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# Framework for evaluating scour risk and optimising scour mitigation

## Cadre d'évaluation du risque d'affouillement et d'optimisation de son atténuation

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**ABSTRACT**: Scour poses a significant risk to seabed foundations. Common practice is to design scour protection to ensure protection against extreme metocean events such as 50-year storms. This may have been acceptable for oil and gas projects but, with the increasing size of offshore wind projects, this could result in excessive costs associated with the transportation and installation of scour protection. This paper aims to provide a framework to evaluate the main factors influencing scour risk such as; soil conditions including surface soils and the depth to potentially scour resistant soils, the metocean conditions which could result in scour, the potential rate of scour, as well as understanding the potential consequences of scour on foundation performance. This understanding will allow the specification of appropriate scour mitigation.

**RÉSUMÉ**: L'affouillement se produisant autour des structures sous-marines peut engendrer un risque important pour la stabilité des fondations. La pratique courante consiste à concevoir une protection contre l'affouillement visant à assurer une protection contre les évènements météo-océaniques extrêmes tels que les tempêtes de période de retour 50 ans. Cette approche était acceptable pour les projets pétroliers et gaziers. Mais, du fait de la taille croissante des projets de développement éoliens offshore, implémenter cette même approche pourrait engendrer des coûts excessifs associés au transport et à l'installation de protection anti-affouillement. Cet article vise à fournir un cadre pour évaluer les principaux facteurs influençant le risque d'affouillement, tels que: les conditions du sol, y compris les sols de surface et la profondeur des sols potentiellement résistants à l'affouillement, les conditions météo-océaniques qui pourraient générer l'affouillement, le taux potentiel d'avancement d'affouillement avec le temps, ainsi qu'une compréhension des conséquences potentielles de cet affouillement sur les performances des fondations. Une telle compréhension permettra de définir des mesures d'atténuation appropriées.

**Keywords:** Offshore foundations; scour protection; scour risk; scour mitigation.

## 1 INTRODUCTION

The installation of structures such as offshore wind turbine foundations is likely to cause a local increase in seabed stresses due to wave and current motions. This increase can result in local erosion of seabed soils around the structure. This process is generally known as scour whereas widespread sediment mobility away from structures is known as 'global sediment mobility'.

Scour can result in reduced foundation capacity and/or a 'softer' foundation response, potentially resulting in natural frequency or fatigue issues. The risk of scour is usually mitigated by using rock berms placed around the foundations to 'shield' the seabed, however, alternatives such as filter units and fronded mattresses can also be used.

Scour assessment and subsequent scour protection design usually consider extreme metocean events such as 50-year storms and assume any significant scour is unacceptable. This may have been acceptable for oil and gas projects but, with the increasing size of offshore wind projects, this could result in excessive costs associated with the transportation and installation of scour protection around hundreds of offshore structures.

The aim of this paper is to propose a framework to better understand the risk of scour and potential consequences, to then determine the most appropriate scour mitigation measures. It should be noted that global seabed mobility is not considered as part of this paper.

## 2 SCOUR PRINCIPLES

Scour processes are commonly triggered as a result of the presence of a structure which disturbs pre-existing flow patterns, increasing the fluid velocity / current speed as it flows around the structure. At the seawater-seabed interface, this increased velocity is translated into a bed shear stress. This can subsequently lead to higher local erosion occurring around a foundation structure, reducing with distance from the structure.

The evolution of the scour mainly depends on several parameters such as soil characteristics, the prevailing metocean conditions, and structure geometry, as discussed below.

## 2.1 Soil characteristics for scour resistance

The characteristics of the shallow seabed soils can significantly influence scour potential. For example, in cohesionless soils: smaller, lighter soil particles are more prone to scour than larger heavy particles. Effective soil cohesion also increases soil scour resistance.

As a minimum, the following soil parameters are required:

- Sediment specific gravity (density of soil grains);
- Sediment size (particle size distribution);
- Cohesion.

Other factors such as grain shape or clay plasticity may also be a factor but are considered less critical.

