Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Risk-based approach for scour susceptibility for offshore wind farms

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ABSTRACT: This paper presents a methodology for the application of erosion test results for scour prediction. Erosion tests on field samples were performed to understand the erodibility and erosion rates of the soil samples. The soil characteristics that affect susceptibility to erosion include: Particle Size Distribution (D_{50}) and Fines Content. These are employed alongside the normalised Soil Behaviour Type (SBT_n) expressed by the index I_c, derived from Cone Penetration Tests (CPT), correlated to the erosion test results, to define parameters where the onset of erosion is observed. Threshold values of the D_{50}, Fines Content, percentage of clay and the I_c values are determined based on the erosion test results to inform the likelihood of scour occurrence in-field. These threshold parameters were then assigned weight factors based on their criticality and applied on soil samples acquired from a field in the North Sea to assess the likelihood of scour susceptibility and its duration. Based on the results, a risk-based approach was developed and implemented to plan and deploy scour protection around the foundations of an Offshore Wind Farm in the North Sea following foundation installation.

Keywords: Scour; prediction; erosion test; mean particle size (D_{50}); Fines Content

1 INTRODUCTION

Fixed-bottom and floating Offshore Wind Farms (OWFs) extend over large areas on the seabed. Currently, fixed-bottom OWFs are constructed in relatively shallow water depth (≤70 m) where the environmental conditions can induce seabed sediment disturbance which is more significant at shallow water depths compared to deeper depths. The presence of seabed obstructions (large diameter monopiles and jackets) usually amplifies environmental conditions in the vicinity of the foundation. This leads to locally higher disturbance of the seabed sediments and potential for initiating movement of these sediments. Scour usually develops due to these effects and once initiated it will propagate with a rate depending on sediment types and the severity of the hydrodynamic conditions. Typically, Scour Protection System (SPS) in the form of circular or elliptical rock berm shape, comprising either one-system layer or two-system layers (filter and armour layers), is installed around the foundations to mitigate potential development of scour and to ensure the integrity of the foundation during the asset lifetime.

2 PAPER MOTIVATION

Field operations during offshore installation campaigns are complex and have many interdependencies. A delay in any operation could significantly affect the overall project schedule and progress achieving certain milestones, especially if the operation is on the critical path of the project. This can lead to a delay in the electrification of a Wind Turbine Generator (WTG). Rock installation vessel availability in the market is currently very limited with high demand from the industry. As such, scour protection installation is considered one of the offshore operations that can dictate the commissioning of a WTG. This high demand requires that a scour protection design is well defined relatively early in the project, to ensure sufficient capacity is secured to deploy the rock volume soon after foundation installation to mitigate scour &

schedule risk. In practice, not all WTG foundations within a development are equally susceptible to scour with the scour initiation and propagation rate varying across foundations. Thus, this paper presents a methodology that can be used to categorise the risk of scour development around the foundations. The basis of the method relies upon erosion tests on soil samples from the field which are linked to key soil characteristics that affect scour initiation, the Particle Size Distribution (PSD) with emphasis on the mean particle size (D_{50}), Fines Contents (FC), silt content and Clay Content (CC)) as well as the index, I_c, deduced from the CPT recording and classification.

2.1 Site conditions

Typically, within an OWF site a number of Boreholes (BHs) are performed at foundation locations. These are supplemented with quicker *in situ* testing via CPT for soil characterisation followed by CPT interpretation to classify the soil. In addition, Vibro-cores (VC) are usually acquired in proximity to the CPTs, at the centre of the jacket or along the inter array cable or export cable routes. Relevant soil tests are then performed on recovered soil samples. Soil classification tests, Particle Size Distribution (PSD) for cohesionless soils, and Atterberg Limits for cohesive soils as well as soil density measurements are usually carried-out. The soil can thereafter be classified based upon test results with primary descriptions of CLAY, SILT, SAND or GRAVEL. These soil samples are then tested in the erosion test as described in the next section.

