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Scour Protection Design for Offshore Substation Platforms

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ABSTRACT

Offshore Substation Platforms are often placed in deep water with a dynamic seabed. The substructure typically consists of a jacket with boat landing, J-tubes and several piles. Pre-installation of scour protection pads is becoming a more common practice to fixate the seabed prior to the installation of the substructure. This paper presents a practical example on the design of the scour protection. The analyses are based on DNV-RP-0618. In the paper, the scour protection design is presented and the strategy discussed, including pros and cons.

1. INTRODUCTION

Wind energy is expected to play a major role to limit climate change and its effects, therefore, Offshore Wind Farms (OWFs) are being developed at an increasingly faster pace in response to society's demand for renewable energy. Offshore Substation Platforms (OSPs) are a key component in the development of OWFs, i.e., as nodal points in the energy production grid for the exportation of power to land.

Due to the complexity of these platforms, the construction of scour protection pads is becoming common practice to fix at the seabed level prior to the installation of the OSP substructure. The typical substructure is either used for offshore substations or offshore HVDC Converters and typically comprises of a jacket with means of access such as one or two boat landing and scape ladders, J-tubes with bell mouths for Export and Inter Array cables, cathodic protection system (either by anodes or ICP), several pipes for mechanical systems installed at the Station as required (i.e. cooling or drain systems), mudmats and several piles.

Scour protection design for jacket structures is an area that requires further research and development due to the complex interactions between waves, currents and the substructure. These interactions increase the turbulence of the flow around the structure and amplify the shear stresses acting on the seabed, as such, laboratory tests are often needed to document the efficacy of a design.

Two types of scour processes occur around jackets, i.e. global and local scour. Local scour develops at the substructure components. The legs, due to their larger diameter when compared to the other components, generate the most significant secondary flows and turbulence at seabed level. Global scour is caused by the integrated substructure, which creates a complex three-dimensional disturbance of the flow and can affect a large area around the substructure. Evidence of this is shown by Angus et al. (1982), Ref. /1/.

The urgency in planning and development of OSPs means that often the design process is accelerated and that testing of scour protection designs in the laboratory is not possible or impractical and for this reason, simplified methodologies and assumptions have to be employed.

The objective of this paper is to present a practical example of a certifiable design of scour protection for one such case. The following example is based on the scour protection design done for the OSP in the Dogger Bank C OWF, a project with total installed capacity of 1.2-1.3GW, owned by SSE and Equinor. COWI was commissioned by Navantia, the EPC Contractor for the OSP HVDC converter station provided by Aibel, to design a scour protection pad to stabilize the seabed prior to the installation of the OSP jacket and cables. The design Cable Protection System (CPS) was not part of the scope and to be provided by the Cable Contractor.

The scour protection design required to satisfy the following considerations:

- Stabilize the seabed prior to the installation of the substructure and cables;
- Be flexible to allow for seabed lowering due to sand waves and/or edge scour;
- Account for installation tolerances;

2. DESIGN CONCEPT

The design concept in Dogger Bank C (DBC) was inherited from Dogger Bank A and B as requested by Equinor. It consisted of a pre-installed single-graded scour protection pad with a horizontal extent of 12m outside of the mudmats. The OSS jacket would then be installed on top of the scour protection and the piles driven through the rock pad.

The main objective of the scour protection pad is to stabilize the seabed prior installation of the substructure and cables. In order to achieve that, the following construction sequence with regards the scour protection, substructure and cables was proposed:

1. Dredging of the seabed;
2. Installation of scour protection pad;
3. Laying of inter-array and export cables;
4. Installation of the jacket, temporarily supported by mudmats;
5. Installation of the piles;
6. Connection of pre-laid cables with OSP and installation of CPS.

Discussions with the Transportation and Installation (T&I) Contractor confirmed that duration of the interim period between the installation of the jacket and CPS would be below 180 days.

In accordance with project requirements, the design of the OSP had to abide to DNVGL-ST-0145 (2016), Ref. /2/, and DNV-OS-H101 (2011), Ref. /3/. Based on the above, a 10 year Return Period (RP) storm event was the design case to consider for the external stability calculations of the scour protection. Internal stability considerations, such as sinking due to winnowing, were designed for the 100 year RP event conditions since this phenomenon develops due to exposure to environmental loads, especially when subject to significant storm events.

