Comparison of Scour in Complex Soils around the Foundations of Marine Harvesting Technologies

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ABSTRACT

Marine harvesting technologies represent a very promising sector in terms of potential and commercial development at the present state of the art. Improving the design of offshore wind turbines can significantly reduce costs. Although monopiles have been widely studied, scour, one of the main causes of ultimate and service limits, still has some knowledge gaps that need to be addressed for several other types of foundations. Little research has been conducted on scour process in complex foundations, such as gravity-based foundations (GBF), or complex soils, such as layered sand. This paper provides an overview of recent studies and relates a small experimental scour study for a monopile and a GBF foundation founded in a single soil layer of soil and various sediment layers. A wave energy converter (WEC) model was also incorporated into the setup to study its effects on local scour patterns. Overall, the results showed greater scour depth for layered soils compared to a single layer of fine sand. The presence of a bottom-fixed WEC can reduce scour depth in the vicinity of both offshore wind foundations by more than 53% for the monopile (both soil configurations) and GBF (layered soils), and 33% for the GBF (single-layer soils).

INTRODUCTION

Marine harvesting technologies, such as offshore wind turbines (OWT), play a vital role in renewable energy and natural resource generation. Offshore wind energy (OWE) is highlighted as one of Europe's key renewable energy investments to achieve net zero carbon emissions by 2050 (WindEurope 2021a).

The continuous growth that the offshore wind industry has experienced over the years has pushed the sector towards optimization, as OWTs entail large investments. Levelized Cost of Energy (LCoE) has been steadily reduced over the years (WindEurope 2021a, 2022). One of the main focuses of optimization has been to reduce the cost of the foundation of the structure. The foundations account for a third of the total investment (Matutano et al., 2013). However, the stability of the structure and foundation is often threatened by scour, one of the leading causes of failure of the bearing capacity and the operating limit.

Scour has been extensively studied in hydraulic engineering. Over the years, the literature has focused primarily on scour in monopile foundations. One of the main reasons for this is the common use of this type of foundation in offshore wind farms, used in 81.2% of cases (WindEurope, 2021b). Nevertheless, interest in other types of foundations has increased over the years, as complex foundations, such as the GBF are considered viable in some cases (Tavouktsoglou, 2018). Scour varies with the foundation's shape, so the scour findings in monopiles cannot be directly applied to complex foundations (Welzel et al., 2019). Welzel et al. (2019) and Tavouktsoglou (2018) identified equilibrium scour depth and extent, scour time scale, and scour protection design as some of these gaps when it comes to jackets and GBFs, respectively. Often, scour at these complex foundations is oversimplified using predictive formulas or concepts derived only from studies on monopiles.

Recently research on the implementation of marine energy converters near offshore wind foundations (Fazeres-Ferradosa et al. 2021) has led to the study of scour phenomena under complex conditions far beyond current knowledge developed only for monopiles. The addition of converters can change the hydrodynamics near the foundation, altering the orbital velocity of waves and the shear stress on the seabed, creating new uncertainties for current scour knowledge and countermeasure methods. However, according to Fazeres-Ferradosa et al. (2021), scour is often suppressed in hybrid structures to the detriment of hydrodynamic performance. Some studies, such as Mustapa et al. (2017), reported the need for scour protection measures at the toe of a vertical caisson breakwater with WECs. Lomónaco et al. (2018) conducted a scour analysis caused by a submerged pressure-differential WEC and reported that conventional scour protection systems are sometimes not economically viable for certain types of WECs, pointing to other mitigation strategies: increasing permeability, increasing the distance to the seabed without compromising efficiency. Chen et al. (2014) were one of the first to investigate scour in a hybrid OWT, by incorporating a coastal cage net of aquaculture into a jacket foundation as a soft scour mitigation measure and presented that the cage net reduced current velocity and scour around the foundation. Nevertheless, to the authors' knowledge, the literature has only recently addressed the scour behavior of offshore hybrid structures (Fazeres-Ferradosa et al. 2021).

