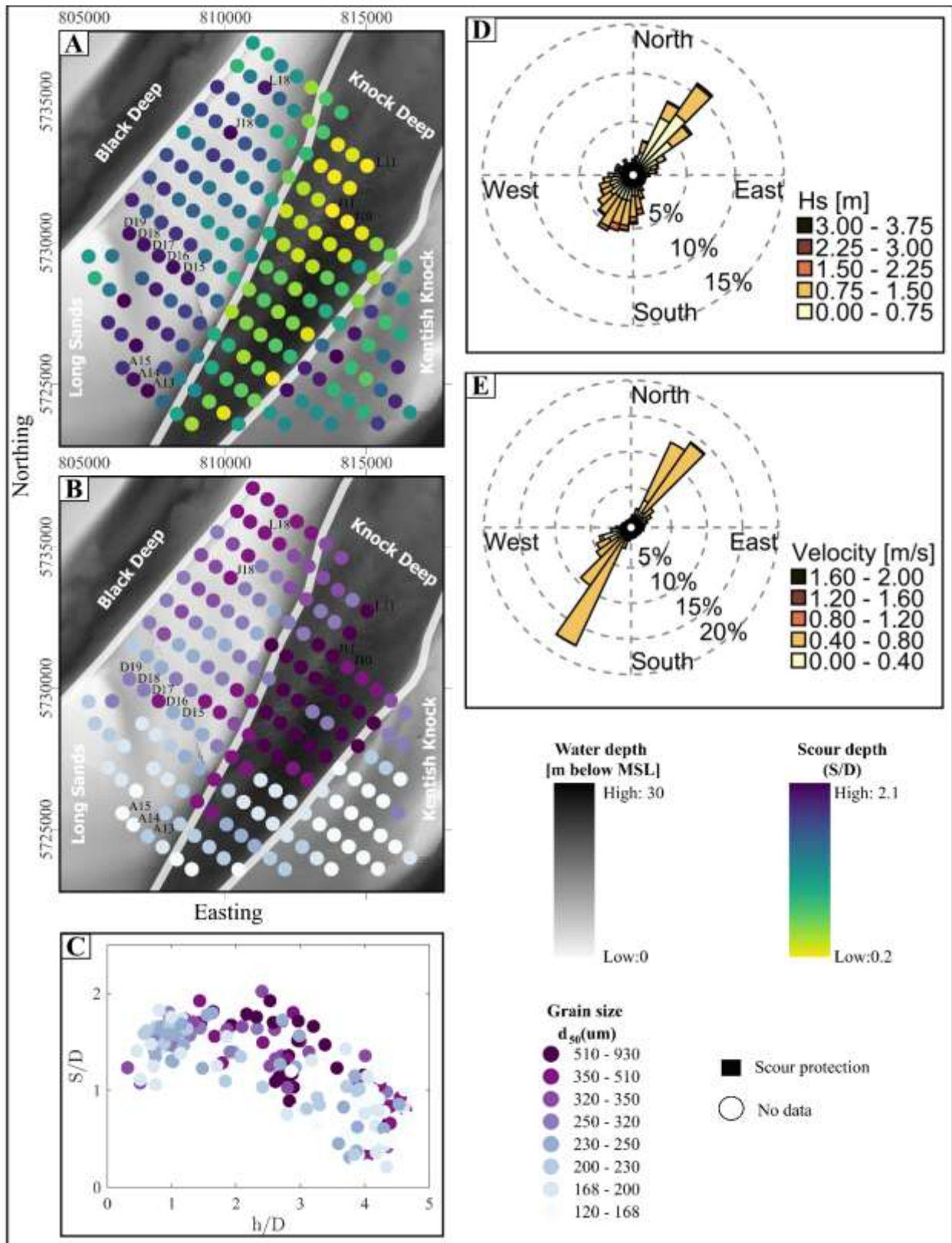
621 Continuing with the spatial overview, Figure 11B introduces the spatial distribution of d_{50} median grain sizes,
 622 which shows a range from coarse to very coarse sands (695 to 1951 μm). The correlation between relative scour
 623 depth and relative water depth is examined in Figure 11C. Similar to Robin Rigg, this OWF does not display the

624 negative correlation as seen globally in Figure 7, suggesting that additional local factors may significantly
625 influence relative scour depth.