## 2.2 Metocean parameters for scour propagation

The prevalent metocean conditions, such as tidal current and waves, can have a significant influence on scour potential. The collection of site-specific metocean data is considered an invaluable asset to aid in the development of the risk-based approach for initial categorising of the site. The following parameters are required as a minimum:

- Maximum current velocity and direction at seabed level (or just above);
- Metocean parameters for anticipated design conditions i.e., 1 year storm, 5-year storm, etc would also add significant value.
- Wave parameters including wave direction, maximum wave height and period.
- Low-water and high-water levels.

Metocean criteria and input for design should be contemplated as part of a site specific metocean assessment. In order to select realistic conditions for a 50-year event, consideration should be given to the realities of climate change. What were previously considered extreme events may become more frequent and therefore expectations of what constitutes an extreme event should be updated as part of the metocean assessment.

## 2.3 Structure size

The classical representation of flow modification around a vertical pile is shown in Figure 1. Local scour is often induced by the generation of the horseshoe vortex (rotation of the incoming flow), vortex shedding (generation of lee-wake vortex behind the pile) and the contraction of the streamlines around the structure (Sumer and Fredsoe, 2002).

The larger the structure, the larger the flow disturbance.

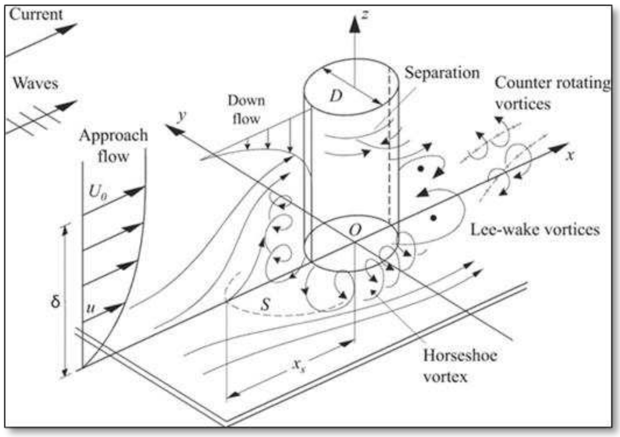


*Figure 1. Flow around a vertical pile – extract Sumer and Fredsoe (2002).*

# 3 SCOUR RISK ASSESSMENT PROCESS

The risk of scour should be considered throughout the development cycle to ensure sufficient information is collected and evaluated to allow for informed decisions without unnecessary or abortive work. The following process is hence recommended:

1. Initial site characterisation (basic soil and metocean parameters);
2. Initial scour risk evaluation and sensitivity analysis;
3. Detailed site characterisation;
4. Detailed scour assessment;
5. Evaluation of scour consequences;
6. Cost benefit analysis of scour mitigation options / measures.

# 4 INITIAL SITE CHARACTERISATION

At early project stages, limited information is likely to be available. Therefore, there should be a detailed desk study including a review of all public domain information and likely conditions across the planned development area including water depth, anticipated seabed sediments, potential bedforms, shallow geology and indicative metocean parameters.

Ideally, the desk study information should also provide an initial qualitative scour risk assessment. Identification of seabed features such as sand waves, megaripples, etc. are meaningful indicators that scour should be considered a risk. Whilst a relatively flat featureless seabed with high strength clay or rock at seabed would be considered lower risk.

Even if the available data are not of sufficient resolution to identify potential bedform features, the indication of water depth and metocean parameters should also be somewhat informative.

The outcome of the initial risk assessment should inform the scope of future survey campaigns. For example; a geophysical survey undertaken in order to accurately identify bedforms, potentially with multiple phases to monitor bedform migration speed. The planned surveys should be scoped to provide the information required for the scour analysis.

Key outputs:

- Qualitative risk assessment across site;
- Input into future survey scopes.

# 5 INITIAL RISK EVALUATION

Once site specific data are available in the form of seabed soils and metocean data, then initial numerical analysis can be undertaken to better understand scour potential. At this stage, a relatively simple numerical analysis is likely to offer reasonable understanding of the risk.

