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Field data-based correlation between scour at offshore wind farms (OWFs) and hydrodynamic drivers

Karen Garcia[1*], Alexander Schendel[1], Christian Jordan[1], Mario Welzel[1], Torsten Schlurmann[1]

[1]Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Leibniz University Hannover, Nienburger Str. 4, 30167 Hannover, Germany, email: schendel@lufi.uni-hannover.de, jordan@lufi.uni-hannover.de, welzel@lufi.uni-hannover.de, schlurmann@lufi.uni-hannover.de

[*]Corresponding author: garcia@lufi.uni-hannover.de

ABSTRACT

Knowledge gaps still exist regarding the interactions between individual offshore structures and the marine environment. Recently, more field data has been made available to the public, providing unprecedented opportunities to validate existing laboratory datasets and further advance knowledge of scour development and its main drivers from data-driven approaches.

This study aims to advance understanding of the drivers of local scour and spatial erosion by comparing bathymetry and scour data from offshore wind farms (OWFs) with hydrodynamic conditions. The focus of the paper lies on the analysis of the spatial distribution of scour within a selected UK OWF and the investigation of the influence of storm events on the time evolution of scour at a tripod structure in the German Bight (Alpha Ventus). Analysis elucidates that at the Robin Rigg wind farm, the distribution of scour depths has a weak relationship with water depths, but a more reasonable relationship with the direction of tidal current velocities. At Alpha Ventus, single storm events can lead to an increase of the scour depth or a significant backfilling, depending on the angle of superposition of waves and tidal current.

INTRODUCTION & MOTIVATION

The expansion of renewable energy is crucial for a sustainable and independent energy supply. The extensive expansion of offshore wind energy as targeted by the European Union (EU, 2020) requires the development of areas with exceptional metocean and geophysical conditions. Furthermore, knowledge gaps on the interactions of individual structures or entire OWFs with the marine environment exist.

In OWFs, in addition to local scour development at individual structures (Schendel, 2018; Welzel et al., 2019), seabed morphology is altered spatially by the cumulative interaction of multiple structures. Large-scale effects of OWFs on ocean dynamics (Christiansen et al., 2022) or sediment mobility (Vanhellemont & Ruddick, 2014) have been documented but drivers and interdependencies governing these processes are only little understood. Induced by turbulent mixing of OWF foundations, potential impacts on the marine environment (Shields et al., 2011) include mixing of waters that are stratified (Carpenter et al., 2016) or enhancing the sediment mobility, possibly leading to either habitat loss or habitat gain (Wilson and Elliott, 2009) of benthic flora and fauna.

A systematic comparison and correlation of in-situ field data could help to improve the prediction of scour and spatial sediment displacement and thus facilitate access to as yet undeveloped offshore wind sites. In-situ observations of scour on individual structures have been described for monopiles (Rudolph et al., 2004) and jackets (Baelus et al., 2018), with data available for both the spatial and temporal development of scour. Baelus et al. (2018) also compared the changes in scour depth with several hydrodynamic parameters as well as storm events and found that single storm events can result in a sudden change of scour depth, depending on the wave direction.

Larger datasets covering several offshore wind farms have been reported by Cowrie (2010) and Whitehouse et al. (2011). By evaluating three OWFs off the UK coast, Melling (2015) has created one of the largest field data sets on monopile scour to date. In his study, Melling (2015) conducted an in-depth analysis of scour hole dimensions and their variability within an OWF and correlated the scour properties to sedimentological and hydrodynamic parameters. Although the study is limited to three OWFs, it already provides valuable insights into the causality between hydrodynamic and geotechnical drivers leading to the development of scour.

Recently, more field data has been made publicly available, including high resolution bathymetry scans from German and UK OWFs, providing an opportunity to complement Melling's (2015) study and further advance the knowledge of scour development and its main drivers with a cross-regional dataset. The data from the UK OWFs provide bathymetries on the scale of whole wind farms for several years but only for selected survey periods. Therefore, an additional study site in the German Bight is included that provides continuous measurements of scour evolution over longer periods but only for one location. This will allow the effects of short storm events on immediate and long-term scour development to be analyzed, complementing the findings on spatial influence with detailed insights into temporal scour development.

As a first step, this paper focuses on the analysis of the spatial distribution of scour depths within a selected UK OWF (Robin Rigg) and the investigation of the influence of storm events on the temporal scour development at a tripod structure in the German Bight (Alpha Ventus).