The design parameters were the following:

Return period [years]	Significant wave height, H_s [m]	Wave peak period, T_p [s]	Current speed 4m above seabed, U_c [cm/s]	Water depth, h [m]
1	7.6	11.3	58	23.6
10	9.2	14.4	72	
100	10.6	15.7	86	

Several scour protection designs were pondered at the start of the project, but it was decided that a trenched solution would best fulfill the Client's requirements while also minimizing the risks associated to the lack of laboratory tests. The advantages of the proposed design are:

- Allowance to use inch-size rock gradings due to the sheltering provided by the surrounding seabed, reducing the risk of pile driving refusal during the installation of the jacket foundation through the scour protection layer;
- Mitigation of the development of global scour within and around the structure's footprint, which would require the design of an internal falling apron and consideration of more complex construction tolerances;
- Provision of a regular surface to support the mudmats bearing the OSS structure prior to the installation of the piles.

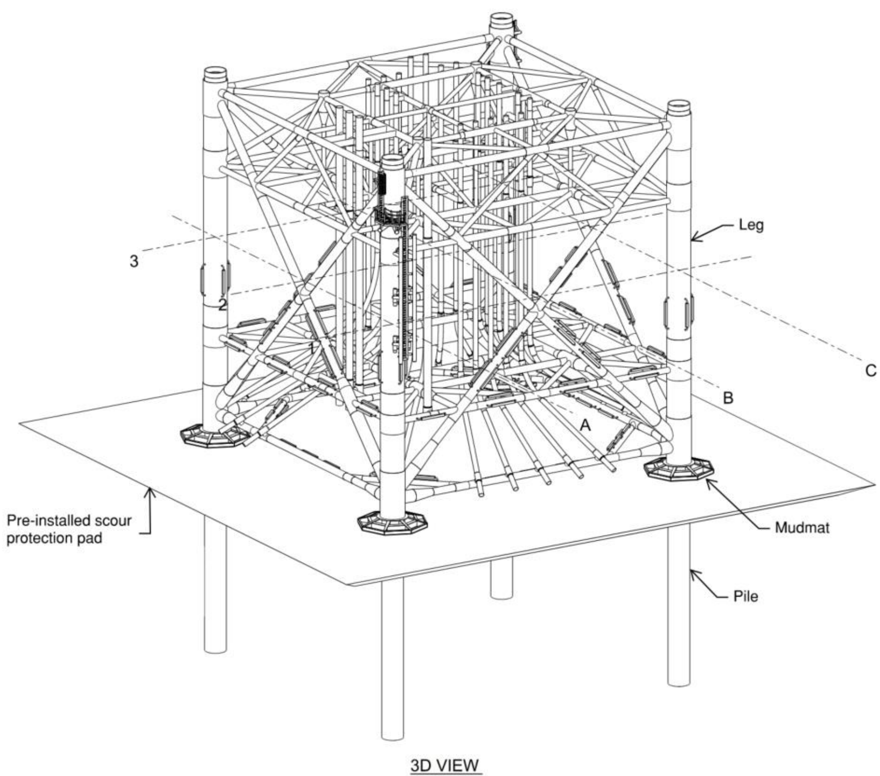

Figure 1 Visualization of the design of the scour protection pad. Please note that the project is ongoing at the time of publishing this paper and the above illustration may not represent the final design of the jacket structure in detail.

2.1 Rock grading

Two high-density single-graded scour protection materials (ρ_s = 3000 kg/m^3) were analyzed based on experience from the previous Dogger Bank sites, a 3-9" rock material (D_{50} = 0.110m) and a 4-10" rock material (D_{50} = 0.145m).

3 Assumptions

The assumptions considered in the design of the DBC scour protection pad were the following.

- **Flow around the structure and turbulence**:

Laboratory tests were not performed in this project, therefore, simplifications had to be made in order to size the scour protection stones needed to stabilize the seabed.

The seabed is subject to shear stresses caused by the turbulence and flow amplification from primary and secondary structures in the horizontal and vertical planes, waves and currents. The amplification of the flow is directly related to the geometry of the obstructing body and rapidly decreases with distance as demonstrated by Whitehouse (1998), Ref./4/, as a consequence, larger elements in the substructure will have a relatively larger impact towards the scour protection.

Based on engineering judgment, it was assumed that the most important secondary flows are caused by the jacket legs due to the relatively small diameter of the J-tubes and braces as well as their relative distance towards the seabed, therefore, only the piles were considered in the determination of the flow amplification.