626 Consequently, the significant wave heights and current velocities from hindcast data are shown in Figure 10D and
627 10E. The highest wave heights, observed from the northeast, and strong tidal currents flowing from southwest to
628 northeast, highlight the dynamic environmental forces at play. The presence of the largest relative scour depth in
629 the Inner Dowsing area align with the direction of the highest tidal current velocities (Fig. 11E) recorded in the
630 northeast part, as well the main direction of waves. Therefore, the direction of both tidal current and waves likely
631 play a significant role for the scour development in this wind farms, as the seabed conditions and relative water
632 depth locally do not exhibit a distinct correlation.

633 3.5.3 London Array OWF

634 Following the previous results, the analysis for London Array OWF shows a wide range of relative scour depth
635 from $S/D = 0.2$ to $S/D = 2.1$. This variability differs markedly from the consistently larger relative scour depth
636 observed at Robin Rigg and the limited maximum depth of up to $S/D = 1.0$ at Lynn and Inner Dowsing. The area
637 of London Array OWF is characterised by an alternating pattern of deep channels (Black Deep, Knock Deep) and
638 sandbanks (Long Sands, Kentish Knock). These topographic features significantly contribute to the local scour
639 patterns. Water depth at this site range from 0 to 30 m, with Long Sands known for its significant variations in bed
640 elevation but general stability of position. Meanwhile, Knock Deep is notable for its eastward shift over time,
641 which has widened the channel and maintained a constant bed level.



642

643 Figure 12: A) Spatial distribution of relative scour depth at London Array OWF from 2010-2014. B) Grain-
 644 size distribution. C) Relative scour depth vs relative water depth, and Grain size classification. D)
 645 Significant wave heights and E) Current velocities. Relative scour depth and grain size data are used from
 646 Melling (2015)

In Figure 12A, the distribution of relative scour depth shows that the variation in scour is strongly influenced by the underlying topography, with significantly greater relative scour depth on the sand banks compared to the channel. Additionally, a correlation of increasing relative scour depth is observed from northeast to southwest, which is particularly notable in the channel area. The smallest scour is observed in the northern part of Knock Deep with a ratio of $S/D = 0.2$ and the largest in the southern part of Long Sands with $S/D = 2.1$. The differences in relative scour depth can be derived directly from the seabed topography, with greatest average relative scour depth found in the Long Sands with $S/D = 1.53$, followed by Kentish Knock ($S/D = 1.37$), and then Knock Deep ($S/D = 0.77$) with the smallest average. The sediment distribution across this OWF, shown in Figures 12B, ranges from very fine to coarse sands. Coarse sands can be found in Knock Deep, where generally the smallest relative scour depth are seen (e.g., L11, J10 and J11). Furthermore, the largest relative scour depth are noticed in the southern part of Long Sands (e.g. A13-A15, D15-D19, J18 and L18), where the sediment varies from very fine to fine medium sands. There is therefore a reasonable correlation between grain size and relative scour depth, which is consistent with the previously observed global correlation. Additionally, Figure 12C shows a negative correlation between relative scour depth and relative water depth aligning with the global correlation observed in Figure 7, i.e. that shallower relative water depth can be associated with deeper scour, while deeper waters tend to have reduced relative scour depth. This correlation may be explained by the findings of Hjort (1975), who demonstrated that bed shear stress decreases with increasing relative water depth for the same flow and structure diameter, potentially leading to reduced scour at greater depth. However, as the relative water depth in the London Array OWF changes simultaneously with the sediments, i.e. coarser grained sediments are present in the deeper water depth of Knock Deep, the cause of the different relative scour depth cannot be clearly attributed to either the sediments or the water depth. Other hydrodynamic, environmental, and topographic factors also play a critical role in shaping these patterns at this OWF, underscoring the complexity of the influences involved.