2.2 Erosion testing description

The erosion rig at HR Wallingford (HRW) (Harris, et al., 2022) consists of a central testing duct and lifting frame for core extrusion; (Figure 1). Water was pumped through the pipework into the duct with an average velocity flow, v_{flow}, up to 2.0 m/s. Core samples were prepared by drilling holes in the top and bottom core caps. Cores were saturated with water prior to testing. The bottom of the core was opened, and a piston was installed into the bottom of the core. The top cap was removed, and the sample was advanced into the bottom of the duct. The core sample was placed in the duct with its natural orientation. As such, part of the core sample was exposed to the induced current causing sample erosion (Figure 2). The rate of erosion (e_{rate}, mm/hr) was calculated, and the remaining part of the sample was extruded up through the sample tube to match the erosion rate.

The site metocean data (waves & currents) were used to determine the flow velocity applied in the erosion tests. An amplification factor was applied on the design near-bed flow speed to ensure the maximum flow rate tested was representative of conditions adjacent to the foundation. Each sample was subjected to flow conditions in ascending order of flow velocity and the erosion was measured at each velocity level held for a period of up to 10 minutes. The erosion rate was determined from the segment of core length eroded over the time interval. The critical flow velocity was then determined by fitting a power law equation to the data using the least squares best fit method.

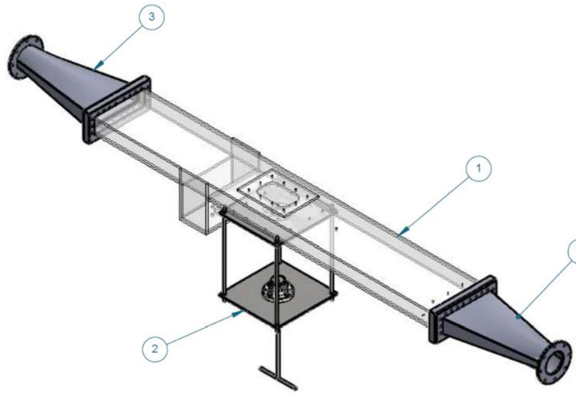

Figure 1. Central testing section of the duct (1), core lifting frame (2), and flow transition pieces (3)

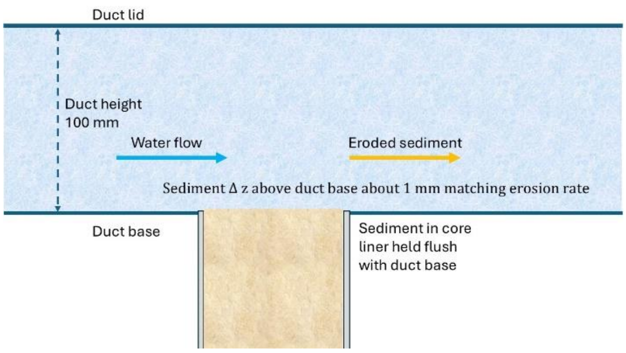

Figure 2. Vertical profile of the duct above the core lifting frame showing how the sediment core is tested

2.3 Testing programme

In total, 19 core samples (each 80 mm diameter and 300 mm length) were tested. Table 1 presents the depths of the tested samples below seabed (i.e. 0 m), and soil description.

Table 1. Description of soil samples tested in the erosion rig

Core No.	Depth [m]		Soil description
	From	To	
1	0.0	0.3	Fine to coarse SAND
2	0.5	0.8	Slightly silty SAND
3	1.0	1.3	Slightly silty SAND

4	2.2	2.5	Very silty SAND
5	1.5	1.8	Slightly sandy SILT
6	1.0	1.3	Slightly silty SAND
7	0.4	0.7	Silty fine to coarse SAND
8	0.0	0.3	Slightly gravelly fine to coarse SAND over SILT
9	0.0	0.3	Silty fine to medium SAND
10	0.5	0.8	Slightly gravelly fine to Medium SAND over CLAY
11	0.9	1.3	CLAY
12	1.0	1.3	Slightly gravelly sandy SILT
13	1.5	1.8	Silty fine to coarse SAND
14	1.5	1.8	Fine to coarse SAND
15	1.5	1.8	CLAY
16	2.0	2.3	Silty fine SAND
17	2.5	2.8	CLAY
18	2.5	2.8	Fine to medium SAND
19	3.0	3.3	CLAY

2.4 *Erosion test results and discussion*

The erosion test results are presented in Figure 3. The erosion behaviour can be classified into two distinct groups. The first group did not erode where the flow velocity was increased from 0.2 m/s to 1.1 m/s and a background erosion rate of circa 0.1 mm/hr was maintained. In the second group, the soil samples eroded rapidly at a rate of 10 mm/hr at flow velocity of 0.2 m/s to erosion rates of 10,000 mm/hr at velocity rates of 1.2 m/s.