- **Mudmats**:

The jacket legs are surrounded by mudmats. The diameter of the legs is 2.81m and the diameter of the mudmats is 8m. Hence, the amplification of the bed shear stress should be found at a normalized distance from the center of the pile of:

$$\frac{\left(\frac{8}{2}-\frac{2.81}{2}\right)}{2.81}=0.92 \qquad \textbf{Equation 1}$$

- **Blockage**:

Blockage by the substructure was conservatively ignored.

- **Sand waves**:

A seabed lowering of 2.2m was taken into account based on data provided by the Client.

- **Breaking waves**:

In accordance with the metocean information available, the site is characterized by the presence of spilling breaking waves. Based on Nielsen et al. (2012), Ref. /5/, scour forced by breaking waves at slender piles is comparable to that caused by non-breaking waves. Given the breaking wave typology encounter on site and their relative slenderness, scour generated by non-breaking waves was considered.

- **Porosity of scour protection layer**:

The scour protection was assumed to be a coarse grading in accordance with C683-The Rock Manual, Ref./6/. The uniformity index exponent n_{RRD} was assumed to be equal to 3.28 in accordance with Table 3.6 in C683-The Rock Manual, resulting in a volumetric porosity, n_v, equals to 0.4 as per Figure 3.23 in C683-The Rock Manual.

- **Marine growth**:

A marine growth thickness of 100 mm was assumed based on project location.

- **Co-directionality of waves and currents**:

Waves and currents were conservatively assumed to be co-directional.

4 Scour protection design

The design was based on the formulae proposed by DNV-RP-0618, Ref. /7/, and DNV-ST-0126, Ref. /8/ in combination with C683 – The Rock Manual. The following section describes the design considerations that led to the stability results of the designed scour protection for the stabilization of the seabed prior to the installation of the OSS jacket foundation and cables.

Other design considerations, such as the internal stability checks, the falling apron and the edge scour were determined by use of the formulations proposed by DNV-RP-0618 and C683 – The Rock Manual. A brief summary of the literature employed is the following:

- Sinking due to winnowing, caused by flow amplification, currents and waves, was determined based on, Sumer et al. (2013), Ref. /9/, and Hoffmans (2012), Ref. /10/.
- Edge scour was determined in accordance with Petersen et al. (2015), Ref. /11/.
- The falling apron was design based on Van Velzen (2012), Ref. /12/.

4.1 External stability

The external stability of the scour protection stones is defined by the mobility number, MOB. The MOB number represents the ratio of the maximum shear stress, θ_{max}, over the critical shear stress, θ_{crit}, and is defined as follows:

$$MOB = \frac{\theta_{max}}{\theta_{crit}}$$

DNV-ST-0126 indicates that motion of the scour protection stones commences at critical Shields Parameter values $\theta_{crit} = 0.05$ to 0.06. It is generally considered that at a $\theta_{crit} = 0.05$ stones rock and at a $\theta_{crit} = 0.06$ stones move, as such, a $\theta_{crit} = 0.055$ was considered for the undisturbed flow.

Note that the MOB number cannot be taken as the traditional utilization ratio used in other engineering disciplines. This parameter indicates the onset of motion and can therefore be used to quantify how much damage a scour protection system takes under design conditions through the execution of laboratory tests. Where laboratory testing is not possible, as was the case of the example presented in this paper, a conservative design criterion of MOB < 1 is recommended.

4.2 Bed shear stresses for uniform flow (no structure)

Seabed shear stresses from waves and currents are calculated by use of DNV-ST-0126 and DNV-RP-0618.

Several interpretations of the wave friction factor, f_w, exist in literature due to a small scatter in the experimental results published to date. Consequently, two wave friction factors were considered in the design to perform a sensitivity analysis of the results.

The following table shows the two wave friction factor formulations, which were considered in the analysis. The left-hand-side columns display the formulations resultant from a combination of Dixen et al. (2007), Ref. /13/, Fredsøe et al. (1992), Ref. /14/, and C683 – The Rock Manual. This formulation is very similar to that proposed by DNV-RP-0618. The right-hand-side columns display the formulation proposed by Dixen et al. (2007).

Table 1 Wave friction factors considered in the design.