DATA BASIS

Robin Rigg

Being completed in 2010, the Robin Rigg OWF is Scotland's first OWF and is located in the Solway Firth estuary, which is connected to the Irish Sea. The Solway Firth is characterized by hypertidal conditions, since spring tidal ranges can be as high as 8 m (Huthnance, 1991). Water depths across the site of the OWF vary from about 1 to 14 m, while sediments mainly consist of fine to medium sands interbedded with silts and sandy muds (COWRIE, 2010). In total, the OWF consists of 60 turbines with monopile foundations, which have a diameter of 4.3 m (COWRIE, 2010). Bathymetric datasets from the Robin Rigg OWF, which are used in this study, were collected via multibeam echosounder (MBES) before, during and after the construction of the wind farm and were afterwards made available by E.ON UK (2008, 2009) via the Marine Data Exchange (MDE) (https://www.marinedataexchange.co.uk/).

For the correlation of scour and hydrodynamic conditions at the Robin Rigg OWF, metocean hindcast datasets (i.e., wave parameters and sea surface currents) by the Copernicus Marine Service (CMEMS) (https://marine.copernicus.eu/) were used (CMEMS, 2023a, 2023b).

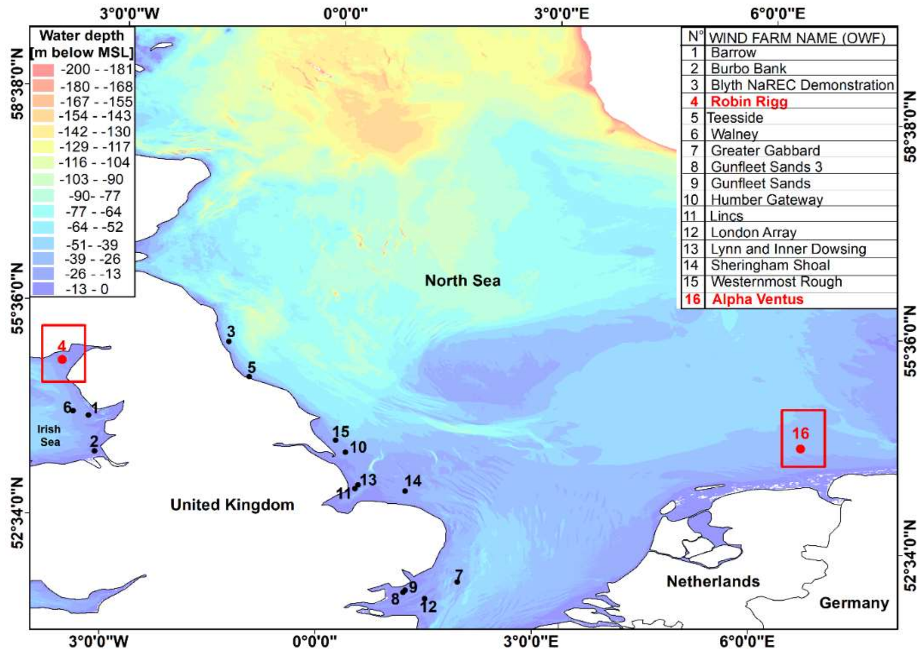

Figure 1: Location of the study area. Numbers 4 and 16 indicate the locations of the Robin Rigg OWF and Alpha Ventus OWF, respectively. Shown bathymetry data originates from EMODET (https://emodnet.ec.europa.eu/en/bathymetry).

Alpha Ventus

The Alpha Ventus OWF, which is located in the German Bight and was commissioned in 2009, is Germany's first test site and provides extensive measurement data for the research and development of offshore wind turbines. In addition to turbine-specific measurements, metocean parameters have also been recorded ever since its installation at the nearby FINO 1 research platform. The Federal Maritime and Hydrographic Agency of Germany (BSH) provides most collected data through the RAVE (research at alpha ventus) initiative (https://www.rave-offshore.de). Alpha Ventus consists of a total of 12 offshore wind turbines, six of which are founded on a jacket structure and six on a tripod structure. Detailed scour data have been collected on both foundation variants since 2009. For this purpose, 19 echo sounding sensors were installed on the tripod on the individual piles and below the central tower segment.