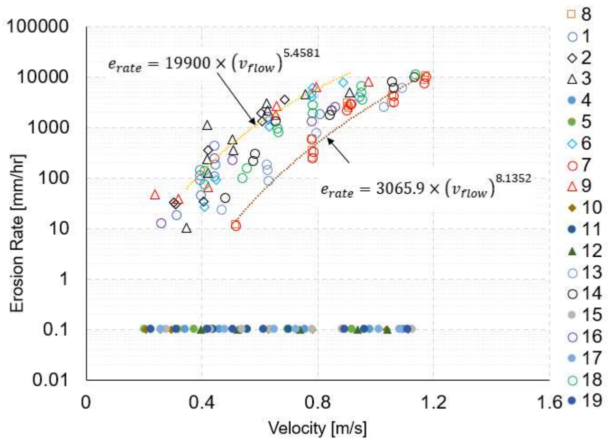

Figure 3. Erosion test results

2.4.1 *Non-eroded samples*

Core samples 4, 5, 10, 11, 12, 15, 17 and 19 did not erode. Sample 4 was classified as very silty SAND. The percentage of Fines (silts & clay) is unknown but believed to be sufficient to restrict the erosion initiation. Core samples 5 and 12 consisted of SILT which arrested the occurrence of erosion. The soils in core samples 10, 11, 15, 17 and 19 were of cohesive type with low to medium strength. These samples did not erode during testing.

2.4.2 *Eroded samples*

The remaining 11 samples experienced significant erosion levels. The observed general trend was that the erosion rates e_{rate} increased with increasing flow velocity v_{flow} (m/s) for all cohesionless samples. The upper and lower bound relationships between the erosion rates and flow velocities are represented as power low relations as expressed below.

$$e_{rate} = 19900 \times (v_{flow})^{5.4581} \quad (1)$$

$$e_{rate} = 3065.9 \times (v_{flow})^{8.1352} \quad (2)$$

2.4.3 *Effect of CPT soil behaviour type index, I_c*

In this section, the effect of the SBT_n index, I_c on the erosion test results is investigated as its values are linked to soil behaviour. The I_c is derived from the normalised cone resistance and friction ratio, Robertson & Cabal (2022) and is expressed by:

$$I_c = [(3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2]^{0.5} \quad (3)$$

Where Q_t, (-) refers to the normalised and dimensionless cone resistance ($Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}}$), q_t, (kPa) is the corrected cone resistance and σ_{vo} & σ'_{vo} are the total and effective overburden pressures (both in kPa), respectively and F_r, (%) is the normalised friction ratio ($F_r = \frac{f_s}{(q_t - \sigma_{vo})} \times 100\%$) with f_s being the measured sleeve friction (kPa).

The I_c values provide distinction between the SBT_n boundaries, however, it does not apply to fine grained soil. I_c values between 1.31 to 2.05 refer to clean sand; sand mixtures are represented by values between 2.05 and 2.6; while silt mixtures are represented by values between 2.60 and 2.95.

As shown in Table 3 and Figure 4, no clear trend was found between the I_c values and the erodibility of the soil samples. For example, core sample 4 did not erode despite its I_c value 1.74 falling within clean sand and silty sand. This could be explained by the high FC within the sample matrix. Samples 5 & 12 were classified as SILT with their I_c values of 1.8 and 1.9, respectively. These samples did not erode. It is possible that the derivation of the I_c at shallow depths below seabed may not be as reliable as at deeper depths. On the other hand, sample 10 had an I_c value of 2.2 (silt mixtures) and did not erode. The remaining samples with I_c values between 1.3 and 1.7 did erode during testing. The test results highlighted some difficulties in relying upon the I_c values to determine soil erodibility.