Combination of Dixen, Fredsøe and the C683 – The Rock Manual formulations, $f_{w,1}$		Dixen formulation, $f_{w,2}$	
0.3	$for\ \frac{a}{K_N} < 1.57$	-	-
$0.32\left(\frac{a}{K_N}\right)^{-0.8}$	$for\ 1.57 \le \frac{a}{K_N} \le 2.9$	$0.32\left(\frac{a}{K_N}\right)^{-0.8}$	$for\ 0 \le \frac{a}{K_N} \le 10$
$0.237\left(\frac{a}{K_N}\right)^{-0.52}$	$for\ 2.9 < \frac{a}{K_N} \le 700$	$0.4\left(\frac{a}{K_N}\right)^{-0.75}$	$for\ 10 \le \frac{a}{K_N} \le 50$
$0.04\left(\frac{a}{K_N}\right)^{-0.25}$	$for\ \frac{a}{K_N} > 700$	$0.04\left(\frac{a}{k_N}\right)^{-0.25}$	$for\ \frac{a}{K_N} > 50$
$a = \frac{U_c T_p}{2\pi}\ \&\ K_N = 2.5D_{50}$			

4.3 Flow amplification

As demonstrated by several authors, flow amplification from jacket structures is complex and can be experienced in a wide area around the structures. Section 4.3 in DNV-RP-0618 suggests a bed shear amplification factor of 2.4 when there is no possibility to perform model tests, however, other studies suggest that amplification factors can reach a value of 2.8 as shown by Deltares (2018), Ref. /15/.

For design stability purposes, it was assumed that the amplification of the flow caused by the multiple components of the structure would not be higher than that produced by the jacket legs.

Since the aim of the scour protection is to stabilize the seabed prior to the installation of the OSS jacket foundation and cables, two design cases were considered with respect to the amplification of the flow. The first design case considered an Amplification Factor (AF) equals to 1.0 to determine the stability of the scour protection before the installation of the jacket. The second design case considered an AF equals to 1.2 to determine the stability of the scour protection during the interim period between the installation of the Oss jacket and the CPS. This value was derived by use of Figure 7 in Whitehouse (1998) and Equation 1 due to the presence of the mudmats, which mitigate the worst effects of flow amplification in the immediate vicinity of the jacket legs.

5. Comparison of the results

The results from the rock stability calculations performed for the 3-9" and 4-10" rock gradings are presented in Table 2.

It can be observed that the 3-9" rock would not be stable around the mudmats during the interim period between the installation of the OSS jacket and CPS, corresponding to the construction load cases, but it would experience little damage once outside the influence zone of the amplified bed shear stresses and therefore, it would be adequate to maintain the existing seabed levels prior the installation of the jacket foundation and power cables. The 4-10" material offers a more stable solution.

When considering the rock stability under long-term (ULS) conditions, it can be observed from Table 2 that both gradings are more dynamic, both around the mudmats and outside the influence zone of the amplified flow.

Table 2 Overview of the mobility number derived from the load cases considered in the design.

		3-9"		4-10"	
Load case	AF [-]	MOB ($f_{w,1}$) [-]	MOB ($f_{w,2}$) [-]	MOB ($f_{w,1}$) [-]	MOB ($f_{w,2}$) [-]
Construction, LC1	1.2	1.46	1.17	1.28	1.09
Construction, LC2	1.2	1.11	0.96	0.97	0.89
ULS, LC3	1.2	1.8	1.36	1.58	1.27
ULS, LC4	1.2	1.49	1.2	1.3	1.11
Construction, LC1	1	1.22	0.97	1.06	0.91
Construction, LC2	1	0.92	0.8	0.81	0.74
ULS, LC3	1	1.5	1.14	1.32	1.06
ULS, LC4	1	1.24	1	1.08	0.93

A 4-10" material grading was specified to be used in the design since it offers a more robust and sustainable solution in the long-term whilst reducing maintenance costs. Additionally, the fabrication and installation costs for the 3-9" and 4-10" materials are not very different due to the use of similar fabrication and installation equipment, so the impact of selecting a 4-10" grading is minimal.

6. Conclusions

A simplified methodology is proposed to produce the design of the scour protection pad at the Dogger Bank C site, where the objective was to stabilize the seabed prior to the installation of the OSS jacket foundation structure and cables. Laboratory testing was not performed in this project, therefore, simplifications had to be made based on assumptions in order to obtain a certifiable design.

The flow around a jacket structure is complex and further research is necessary to standardize scour protection design for jacket structures, so careful consideration must be made when making assumptions. The objective of this paper is to provide an example on how defining a clear objective for the scour protection design is necessary to establish the assumptions necessary to produce a design when testing is not possible.

In this project it was observed that the assumptions made related to the wave friction factors at the seabed can have a significant impact in the results, therefore conservative assumptions were made and a robust monitoring plan was suggested.

7. Afterword

The authors of this document would like to extend their gratitude to Navantia, Aibel, Equinor and the organizers of this conference who have allowed the publication of this article.

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