## 5.1 Metocean seabed stresses

The seabed stresses developed by the current are dependent upon the current velocity, water density and the turbulent flow regime. Specific formulation can be used to estimate current induced seabed stresses.

## 5.2 Shields stability method

Shields (1936) proposed a detailed, rational approach to the problem of hydrodynamic stability by defining the erosion limit in terms of the particle Reynolds number (a dimensionless parameter detailing the ratio of inertial to viscous forces) and the critical Shields parameter (normalised critical seabed stresses). Shields‘ theory can then be extended to the combined action of currents and waves.

It is noted that based on the randomness of the packing of the particles at the seabed, McEwan and Heald (2001) observed that, for a given bed stress or shear velocity, some particles are more vulnerable to erosion than others. The physical significance of this phenomenon was better described by Sato (1966), who studied erosion under wave action. Sato defined two levels of seabed mobility, called "surface layer movement" and "completely active movement", respectively. Surface layer movement corresponds to the state where the first layer of particles of the seabed moves in the direction of the wave propagation. Completely active movement corresponds to such movement of bed material as to produce a notable variation in the seabed profile and Sato classifies "completely active" behaviour as more than 8% of sediment by volume.

## 5.3 Initial risk evaluation outputs

The initial risk assessment shall assess the conditions across the planned site for a number of potential metocean conditions to better understand scour risk.

The site could be split into zones of similar seabed sediments and water depth (and metocean conditions) and then an assessment undertaken to understand scour risk for the different conditions. For example:

- Zone A (deep water, high strength clays) – low risk;
- Zone B (medium water and coarse sands) – potential surface movement (medium risk);
- Zone C (shallow water, fine sands) – potential for 'completely active' movement (high risk).

# 6 DETAILED SITE CHARACTERISATION

The initial scour risk assessment should provide an indication of scour risk across the potential development area. The planned surveys including sediment sampling and potentially in-situ testing should be tailored based on these results. The site characterisation should aim to identify the main soil units anticipated across the development area, map the lateral and vertical distribution of these units, and provide sufficient information to allow scour potential to be accurately determined for each of the soil units.

In zones where a high risk of scouring is indicated, it may be necessary to plan additional tests potentially including benthic flume testing.

## 6.1 Sediment sampling

Representative seabed sediment core samples should be collected from across the site. The planned campaigns should obtain sediment samples of the main shallow soil units anticipated across the development area.

These soils can be targeted based on the scour risk assessment previously undertaken. Engineering judgement should be applied in order to obtain and preserve as many intact samples as necessary, particularly in higher risk zones to potentially perform erosion tests as discussed in section 6.1.2. Additionally, it is important to perform sufficient index testing of the surface sediments in order to properly characterise the soils.

Samples shall generally be obtained using vibrocores or boxcores (and potentially even boreholes) in order to obtain a better understanding of the most surficial soils and allow for a number of subsamples for testing (and for example, to verify cohesion).

### 6.1.1 Onshore laboratory testing - classification

As outlined above, soil characteristics which have the largest effect on scour occurrence and severity are:

- Soil type. Clay soils are most resistant to scouring whereas sands are often prone to scour.
- Particle size and specific gravity. Larger heavier soils tend to be more scour resistant.
- Cohesion. Experience indicates that sands which possess some levels of cohesion are far more scour resistant than those without.

As part of the geotechnical testing campaigns, it is vital to identify the main soil units present across the development area, and characterise each unit with sufficient index and other laboratory tests such as:

- Particle density (specific gravity);
- Particle size distribution (PSDs) for d50 and fines content;
- Shear box testing for cohesion.

### 6.1.2 Onshore laboratory testing – erosion

The initial numerical assessment detailed in section 5 is considered a useful indicator, but physical erosion testing should be considered to validate and/or optimise these results, particularly in high-risk areas.

Erosion testing generally comprises placing a soil sample in a flume and increasing the flow speed to investigate the sediment erosion with current speed.