Another issue affecting scour behavior is soil stratification and composition. Scour in single-layer non-cohesive soils is well documented in the literature. Although other studies also refer to scour in cohesive (*i.e.*, clay, silt) or complex soil combinations (*i.e.*, sand/gravel or sand/gravel/clay), they have not been treated as extensively in the literature. Soils in the North Sea, where 79% of the existing OWT is implemented (WindEurope, 2021b), have a complex composition and can change rapidly over a short horizontal distance – slender sand layers interspersed with over-consolidated clays and silts (Bond et al. 1997, Harris et al. 2023). Typically, the time scale for scour development is slower in complex soils, so methods based on a single sand layer are not representative (Harris et al. 2010a). Mitchener et al. (1996) presented a review of laboratory and field results on the erosion behavior of coastal cohesive and non-cohesive soil mixtures to try to characterize them for predictive models; Harris et al. (2010a) applied Annandale's (1995, 2006) Earth Materials approach to three case-study sites with different soil compositions supported by *in-situ* surveys and concluded that the method has the potential to predict scour depth in complex soils. Whitehouse et al. (2011a) report on a series of *in-situ* measurements at offshore wind farms with monopiles in the North Sea and Irish Sea and demonstrate the variability and differences in scour depths for sandy, non-cohesive soils and complex, clay-influenced soils. Whitehouse et al. (2011b) evaluate scour in GBFs, comparing *in-situ* scour depth values with predictive formulas, as he also reports some cases of scour in clay or layered soils. Porter et al. (2012, 2013) studied scour development around a circular cylindrical pile in stratified and mixed granular soils, but only for unidirectional currents. Harris et al. (2013) applied a modified model of the Scour Time Evolution Predictor (STEP) of Harris et al. (2010b) – for single-layer soils in unidirectional currents – to include stratified soils. It failed to correctly predict the early rapid growth reported by Porter et al. (2012, 2013) but performed well in predicting equilibrium scour depth. Whitehouse and Harris (2014) created a conceptual scour model to preview how different soils would erode in the presence of OWT. Harris et al. (2023) presented a case study for a proposed offshore wind farm in the Baltic Sea, combining the Erodibility Index method with experimental soil tests on complex soil samples in situ. However, there are few studies in the literature dealing with the scouring of combined waves and currents in complex soils for OWT foundations, compared to the single-layer cases.

Therefore, this paper aims to highlight the value of properly evaluating scour for different types of foundations by reporting a series of tests with a monopile and a GBF) and different soil configurations (single and multi-layer soil). The effects of the presence of a WEC nearing an OWT foundation on scour assessment, are also discussed using a physical model.

METHODS

In this study, a small example of a series of physical model tests is presented by Miranda (2022) to show that scour depth can vary depending on factors such as foundation type, soil properties, and the presence of other marine energy harvesting devices. This could allow further discussion of hybrid structures and scour predictions for complex soils, and help with future design methods for scour protection.

The physical model consisted of two foundations (Figure 1) that were tested simultaneously for two types of soil compositions – single-layer fine sand and layered sand with upper coarse sand (Figure 2), with and without the presence of a WEC. The fine sand material had a mean diameter (d_s) of 0.273 mm and a density (ρ_s) of 2650 kg/m^3. For the complex soil, a 1.5 cm layer of coarser sand (d_s= 0.4 mm, ρ_s= 2694 kg/m^3) was placed on top of a fine sand layer. Both materials were sieved according to the Portuguese standard NP EN 933-1.

The model had a geometric scale of 1:50 and followed Froude's similitude. The test included the effects of waves and currents in combination.

For the scour measurements, a comparative analysis between bathymetric profiles acquired with a FARO laser scanner (measurement error: ±1 mm, angular accuracy: 19 arc seconds) and post-processed to point clouds with the software SCENE was performed using the CloudCompare software. This software allows a cloud-to-cloud distance comparison between the initial, intermediate, and final bathymetric profiles.

The monopile model had a diameter ($D_{p,model}$) of 0.11 m, while the GBF had a 60º conical shape with a cylindrical skirt configuration with a diameter of the skirt ($D_{GBF,model}$) of 0.18 m (Figure 3).