Significant wave heights and current velocities, as shown in figures 12D and 12E, provide important insights into the scour dynamics at the London Array. These figures show that, in addition to relative water depth and sediment grain sizes, wave and current dynamics might be critical factors at this wind farm. The predominant direction of both waves and currents is northeast to southwest, consistent with the estuarine influence of the area, where river discharge also significantly affects hydrodynamic conditions. This influence is particularly evident at the Long Sands and Kentish Knock sandbanks, which are shaped by the combined action of waves and currents (London Array Ltd, 2005).

Figure 12D shows that the highest wave heights are observed coming from the northeast, with values exceeding 3.0 m, and lower wave heights propagating from the southwest. This gradient in wave height suggests a correlation with increased relative scour depth in regions exposed to higher wave energy, suggesting a strong link between wave dynamics and seabed modification. However, estimated KC_{99} numbers remained relatively low across most sites, indicating limited wave-induced orbital motion near the seabed. This suggests that wave action plays a secondary role in scour development compared to currents. Similarly, Figure 12E highlights a larger number of strong currents coming from the southeast. These higher velocities correspond to areas with more pronounced relative scour depth, highlighting the role of strong currents in influencing sediment transport and depositional patterns.

In addition, the local tidal dynamics vary significantly across the wind farm, with the flood tide dominating the southern banks and the ebb tide more influential on the northern banks (Kenyon and Cooper, 2005). This variation is due to the sheltering effect of the sandbanks, which are slightly offset from the orientation of the ebb tide, and

688 is particularly pronounced at Long Sands (London Array Ltd, 2005). The interplay of river discharge, wind stress,
689 tidal surge and density driven currents follow the pathways created by the existing topography, further
690 complicating the hydrodynamic environment and its effect on scour at the London Array OWF.

691 After analysing the relative scour depth at 9 wind farms and with different ranges of relative scour depth, the
692 variation of relative scour depth can also be noticed in individual OWFs, as in the case for London Array OWF.

693 4. Discussion

694 4.1 Implications for scour predictions for OWFs

695 Overall, this study extends the investigation of scour dynamics to a regional scale by analysing correlations
696 between relative scour depth and site conditions across multiple OWFs to identify consistent scour patterns and
697 correlations. The PCA analysis highlights a significant negative correlation between relative scour depth with
698 relative water depth, suggesting that relative water depth plays a critical role in scour processes, confirming the
699 correlations observed with previous Whitehouse et al. (2010) and Melling (2015) for field data. The decrease of
700 the relative scour depth with decreasing relative water depth seems unexpected and contradicts common scour
701 prediction approaches such as Breusers et al. (1977), which however are often derived for flow conditions with
702 shallow relative water depth. Harris and Whitehouse (2014) argued that in deeper water, a weaker downflow and
703 hence a weaker horseshoe vortex can be expected, ultimately leading to smaller scour depth. This finding implies
704 that scour prediction approaches should place greater emphasis on relative water depth, particularly in offshore
705 environments where deeper flow conditions dominate.

706 A second notable correlation was identified between the relative scour depth with the relative grain size. This
707 broad correlation, consistent across different geographic locations and environmental conditions, reinforces the
708 fundamental role of sediment size in scour processes, as documented in the extensive work of Vanhellemont et al.
709 (2014) and Rivier et al. (2016).

710 However, the analysis also indicates that the sediment erodibility alone cannot fully account for the observed
711 variability in relative scour depth. The PCA analysis further reveals a positive correlation between the relative
712 scour depth and both the Keulegan Carpenter number and the sediment mobility parameter. The strong positive
713 correlation with KC_{99} supports previous studies (Sumer and Fredsoe, 2001; Qu, 2024), highlighting the importance
714 of flow unsteadiness that is typical in tidal and wave-dominated environments. Similarly, the positive association
715 with the mobility parameter underscores its relevance as a key indicator of sediment entrainment and a useful
716 metric for distinguishing between different sediment transport regimes.