It is important to use test conditions that are representative of the site and preferably based on measured metocean data.

The soil samples should undergo detailed assessment prior to onshore flume testing to ensure that they are representative of the anticipated soil units to the base of the potential scour depth.

The flow speeds should be carefully specified to represent anticipated field conditions and provide an accurate indication of the flow velocity to initiate erosion.

The main aim of erosion testing is to identify:

- Flow velocity at which mobility begins;
- Erosion rate at various current speeds.

Examples of results from indicative soils including sand, silt and clay are shown in Figure 2 below. These results indicate clays are generally highly resistant to scour with limited erosion even at significant current speeds (>1m/s), sands can erode at relatively low current speeds and even relatively limited cohesion can provide significant additional resistance against scour.

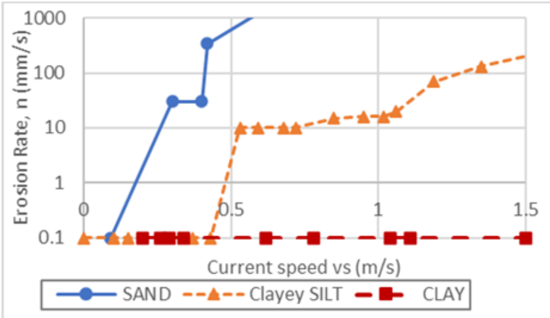


*Figure 2. Erosion test results example.*

It should be noted that testing a reasonable sample size can provide indications of the bulk behaviour of the soils. For example, there may be preferential erosion of smaller particles which leaves a layer of coarse sediments, shells and gravel at surface which is more resistant to scour. If this occurs, then it is recommended to carefully observe the test to understand the potential for sediment winnowing and the point at which the 'shield' layer becomes unstable. Consideration could also be given to testing the 'shield' layer at reduced velocities to better understand the benefits of this shielding.

Key outputs:

- Current velocity to initiate scour for each soil unit;
- Scour rate for each soil unit;
- Understand potential for formation of 'shield' layers and the potential benefits.

### 6.1.3 In-situ benthic flume testing

The Seaflume (KC Denmark, 2023) is a device which can provide an understanding of the in-situ erodibility of seabed sediments, particularly sands, fine gravels, and silts.

In-situ testing like this should be considered in zones which are high risk as it can provide a rapid insight to the reality and severity of erosion at an expected "worst-case" location. However, it should be noted that seabed flume testing is likely to incur additional offshore time and costs, and should be carefully planned as part of the survey campaigns.

Key outputs:

- Current velocity to initiate scour at representative locations;
- Scour rate for representative locations at anticipated flow velocities.

#### 6.1.4 Near-bed flow monitoring

Collection of flow data (current speed and direction) very close to the seabed (within 2m) and through the water column at relatively small vertical intervals (0.25 m or 0.5 m maximum) is recommended. This requires specific instrumentation; it aims to provide valuable site-specific data on those flows which are most relevant to scour assessment and within the scour protection zones.

A current measuring system within a configuration which permits very near-bed flow measurement, detailed water column resolution and which preferably can also measure waves is suggested. Data should be collected for a period which includes more quiescent tidally dominated conditions (e.g., summertime) and more energetic wave dominated conditions.

## 7 SCOUR PROPAGATION ANALYSIS

In order to undertake a detailed evaluation of the risk of scour to the installation, it is necessary to undertake detailed modelling, utilising the results of site-specific testing and site specific metocean data and their analyses.

### 7.1 Sub-structure influence

The presence of the substructure is likely to result in acceleration and/or disturbance of the flow which would increase the seabed stresses. The magnitude of the stress increase could be determined using Computational Flow Dynamics (CFD) and/or scale model testing.

Key output:

- Relevant flow acceleration factors for the structures.

### 7.2 Numerical model

Numerical model using the time domain metocean data, scour test results, and sub-structure flow modification to estimate scour propagation with time can be valuable to understand anticipated scour depth and propagation timescales for various events i.e., 1-year, 5-year and 50-year storms.