For the WEC device, a model of an oscillating wave surge converter was implemented with different distances (d_{WEC}) from the foundation – 0.15, 0.25, and 0.35 m (Figure 4). The model had a 0.40x0.20 m base with a 0.15x0.10 m paddle that was rotatable by one degree transverse to the wave propagation direction via an axis connected to the base. The oscillating motion was achieved by attaching a spring connecting the base to the back of the paddle. The model was a simplification given the complexity of the prototype – curvature of the paddle, spring stiffness, and other properties that were not scaled.

The foundation models from OWT were subjected to a mean significant wave height (H_{m0}) of 0.10 m (5 m for the prototype) and a mean peak period (T_p) of 1.40 s (10 s for the prototype). Waves were conducted for an irregular sea state and a peak enhancement factor (ϒ) of 3.3, typical conditions for the North Sea. A total of 3000 waves were generated for different combinations of setup (single-layer soils/complex soil +absence/presence of WEC) for the same hydrodynamic conditions – corresponding to a storm duration of 1h 10min (8h 15min in the prototype). The depth-averaged current velocity (U_c) was measured at 40% of the mean water level (h), counting from the flume bottom– 0.172 m/s in the model value, 0.471 m/s in the prototype value. Wave-generated bottom orbital velocity (U_m) was determined as in Wiberg and Sherwood (2008), with a mean value of 0.12 m/s (0.85 m/s in the prototype) recorded.

Figure 1. Monopile (left) and GBF (right) models – adapted from Miranda (2022).

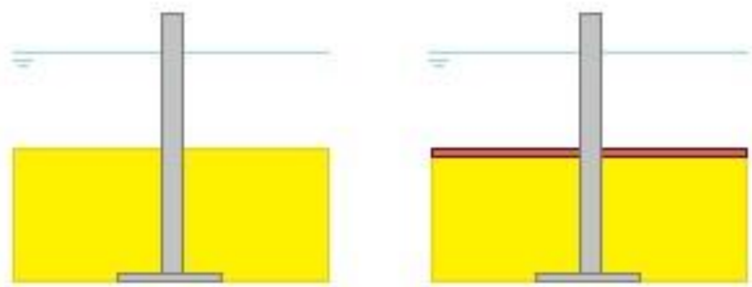

Figure 2. Model setup for the monopile (Left: Single-layer fine sand soil; Right: Layered soil with upper-layered coarse sand).

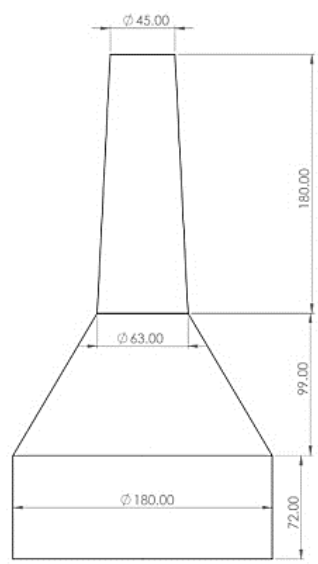

Figure 3. Dimensions of the 60º conical GBF model with a cylindrical skirt (dimensions in mm) – adapted from Miranda (2022).

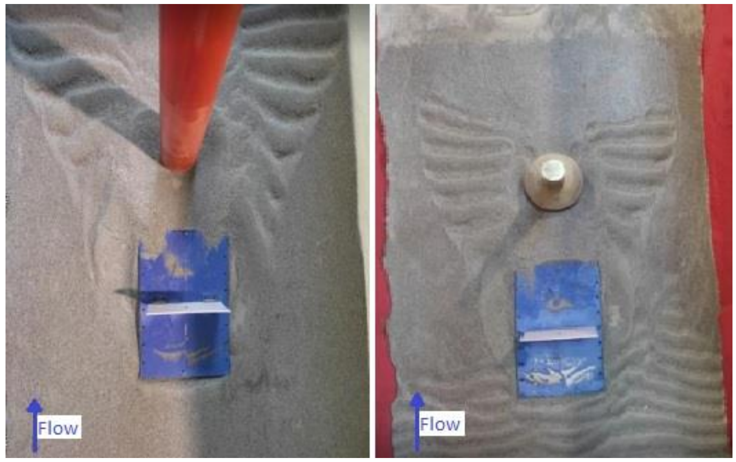

Figure 4. WEC position (left: monopile, right: GBF) – adapted from Miranda (2022).