METHODOLOGY

Robin Rigg

Bathymetric datasets used here, were interpolated onto a grid with a horizontal resolution of 2 x 2 m and were converted to Ordnance Datum Newlyn (ODN). During the processing of bathymetric maps, a tile of 100 x 100 m was created for each turbine, with the turbine at the center of the tile. Figure 2 highlights the methodology used to analyze the bathymetry maps and to obtain scour information by calculating the difference in bed elevation at a turbine location between two different years. The deepest scour at each turbine location was then extracted from the difference map (Figure 2c). In addition, the extent of the scour was determined along two cross-sections through the monopile foundation, one in the North-South axis and one in the West-East axis.

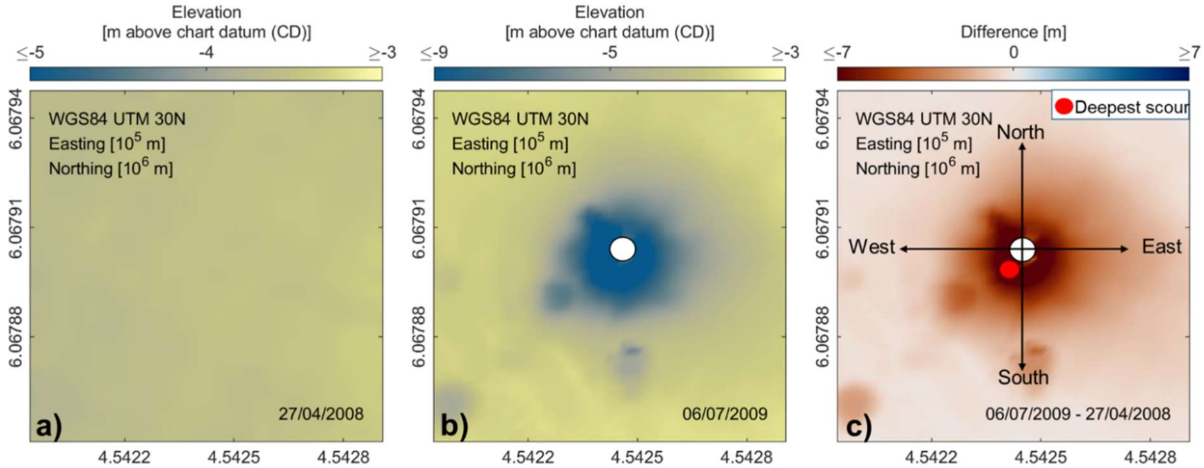

Figure 2: Methodology used to assess the scour evolution. a) Pre-installation scan taken in March/April 2008, b) post-installation scan taken in June/July 2009, c) change in seabed elevation (a-b), deepest scour and scour extension.

To correlate the distribution of scour depths and scour extent with spatial variations in metocean and geological conditions, these parameters were then integrated into a GIS map. According to the hindcast data (CMEMS, 2023a; CMEMS, 2023b), the median of the significant wave height H_s at the Robin Rigg OWF was of the order of 0.46 m, while the 99th percentile of H_s was as high as 2.42 m between March 2008 and July 2009. During the same time, the median of the velocity magnitude (v_m) of sea surface currents was around 0.77 m/s, with peak velocities (99th percentile) being as high as 1.64 m/s.

Alpha Ventus

On the basis of the available long-term measurements, the temporary influence of individual extreme storm events on long-term scour development was estimated and dependencies between storm parameters and scour behavior were defined. The used definition of storm events is based on Hildebrandt et al. (2019), according to which a storm event exists if wind speeds of more than 16 m/s are measured over a period of more than 6 hours. A total of 185 storms were identified over the entire period, of which scour, flow and wave data were also available for 68 events.

RESULTS

Robin Rigg

The distribution of scour depth and scour extension within the Robin Rigg wind farm is shown in Figure 3. Spatial scour depth distribution is shown (Figure 3a) by means of colored dots that represent the range of scour depth, which varies from S = -3.7 m to -7.6 m. The gray underlaid colormap represents the water depth in the wind park. The trend of increasing scour depth from South-West to North-East appears to be consistent with the main axis of the tidal current (Figure 3c). However, the highest tidal current velocities occur from southwesterly directions and not from the northeast as expected. Therefore, in addition to the water depth and both the directionality and intensity of the tidal current, other interdependent or complementing controlling factors must be important for the generation of scour.