The FC was observed to have a major effect on the erodibility despite soil classification as sand or silty mixtures. To increase the reliability of any prediction and recommendation, other parameters such as PSD and FC, were investigated.

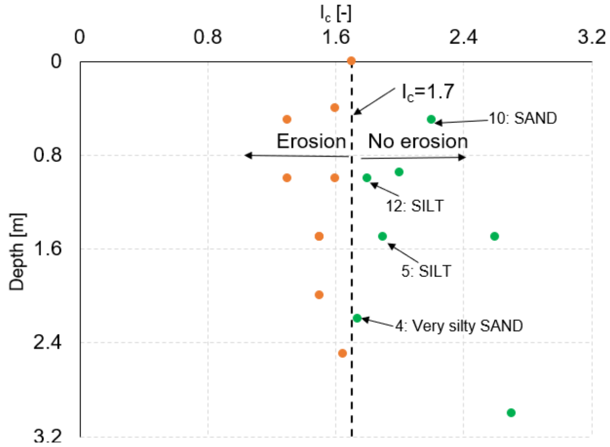

Figure 4. Soil type Ic for tested samples

2.4.4 *Effect of mean particle size (D_{50})*

The mean particle size, D_{50}, is one of the main soil characteristics that affects scour development in cohesionless soils, Soulsby (1997). The PSD test results are examined to identify a critical D_{50} at which erosion took place. Figure 5 presents the various D_{50} values of the tested samples for erodibility.

Samples with a D_{50} larger than 0.138 mm experienced erosion while samples $D_{50} \leq 0.138$ mm did not erode. It is found that fine sand was less vulnerable to erosion in contrast to the medium and coarse sand. To conclude, a D_{50} was determined as the threshold of onset of erosion development. The D_{50} should be evaluated with caution as larger sizes, corresponding to coarse sand and gravel, could be less susceptible to erosion.

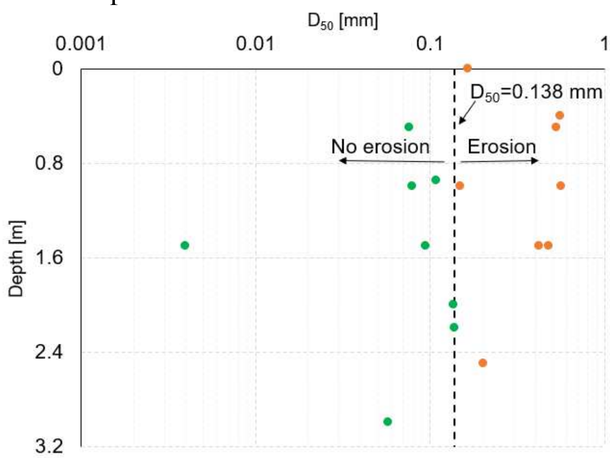

Figure 5. Effect of mean particle size, D_{50}, of tested samples on erodibility

2.4.5 *Effect of Fines Content*

While the D_{50} criterion is very useful, it may not be fully representative if considered alone. For example, a soil sample can have D_{50} of larger than 0.138 mm (medium sand) but with FC > 35% (black dashed line in Figure 6), i.e. silty sand or clayey sand (≤0.06 mm in size), could be less susceptible to erosion. Figure 6 shows the effect of FC on erodibility.

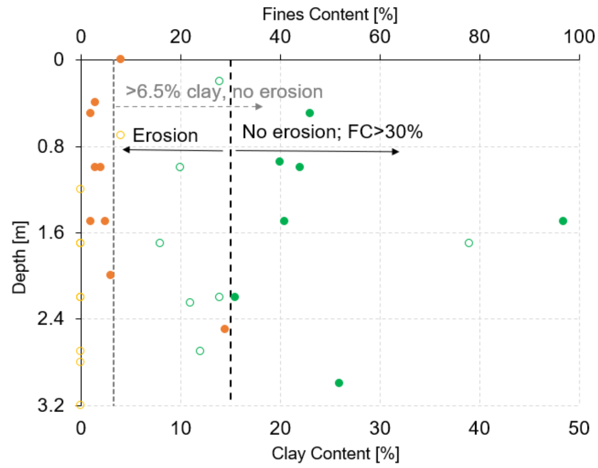

Figure 6. Clay (empty symbols) and fines content (solid symbols) percentages for tested samples