RESULTS AND DISCUSSIONS

The results are summarized in Table 1, where the S/D (relative scour depth) and the $\Delta S/D$ (rate of change of relative scour depth) were determined. $\Delta S/D$ is the percentual difference between the test with and without the WEC presence. Scour depths in the monopile were consistently higher than in the GBF throughout the tests, consistent with the observations of Tavouktsoglou (2018). A probable reason could be the difference in the area of influence of the two foundations ($A_{monopile}$<A_{GBF}). The results obtained were less pronounced than in Tavouktsoglou (2018), although layered soils were not used, and then in Porter et al. (2012, 2013), even though the upper layer was composed of fine sand instead of coarse material. One possible reason could be the fact that the physical model registered U_c/U_{cr} values of less than 0.8. An U_c=0.172 m/s was much lower than the critical value – U_{cr}= 0.27 m/s (fine) and 0.277 m/s (coarse) –, resulting in a ratio of 0.64 and 0.62, which is classified as a low mobility ratio (Tavouktsoglou, 2018). The overall combination of waves and currents was likely insufficient to mobilize a generalized sediment transport. Future test conditions will therefore consider higher mobility ratios for the same test setups.

Regarding the presence and influence of the WEC, it is noted that the presence of the energy converter resulted in an overall average decrease in scour depth for both foundations (Figure 5 and Figure 6). An average reduction in scour depth of 58% and 33% in fine sand was observed for the monopiles and GBFs, respectively. In layered soil, the average reduction in scour depth increased with the presence of WEC to 68% and 73%, respectively. The WEC location upstream of the foundations increased sediment deposition between the converter and offshore wind foundations, filled some scour holes observed in the initial configurations, and acted as a scour reducer. These sediment deposits could also cause the device to malfunction, as they could impede the movement of the paddle. A direct relationship between the specific positioning of the device and scour reduction was not apparent, so further testing should be conducted with greater variability in experimental conditions and a wider range of spacing.

Without the presence of the WEC, the monopile foundation had a higher S/D value for the complex soil than the single-layer tests when comparing scour depths. For the GBF, the scour depths were approximately the same.

Rippling patterns and scour holes' boundaries were less evident for both foundations for the layered soil (Figure 7). Although the sediment size and coarse material density are higher, this does not necessarily result in less scour, even though for movement threshold and critical shear stress required to initiate sediment transport are higher. The highest and lowest S/D values were recorded for the stratified soil – monopile without WEC (S/D=0.45) and GBF with WEC for a d_{WEC}= [0.25, 0.35] m (S/D=0.02), respectively. The highest S/D occurred when the area of the upper coarse layer was completely eroded. Similar results were observed by Porter et al. (2012, 2013).

Table 1. Scour results.

Foundation model	h [m]	D_p [m]	Soil	d_{WEC} [m]	S/D [-]	$\Delta S/D$ [%]
Monopile	0.36	0.11	Single-layer sand	-	0.30	-
				0.15	0.12	- 60.0
				0.25	0.14	- 53.3
				0.35	0.12	- 60.0
			Layered sand	-	0.45	-
				0.15	0.16	- 64.4
				0.25	0.12	- 73.3
				0.35	0.15	- 66.7
GBF	0.36	0.18	Single-layer sand	-	0.09	-
				0.15	0.06	- 33.3
				0.25	0.06	- 33.3
				0.35	0.06	- 33.3
			Layered sand	-	0.10	-
				0.15	0.04	- 60.0
				0.25	0.02	- 80.0
				0.35	0.02	- 80.0