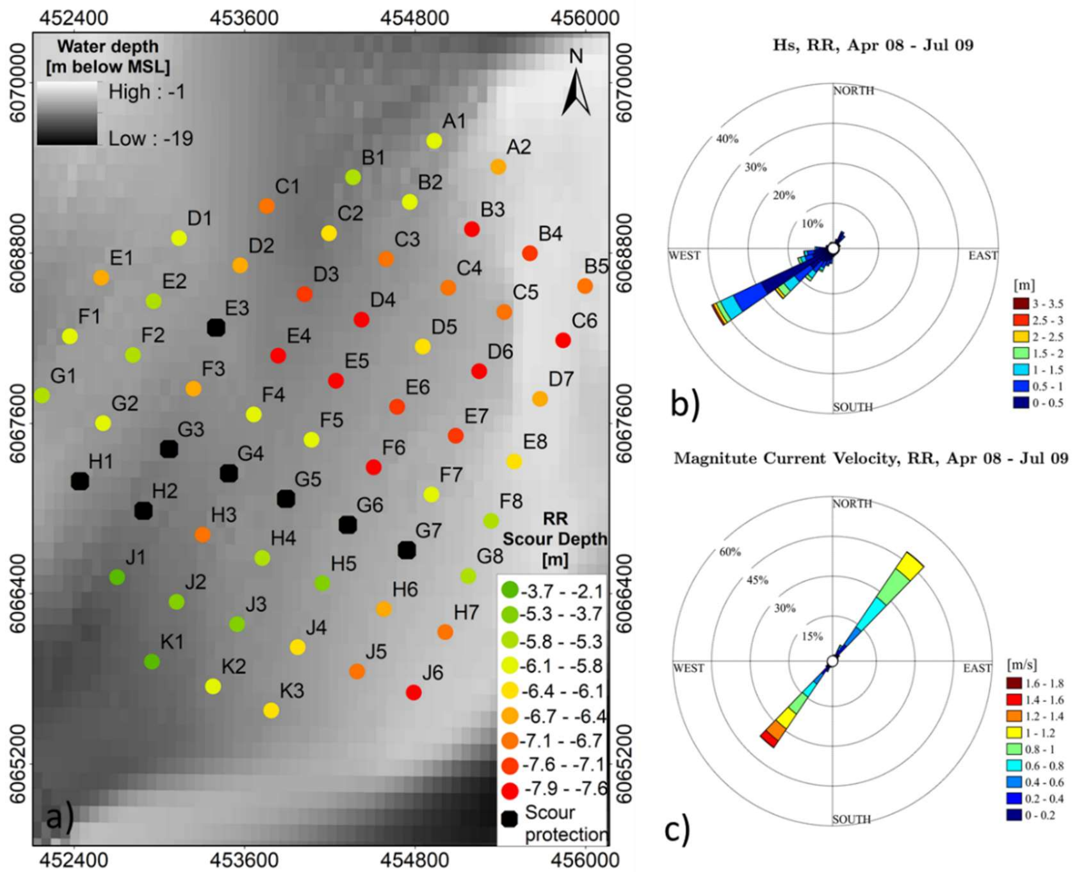

Figure 3: Spatial scour depth distribution in relation with meteocean conditions. a) Distribution of increase of scour depth from April 2008 – July 2009, b) significant wave heights from April 2008 – July 2009 and c) current velocities from April 2008 – July 2009.

Figure 4 compares the scour depths directly with the water depths. Although the correlation between water depths and scour depths does not appear to be very strong in the given example, there is still a tendency for scour depths to decrease with increasing water depths, which is in contrast to most existing scour prediction approaches. Data from Cowrie (2010), who analyzed measurements from the same wind farm but from an earlier bathymetry scan, show a similar trend.

Melling (2015) also found a reduction in scour depth with increasing water depth for three considered wind farms, albeit only in deep water conditions with the ratio of water depth to pile diameter h/d > 1.66. In shallow water conditions, h/d < 1.66, the trend was reversed. Experiments by Hjorth (1975), as pointed out by Melling (2015), showed that with an increasing water depth the bed shear stress decreases for the same flow and structure diameter, which may explain the decrease in scour depth in deeper water.