The general trend observed is that soil samples with FC greater than 30% did not erode during testing. The 30% limit is close to the 35% FC boundary where the soil can be described as CLAY or SAND with secondary descriptions of sandy, silty or clayey. Also, samples with CC >6.5% did not erode (grey dotted line in Figure 6). This is a key observation considered when assessing scour development. Table 2 presents summary of the threshold values of I_c, D_{50}, FC and CC.

Table 2. Summary of the threshold values

Parameter	I_c [-]	D_{50} [mm]	FC [%]	CC [%]
Value	1.7	0.138	30	6.5

2.4.6 *Application to design*

Table 3 summarises all tested samples for erodibility and the various parameters investigated in this paper. In the design, a scour allowance of 1 m was considered. Higher scour values were deemed to affect the caisson's in-place performance. Therefore, the time for scour development was assessed (Table 4). Very short durations, less than a week, were anticipated for scour development at primarily sandy soil samples. Samples with CC of greater than 6.5% showed longer durations for scour development (> 60 days). Soil sample 7 did not erode which was believed due to the 30% gravel content.

Table 3. Summary of tested samples with key parameters used to define erodibility

Core No.	Depth [m]		Soil	q_c [MPa]	I_c [-]	D_{50} [mm]	Silt [%]	Clay [%]	Fines [%]	Eroded Y/N
	From	To								
1	0.0	0.3	sand	1.25	1.9	-	-	-	-	Y
2	0.5	0.8	sand	7.25	1.3	0.528	2	0	2	Y
3	1.0	1.3	sand	10.66	1.3	0.564	3	0	3	Y
4	2.2	2.5	sand	22.0	1.7	0.138	21	10	31	N
5	1.5	1.8	sand	17.2	1.9	0.095	33	8	41	N
6	1.0	1.3	sand	5.12	1.6	0.150	4	0	4	Y
7	0.4	0.7	sand	4.22	1.6	0.555	3	0	3	Y
8	0.0	0.3	sand / silt	-	-	-	-	-	-	-
9	0.0	0.3	sand	1.36	1.7	0.165	8	0	8	Y
10	0.5	0.8	sand /clay	1.5	2.2	0.076	34	12	46	N
11	0.95	1.3	clay	9.76	2.0	0.109	29	11	40	N
12	1.0	1.3	silt	17.93	1.8	0.079	30	14	44	N
13	1.5	1.8	sand	10.3	1.5	0.481	5	0	5	Y
14	1.5	1.8	sand	7.43	1.5	0.423	2	0	2	Y
15	1.5	1.8	clay	0.87	2.6	0.004	58	39	97	N
16	2.0	2.3	sand	9.77	1.5	0.137	6	0	6	Y
17	2.5	2.8	clay	0.89	2.6	-	-	-	-	N
18	2.5	2.8	sand	6.28	1.7	0.202	25	4	29	Y
19	3.0	3.3	clay	1.39	2.7	0.058	37	14	52	N

Table 4. Predicted duration for 1.0 m of scour development at one water depth with percentage exceedance

Core No.	Depth [m]		Soil	Scour development duration [day]		
	From	To		90^{th} %	50^{th} %	10^{th} %
1	0.0	0.3	Sand	2	8	20
2	0.5	0.8	Sand	1	6	16
3	1.0	1.3	Sand	1	5	15
6	1.0	1.3	Sand	5	17	52
7	0.4	0.7	Sand	>60	>60	>60
9	0.0	0.3	Sand	1	6	16
10	0.5	0.8	Sand over clay	>60	>60	>60
13	1.5	1.8	Sand	>60	>60	>60
14	1.5	1.8	Sand	4	14	35
16	2.0	2.3	Sand	2	8	20
18	2.5	2.8	Sand	2	9	23

3 SCOUR PROTECTION AND SUPPLY CHAIN

Various constraints can affect scour protection installations such as; the foundation installation completion (e.g., heavy construction vessel and jack-up installation vessel), rock installation vessel, grouting operations, weather conditions, and other field operations. Any delay in scour protection installation could affect the foundation integrity and the structural response if no scour allowance was accounted for in the design or should scour develop and propagate quickly. To overcome such challenges, a risk-based approached was developed based on the observations from the erosion test results and soil characteristics as described in the next section.