717 These findings underscore a complex dynamic that is frequently oversimplified in existing models. The results
718 indicate a necessity to incorporate nonlinear hydrodynamic models into scour prediction frameworks. The results
719 of the PCA reveal the necessity for a diversified approach to the modelling of scour in complex field conditions,
720 which extends beyond the scope of traditional uniform applications.

721 This analysis demonstrates that individual OWFs exhibit unique environmental and sediment conditions, which
722 can either amplify or moderate broader correlations. The London Array OWFs serves as a prime example of the
723 predictive reliability of observed regional correlations, as local data closely mirrors general correlations.
724 Conversely, sites such as Robin Rigg and Lynn and Inner Dowsing exhibit deviations from these correlations due
725 to their distinct sediment compositions and hydrodynamic conditions, underscoring the necessity for site-specific
726 adjustments to scour prediction models. These findings underscore the intricacy of employing global models on a

727 local scale and underscore the significance of site-specific data in validating and refining these models to enhance
728 their accuracy and applicability.

729 **4.2 Limitations and future research**

730 Although this study provides a detailed analysis of relative scour depth at nine OWFs, certain limitations must be
731 addressed to improve the interpretation of the findings. Although the dataset spans multiple years, it represents
732 snapshots in time and may not fully capture the dynamic evolution of scour processes under fluctuating metocean
733 conditions (Matutano et al., 2013; Carpenter et al., 2016). Hindcast data, while valuable for long-term correlations,
734 are often based on limited spatial resolution that may underestimate short-term extreme events such as storm surges
735 or localized current variations (Whitehouse et al., 2010; Sturt et al., 2009).

736 Using PCA is effective in identifying dominant linear relationships between relative scour depth and key variables;
737 however, it may miss critical nonlinear interactions that drive scour processes (Schendel et al., 2020; Lyu et al.,
738 2021). While this study incorporates parameters such as the Keulegan-Carpenter number and the mobility
739 parameter, the accuracy of these parameters is limited by temporal resolution and data availability. Valuable insight
740 was provided into the role of hydrodynamic forcing on sediment mobility through their inclusion; however, more
741 detailed and site-specific input data are needed so that their predictive potential can be fully exploited (Sheppard
742 et al., 2004; Zhao et al., 2012).

743 The next step in this research is to develop data-driven models and investigate the broader implications for regional
744 sediment dynamics. Future studies will focus on OWFs located in fine and medium sands where significant scour
745 activity is observed. By focusing on these environments, we aim to improve prediction capabilities and better
746 understand the mechanisms that drive scour, particularly in areas that are susceptible to substantial sediment
747 mobilization.

748 Finally, while the present study focused on localized scour processes, the cumulative effects of OWF structures
749 on regional sediment transport and marine ecosystems remain a significant knowledge gap (Christiansen et al.,
750 2022; Schultze et al., 2021). Future research must employ interdisciplinary methodologies to rigorously assess the
751 ecological impacts of sediment mobility and scour on marine habitats. By integrating regional sediment transport
752 models with comprehensive ecological assessments, we can optimize offshore wind energy development to meet
753 both sustainability and environmental protection goals, ensuring long-term benefits for infrastructure resilience
754 and marine ecosystem health.

755 **5 Conclusion**

756 Achieving the European Union's (EU) offshore wind energy targets requires development of OWFs in regions
757 with diverse and often poorly understood meteoceanic and geophysical conditions. However, this demand
758 underscores critical knowledge gaps regarding the interaction of these installations with the marine environment,
759 particularly with respect to scour processes and sediment mobilization. A comprehensive understanding of scour
760 dynamics is essential, not only to ensure structural integrity, but also to assess potential impacts on regional
761 sediment transport and broader ecosystem functions.