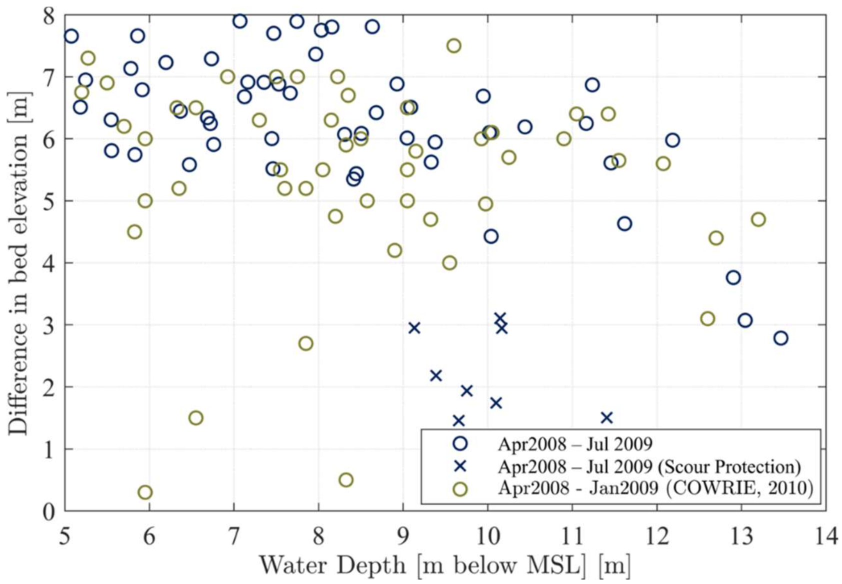

Figure 4: Relationship between scour depths and water depths.

Given the weak relationship between scour and water depth, further drivers and influences of scour development at Robin Rigg are likely and are subject to be investigated in future studies. As found by Melling (2015), the scour depth in OWFs can be strongly dependent on the sediment properties. The distribution of scour extent in the structural near-field was analyzed for a West-East and North-South direction. The extent ranges from 34 m to more than 78 m, with the largest extents developing in West-East direction. In this direction, most turbines have an extent greater than 61 m. To further elaborate on the relationship between scour depth and extent, both values are directly compared in Figure 5.

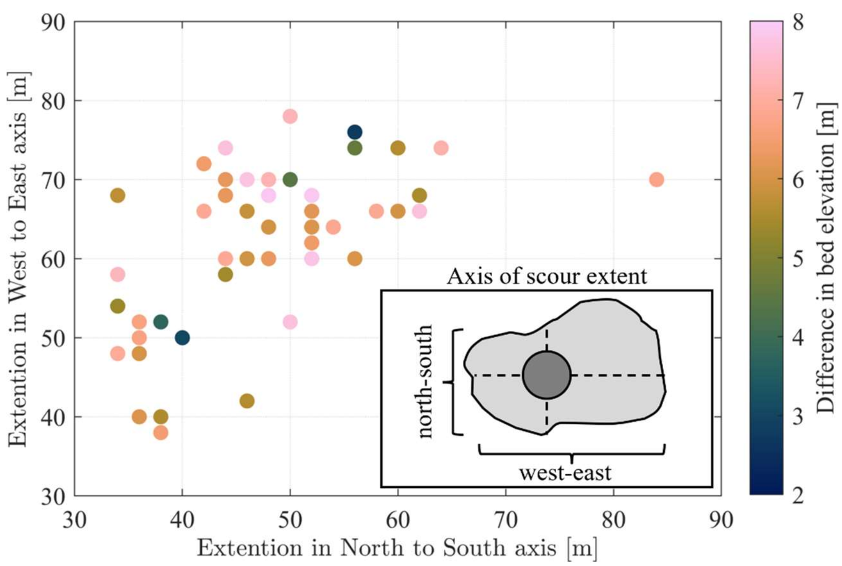

Figure 5: Scour extension in relation to scour depth.

First, Figure 5 confirms that the scour extent in the North-South direction and West-East direction are not proportional and the extent tends to be larger in the West-East direction. Secondly, scour depth tends to increase with scour extent, although some outliers suggest that other factors influence the relationship between these two values. Here, it must be noted that the extent in the selected direction does not necessarily represent the maximum extent of the scour hole.

Alpha Ventus

Figure 6 shows the development of the mean scour depth at each individual pile and below the central tower segment over the entire measurement period. The mean scour depths shown, represent the mean value of all measurements around a pile. For easier comparison, the respective scour depths were additionally normalized to the first measured value.

The long data gaps at the end of 2012 and between 2015 and 2016 are presumably caused by sand replenishment and the installation of scour protection, respectively (BSH, internal communication).