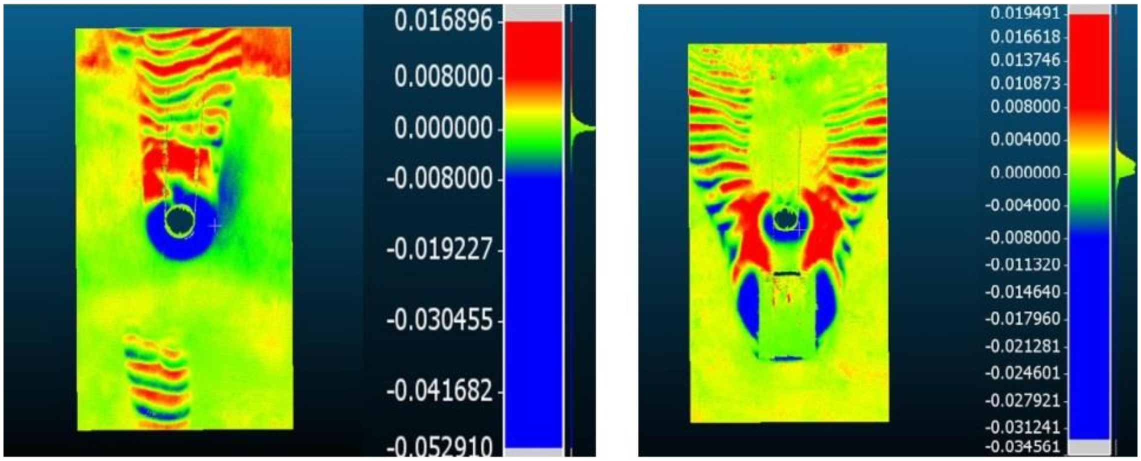

Figure 5. Comparison between two bathymetric profiles for monopile foundation in layered soil (left: without WEC, right: WEC at 0.15 m) – flow direction: bottom to top, blue: erosion, red: accretion (adapted from Miranda 2022).

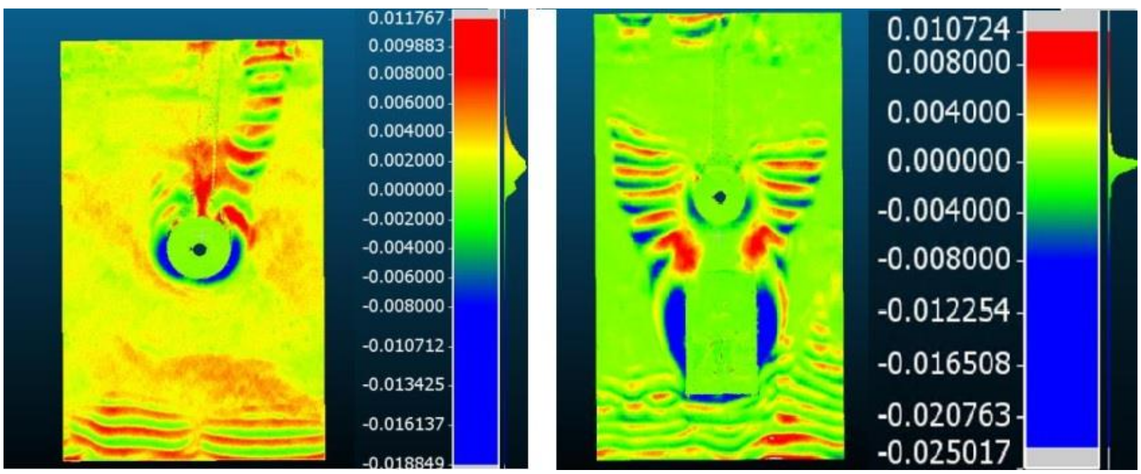

Figure 6. Comparison between two bathymetric profiles for GBF foundation in layered soil (left: without WEC, right: WEC at 0.15 m) – flow direction: bottom to top, blue: erosion, red: accretion (adapted from Miranda 2022).