The numerical study should also consider the potential for 'natural' backfill with time after the significant design events.

## 8 SCOUR CONSEQUENCES

The consequences of scour can vary significantly depending upon the substructure and foundation types as outlined below:

- Monopiles – Significant scour could result in a reduced lateral capacity and a shift in the natural frequency which may have implications for the structure fatigue life;
- Jacket pin-piles - The axial capacity of jacket piles is generally the design driver. Scour may not have a significant influence on the design capacity, however, stiffnesses and frequency response should be checked;
- Suction caissons -The axial capacity of suction caissons is usually the design driver for jacket structures. Scour could result in a significant reduction in design capacity;
- Gravity Base Structures - GBS structures rely on full base contact. Scour could result in uneven settlement and/or foundation 'rocking'. Therefore, any scour risk is likely to be unacceptable.

The sensitivity of the structure type to scour should be carefully considered. It should also be noted that the overall foundation 'stiffness' can change with time; i.e., thixotropy effects increasing stiffness of piles / caissons. Cyclic loading potentially 'softening' stiffness after a significant storm.

Sensitivity checks could be undertaken to determine allowable stiffnesses and associated scour depths in conjunction with other considerations such as thixotropy. This could be used to develop an understanding of 'acceptable' scour depth and timescales as well as understanding timescales for remediation, for instance:

- 2.5m scour during 5-year storm – acceptable;
- 4.5m scour due to 50-year storm – soft response increases fatigue – must be remediated within 3 months.

## 9 SCOUR MITIGATION OPTIONS

### 9.1 Scour allowance design and observation

The main suggestion of the proposed framework is to understand storm risk and incorporate a suitable scour allowance into the scour protection design. This option would require regular monitoring of the scour evolution and resultant effects on the foundation dynamic response.

Highly specified monitoring of the offshore environment is recommended as the usual means of de-risking the engineering work into the future and for providing the project development team with a suitable level of reassurance that an accurate understanding of marine conditions as they relate to recent scour issues is available (as far as it can be in practice).

Implementation of some form of monitoring is considered to be crucial to de-risking the issues related to scour and to improving asset integrity over the timeframes of an offshore windfarm (typically 25-30 years).

### 9.2 Full scour protection (Rock Berm)

Rock berms are one of the most common scour protection solutions. The thickness and lateral extent of the rock berm, and resultant required rock volume, will depend on multiple factors including the berm design approach, water depth, metocean input, ground conditions, and stone gradings, amongst others.

The rock berms are generally designed to be stable under 50-year design conditions. Additionally, the rock berms are usually surveyed regularly to ensure they remain stable. Measurement errors and tolerances must also be considered. Monitoring and inspection are generally undertaken every six months for the first 2 years, covering the seabed level, local scour at the unprotected areas around the foundations, and the condition of the scour protection at each location, using appropriate methods.

The cost of rock berms and post construction survey is usually significant. However, rock berms are considered highly effective as long as they are properly designed to account for design metocean events, winnowing, and edge scour.

### 9.3 Alternatives (anti-scour frond mattresses)

The market offers other alternative and proven solutions for preventing scour that could potentially be economically advantageous. An example of this is the anti-scour frond mattress constructed of aerated polyethylene fronds that when installed on the seabed will naturally float to resemble natural seaweed. As the sediments are transported through the frond mattresses with the current, the soils amass onto the mattress forming a natural fibre reinforced sand bank protecting the area of interest.

Installation methods for this type of solution may include; weight ballast bags attached around the perimeter mattresses, the use of frond mattresses pre-fitted to a concrete mattress offering instant scour protection and easier installation in a high subsea current environment, or the use of divers with anchors driven into the seabed.

The cost of fronded mats is lower than rock berms; however, they may be less effective, resulting in higher residual risk.

## 10 CONCLUSIONS

The paper provides a framework to understand and make an informed decision on the optimal risk mitigate strategy for scour.

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