762 In this study, high-resolution bathymetry data were used to analyse field-measured relative scour depth of 460
763 monopiles across nine British OWFs. The analysis included a PCA in which eight hydrodynamic and geotechnical
764 variables were considered to identify the dominant driver influencing relative scour depth variability. This analysis

provided a basis for understanding the primary correlations between relative scour depth and metocean site conditions, but also highlighted the complexity of these relationships, requiring further refinement.

The main conclusions can be summarized as follows:

- (1) **Universal drivers of scour:** Across all nine OWFs, the PCA the relative water depth, the relative grain size, the Keulegan-Carpenter number and the mobility parameter as the most influential variables governing scour depth variability. Among these, the relative water showed the strongest correlation (Fig. 7), where greater relative scour depth occurred in shallower waters, particularly at location with sediments composed of ($63 \leq d_{50} < 200 \mu m$) and medium sand ($200 \leq d_{50} < 630 \mu m$). In shallow waters the increased kinetic energy promotes stronger down-flow and vortex activity around the pile, enhancing scour, whereas in deeper water, hydrostatic pressure dominates, weakening these effects (Melville, 2008; FHWA, 2012). Furthermore, inclusion of the relative grain size captures the effect of grain-pile scaling, while the Keulegan-Carpenter number and the mobility parameter reflect the influence of flow unsteadiness and sediment mobility thresholds, reinforcing their relevance in realistic scour prediction frameworks.
- (2) **Sediment-specific correlations:** In order to explore the variability within soil classes, the data set was clustered according to d_{50} , and a PCA was applied to each cluster. For fine sand (63 to 200 μm) and medium sand (200 to 630 μm), relative water depth was found to be the dominant driver of relative scour depth, demonstrating the sensitivity of these sediment types to hydrodynamic forcing in shallower relative water depth. For coarser sediments, such as coarse sands (630 to 2000 μm) and fine gravels (2000 to 6300 μm), the correlations were less pronounced, reflecting a greater resistance to scour. This sediment-specific analysis highlights the importance of considering sediment type when assessing scour susceptibility and designing OWFs, and how different sediment types can influence sediment transport patterns.
- (3) **Site-specific variability:** Due to local factors such as sediment conditions, hydrodynamic conditions, and topography, individual OWFs exhibited unique relative scour depth patterns. For example, London Array (Fig. 12C) showed correlations similar to the global results (Fig. 7), with relative water depth and site topography as the primary influences on scour, followed by current and wave conditions. In contrast, OWFs such as Robin Rigg and Lynn and Inner Dowsing showed no discernible correlations between relative scour depth and the key drivers obtained from the global PCA, highlighting the need for individual analyses to account for local complexities.

This study also highlights the potential environmental impacts of scour-induced sediment transport. While the primary focus was on identifying the physical drivers of scour, the findings could provide a first step in assessing potential impacts of OWF on the marine environment due to a changed regional sediment mobility. The entrainment of eroded sediment into the water column, with subsequent long-range transport, raises concerns about sediment deposition and potential impacts on benthic habitats and marine wildlife in far-field regions. Future research should prioritize the refinement of predictive scour models that incorporate temporal data and expanded hydrodynamic parameters to improve accuracy in diverse sedimentary environments. In addition, integrated approaches that combine regional sediment transport modelling with ecological assessments are critical for evaluating the cumulative impacts of OWF facilities on marine ecosystems. These efforts will facilitate the development of sustainable OWF designs that minimize environmental disturbance while advancing renewable energy goals.

Data availability: The data set used in this study is available in the Marine Data Exchange (MDE) (<https://www.marinedataexchange.co.uk/>) and by the Copernicus Marine Service (CMEMS) (<https://marine.copernicus.eu/>)

Authors contribution: **K. G.:** Writing – original draft preparation, visualization, formal analysis, conceptualization, methodology. **C.J.** Writing – review & editing, supervision, conceptualization, project administration. **G.M.** Writing – review & editing, resources. **A.S.** Writing – review & editing, methodology. **M.W.** Writing – review & editing, Supervision. **T.S.** Writing – review & editing, Funding acquisition, Supervision.

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