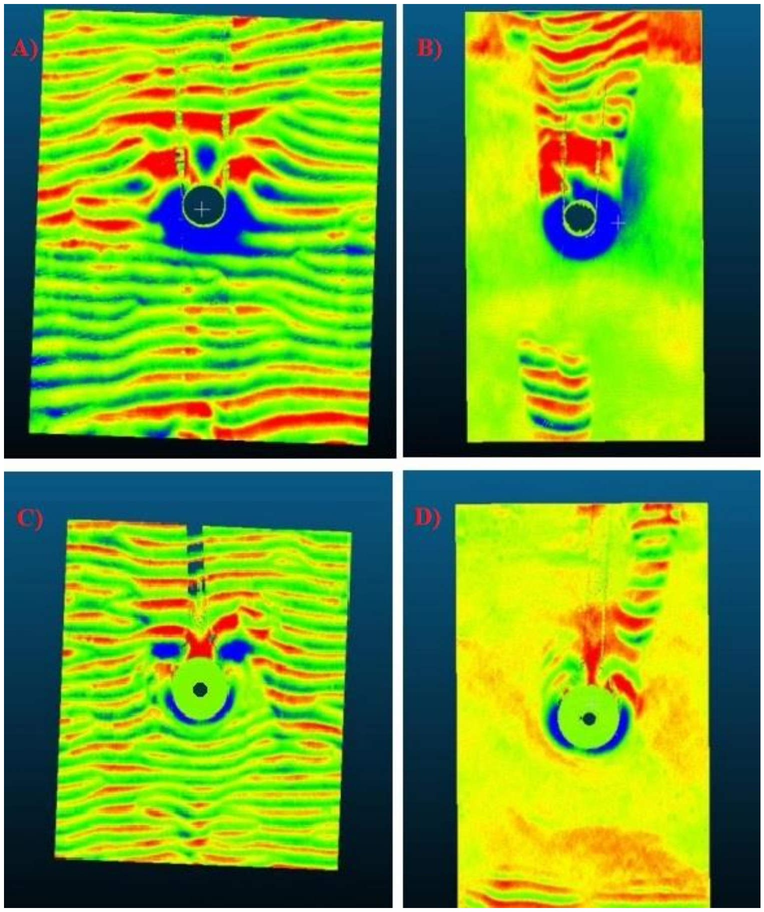

Figure 7. Pattern differences registered for different soil compositions – A) monopile in single-layer soil, B) monopile in layered soil, C) GBF in single-layer soil, and D) GBF in layered soil (adapted from Miranda 2022) - flow direction: bottom to top,.

CONCLUSION

Evaluation of scour behavior is critical to ensure appropriate countermeasures and design of protection systems, as well as to assure stability of offshore structures to prevent potential failures. Although the literature has extensively studied scour behavior in OWT monopile foundations for single-layer non-cohesive soils, there are still knowledge gaps that require further explanation, such as: scour in complex foundations, scour development depths in complex soil compositions, and the influence of hybrid structures on scour behavior (namely with the presence of WECs).

This research is part of ongoing work in FEUP's Hydraulics laboratory that addresses the effects of scour in marine energy harvesting technologies. Using a small data set of tests conducted in two different foundation models from OWT for two different soil compositions with and without the inclusion of a WEC, the following was found for the conditions tested:

- Scour depth was significantly reduced by the presence of the wave energy converter upstream of both the monopile and the GBF. On average, the reduction was over 60% for both soil configurations for the monopile and the GBF in the layered soil.
- The greater scour depths were obtained for the layered soil when the upper layer of coarse material was completely washed out, which increased scour in the lower layer. In the remaining cases where the underlying layer was not reached, the layered soil had a lower S/D than the single-layer soil, as reported by Porter et al. (2012, 2013).
- Scour patterns, holes, and shapes are quite different in the two soils. Due to its lower critical shear stress, the single layer of fine sand had more ripples and scour holes.
- A direct correlation between WEC spacing and scour depth could not be established, and further testing is needed to investigate this aspect.
- The presence of the WEC also increased sediment accumulation between the converter and the foundation.

The results presented here are from a limited data set that will be further expanded in future studies to validate and generalize the findings.

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