4 PRACTICAL APPLICATION

The erosion test results have been utilised to determine threshold values of the I_c, D_{50}, FC and CC for the onset of soil erosion. These threshold values have been utilised to assess scour susceptibility and duration for scour development at field samples acquired across the site including those for which erosion tests were not conducted. Scour duration in-field, for 26 WTG locations, was then estimated.

The threshold criteria of I_c, D_{50}, FC and CC values will influence the overall results. Thus, various Weight

Factors (WFs) were assigned to each parameter depending on the confidence level of that parameter. The WFs are subjective and engineering judgement is used to select their percentage. The availability of soil samples with associated PSD test results has high certainty in the results. The CPT interpretation usually carries some uncertainty.

- The D_{50} has a significant influence on scour development and is one of the main input soil parameters for scour assessment. Thus, a WF of 30% is assigned,
- The FC was shown to contribute more to sample erosion. As the rate of scour development depends on the fines content, a WF of 40% is given to the FC,
- Samples with higher CC will require a longer period to initiate scour. As there is overlap between the D_{50}, the FC and the CC, a WF of 10% is assigned, and
- A WF of 20% is allocated to the I_c due to the uncertainty associated with its derivation and its influence on scour development.

The likelihood of scour susceptibility and its fast development, Table 5, is determined from the summation of the contribution of each parameter. Values of “0” and “1” in Table 5 refer to no erosion (or slow scour) and erosion (or fast scour). Fast scour is considered to occur in the case of only relying upon CPT results for granular soils. The likelihood based estimate placed 12 foundations in the no erosion (slow scour) category allowing the other 14 to be prioritised for early interventions.

Table 5. Determination of likelihood of fast scour development

ID	**D_{50}**	**FC**	**CC**	**I_c**	**Likelihood**
WTG	**30%**	**40%**	**10%**	**20%**	**%**
1	0	0	0	0	0
2	0	0	0	1	20
3	0	0	0	0	0
6	0	0	1	1	30
7	0	0	0	1	20
9	0	0	0	0	0
10	1	1	1	1	100
11	0	0	0	0	0
12	1	1	0	0	70
13	0	0	0	1	20
14	0	0	1	0	10
15	0	0	0	0	0
16	0	0	1	1	30
17	1	1	0	1	90
18	1	1	0	1	90
19	0	0	0	1	20
20	0	0	0	0	0
21	0	0	1	1	30
22	0	0	0	0	0
23	1	1	1	0	80
24	0	0	0	0	0
25	0	0	0	0	0
26	0	1	0	1	60
27	0	0	0	0	0
28	0	0	0	0	0
29	0	0	0	0	0

5 *CONCLUSIONS*

This paper presented the erodibility test results conducted on soil samples. The effect of I_c, D_{50}, FC and CC were examined and threshold values were determined for onset of erodibility. Higher WFs were given to soil samples where the effect of D_{50}, FC and CC are of significance. These values were then utilised for field soil samples to provide risk-based decisions for susceptibility of scour and whether fast or slow scour would be realised at 26 WTG locations. These results, assisted in project planning to prioritise those locations to be scour protected.

AUTHOR CONTRIBUTION STATEMENT

Nawras Hamdan, Mark MacBeath, David Grace, Treveon Joseph, Sofia Michelaki and Richard Whitehouse: conceptualisation, writing, review and editing.

ACKNOWLEDGEMENTS

Opinions expressed in this paper represent those of the authors and not their representative organisations. RJSW acknowledges the contribution of Dr Ian Chandler in delivering the erosion testing and Dr Nick Tavouktsoglou with scour duration estimates.

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