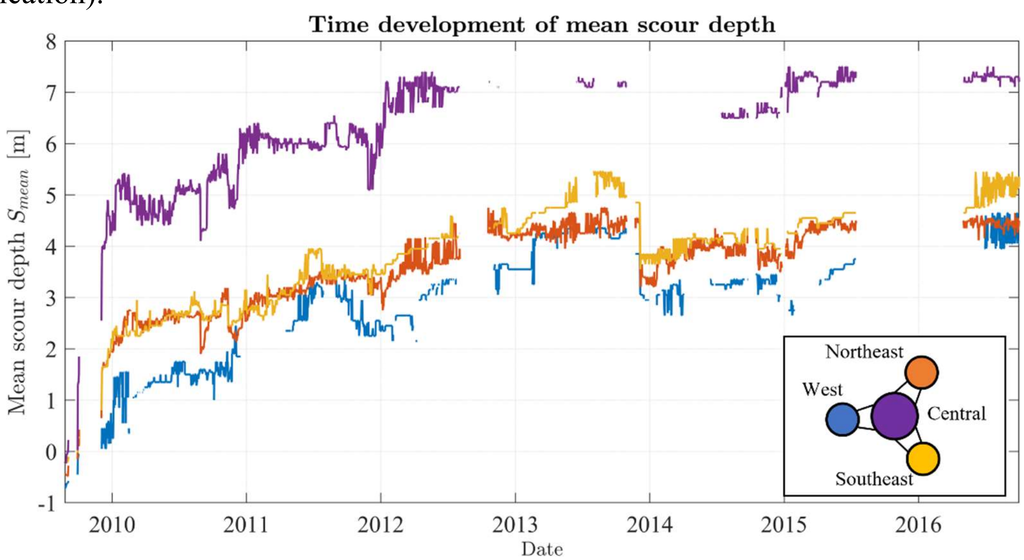

Figure 6. Development of mean scour depth over time.

While the scour development was subject to greater fluctuations, the scour depth nevertheless increased continuously at all piles and under the central tower segment. Thereby, the scour depth below the central tower segment was always significantly greater, up to twice the depth, than directly at the piles. These observations are consistent with the findings of Stahlmann and Schlurmann (2012) who found from scour studies of tripods in laboratory facilities that large scour depths form below the central tower segment in particular in the case of wave load.

Comparing the local scour directly at the piles, it is evident that the smallest scour occurs at the western pile. Stahlmann and Schlurmann (2012) already showed that the orientation of the tripod to the flow direction has a considerable influence on the scour formation at the respective pile. At the Alpha Ventus site, the main tidal flow direction is west-east with slightly stronger components from the east, which could explain the lower scour at the western pile compared to the eastern piles.

Figures 7 and 8 show the scour development as well as sea state and current flow parameters during two selected storm events. The scour depths (ΔS) shown are given as the difference from the scour depth at the beginning of the respective storm event.

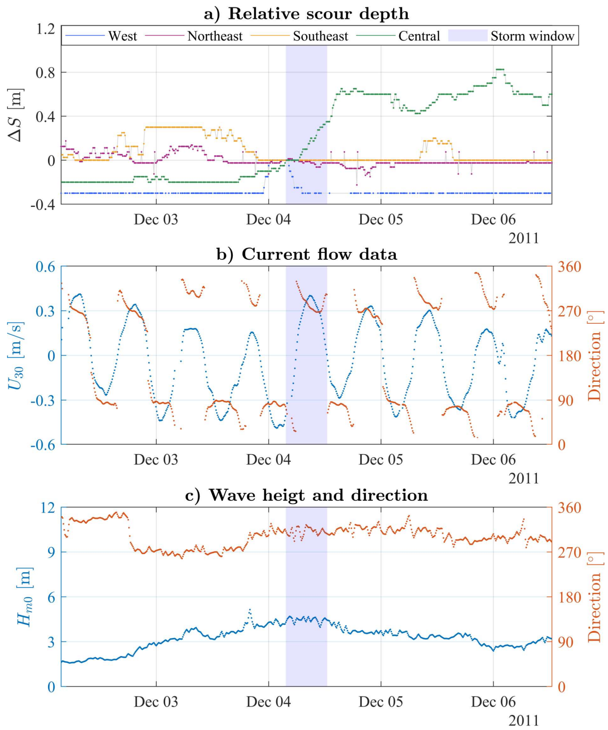

Figure 7. Scour development and change of sea state and current flow conditions during storm event Nr. 56, 4th Dez. 2011.

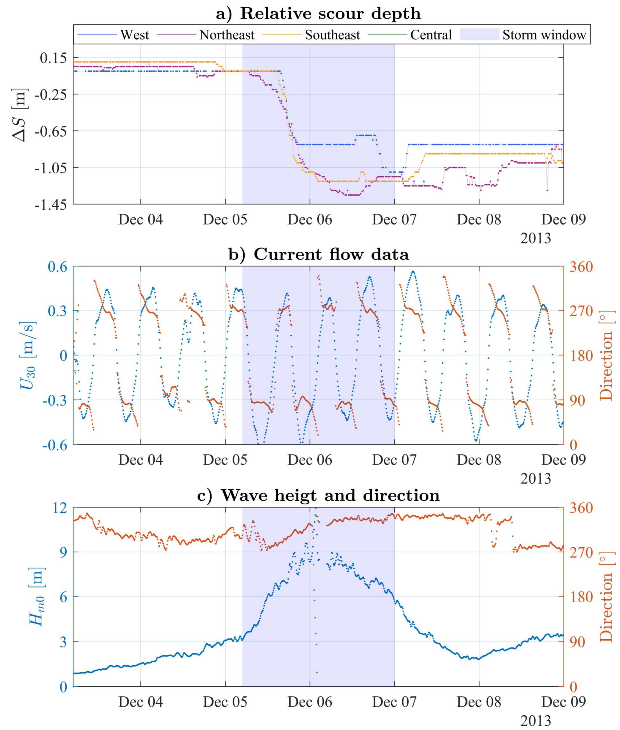

Figure 8. Scour development and change of sea state and current flow conditions during storm event Nr. 106, 5th Dez. 2013.

The two storm events differ significantly not only in wave height and wave build-up duration but also in their effects on scour development. During the storm on 4th Dec. 2011 (Figure 7), a clear increase in scour depth occurs below the central tower segment, while the scour depth directly at the piles remains almost constant. The second storm on 5th Dec. 2013 (Figure 8), storm Xavier, on the other hand, led to a significant and sudden backfilling of the scour at all three piles. Unfortunately, no measurements are available for this period below the central tower segment.

Nearly all storms hit Alpha Ventus from the west or northwest. Looking at all 68 identified storm events, there is a tendency for the scour to refill when the wave load is maximum at the time of the ebb flow (from the east). On the other hand, if a storm is at its maximum intensity during a flood flow (from the west), the scour is more likely to deepen. Similar to Robin Rigg's results, the direction of loading appears to be an important factor in the development of scour.

On the other hand, it is remarkable that the scour at the piles only responded to high wave loads, whereas the scour below the central tower segment was already affected by comparatively low wave loads. Stahlmann and Schlurmann (2012) have described the sensitivity of the scour below the central tower segment to wave loading. The additional load from small wave heights might increase the shear stresses below the central tower segment to such an extent that scour increases here. At the same time, however, the load is not sufficient to mobilize sand over a large area, even from outside the tripod, and cause the scour to backfill, as has been observed during severe storm events.

CONCLUSION

This study aims to provide insights into the precondition and development of scour in offshore wind farms. Focus is set on large scale changes in seabed morphology induced by hydrodynamic drivers by analyzing a comprehensive dataset of freely available bathymetry field and metocean data. In a first step, we analyzed the spatial distribution of scour depths in correlation with local sea state and tidal currents within the Robin Rigg offshore wind farm (UK). In a further approach we investigated the influences of single storm events on the temporal development of scour at a tripod structure in the Alpha Ventus wind farm (Germany) to better understand mechanisms and driver of structure-induced changes in near-field morphology.

At Robin Rigg, the spatial distribution of scour depths and extent was compared and assessed in connection with individual water depths, wave heights and tidal current velocities for each structure within the park. The distribution of scour depths was found to have only a weak relationship with the water depths, but a more reasonable relation with the main direction of tidal current-induced flow velocities was determined. However, the hydrodynamic factors studied so far do not explain all scour depths and scour extents, and other factors, such as geological conditions on site are assumed to play a role.

At Alpha Ventus, the scour evolution and the influence of single extreme storm events were analyzed. Similar to conditions observed at Robin Rigg, a strong dependency of the scour pattern to the direction of the main tidal current could be discerned. Regarding the influence of single storm events on the scour development, the angle of superposition between the waves and the tidal flow appears to be important in determining whether the scour is deepened or backfilled.

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