Scour prediction and scour protections in offshore wind farms

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A B S T R A C T

This paper is the result of research whose main objective is to analyse different methods used for the prediction of maximum scour depth and scour extension, and for the design of scour protections in offshore wind farms located in shallow water, using medium and large diameter monopile foundations. Physical agents such as waves, currents and wind play a major role in the design of structures like offshore farms. As a result, the study has highlighted the need for introducing experience backed climate monomials such as the dimensionless wave height parameter (H_0) and proposes the use of formulations that can express the extent of scour protections as a function of waves in transitional waters.

1. Introduction

The increasing development in offshore wind farm planning and construction in recent years is associated with the need to improve the design of these structures and to optimize the costs involved in their implementation. Short term experience in the field of offshore wind technology has led to methodologies being established in order to recommend all necessary steps in the design of these facilities [1]. On the other hand, it is important to know how the presence of offshore wind farms may affect littoral processes to prevent or avoid this impact [2].

Nowadays, the cost of offshore wind turbine support structures represents almost 30% of the total cost of an offshore wind farm [3]. During 2011, 866 MW were installed, representing almost 23% of total capacity installed so far (3812.6 MW). The target of between 40,000 and 50,000 MW is expected to be achieved in the year 2020, according to the Seventh Framework Programme (FP7). However, despite the current boom in offshore wind farms, there is still a need for research on issues such as the design of foundations and transition components or the sizing of scour protection which is dealt with in this paper.

The scour phenomenon jeopardizes the operating capacity of offshore structures since it compromises their stability. So far, different investigations have been carried out linked to the origin of the scour process and its development in bridge piers (generally under steady current conditions). The study of this phenomenon in the marine environment for different authors such as [4] or [5], began only a few years ago and considered that these structures are subjected to currents, tides and waves in a different regime than bridge piers over rivers studied by authors such as [6].

Much research work carried out on scour phenomenon in offshore wind farms with monopile foundations led to different formulations and methods that allow this phenomenon to be characterised by predicting maximum scour depth (S_{max}) and maximum scour extension (L_{ext}) in the vicinity of the pile. Some of this research, such as [7] and [8], enabled scour depth development over time to be assessed.

The characterization of this phenomenon, knowing the serious consequences related to its occurrence (loss of structural stability, sliding, etc.) has, over the last few years, brought to the fore the need to develop methods and systems for protecting these offshore structures, as recommended in Ref. [9]. Scour protections are required to prevent problems of structural stability and may also be required to protect the inter-array and export cables [10].

A thorough review of offshore wind farms has been performed in order to evaluate the different methods used in the prediction of maximum scour depth and in the design of scour protections in them. The main meteocean characteristics (maritime climate, correlation between wave height and period associated with a given recurrence), the type of foundation and main dimensions, and the type of scour protection used (weight average, nominal diameter in the case of breakwater type protection, width and performance) have been defined from one of the first experiences in 1991 (Vindeby Wind Farm, Denmark) to that recently implemented and proposed in the UK (Lynn and Inner Dowsing) or in the Netherlands (Q7).

Taking into consideration experience with offshore wind farms in current operation, the design data analysis, the basis of climate and the soil–structure interaction, the dimensionless wave height parameter (H_0), the erosion extension (L_{ext}) and the quantification of maximum scour depth (S_{max}) have been calibrated for a preliminary design of protections around a large diameter pile.

2. State of the art

2.1. Overview of offshore wind farms

A large number of offshore wind farms are currently operative in Europe. Monopile foundations remain the most common substructure for offshore turbines. Around 75% of all units installed since 1991 are monopiles, followed by 21% of gravity based structures (GBS) (see Fig. 1). Data collected in this research refer to both types of substructure, although information on only two offshore wind farms with gravity based foundations has been obtained.

Information from the research has been collected through several studies and papers published up to date. Wind facilities studied were selected according to information found during the investigation. Fig. 2 shows the location of the European offshore wind farms considered in this analysis.

The UK is the largest market, representing over half of all installed offshore wind capacity in Europe, and, in addition, the future is very promising there due to major support from the Crown State. Denmark, the Netherlands, Germany, Belgium and Sweden follow the UK in the development of offshore wind farms in Europe.

Table 1 contains the main information on offshore wind farms (type of foundation, maritime climate information and technical specifications of turbines) regarding this research.

During the investigation work, a large amount of information available on energy production, location, or the geometry of different wind farms in Europe was detected. Similarly, as shown in

Fig. 1. Types of substructure for European offshore wind farms (online) from Ref. [11].

Table 1, a lack of information on climatic variables taken into account during the design process was also detected, such as the design wave height (H_D) or the peak period (T_p). This is partly due to the confidentiality present in the documentation associated to these types of project.

In this regard, recommended experience would be useful to have as would knowing the ratio between wave height and wave period at each site ($T = f(H)$). This is a ratio that would design offshore structures through knowledge of the maritime climate. The characterization of this expression is not under investigation but is within the lines of research inside the research group.

2.2. Dimensionless wave height parameter (H_0)

H_0 parameter is defined as $H_s/(\Delta \cdot D_{50})$, where H_s is the significant wave height, Δ is the relative mass density and D_{50} is the characteristic diameter of gravel, stone or sand, and is used to classify different structures. For example, caissons or similar structures with larger armour units are related to low values of H_0 (see Fig. 3).

Maritime climate data (H_s, T_p) from selected offshore wind farms were used (see Table 8) to characterize H_0. As discussed below under the heading of results, figures of H_0 between 6 and 15 were obtained for all offshore wind farms studied, and a new classification was proposed at the end of this research.

3. Methodology

In the first phase of the study, collecting information from different wind farms enabled the different formulations used so far for the prediction of maximum scour depth to be assessed.

During this phase, available information on climate variables such as wave height and characteristic wave peak period at each location, which plays an important role in the design phase of these structures, was found to be lacking. To this effect, a gap in terms of the existence of formulas connecting the wave height and period in each zone ($T = f(H)$) was also detected.

Secondly, with the data previously collected, the monomial H_0 was characterized taking into account that the existing scour protections around these structures may behave dynamically, in a similar way to that characterized by Ref. [12], defining rock slopes and beaches where the rock diameter is relatively small, with H_0 valued between 6 and 20.

Analysis of other protections against undermining was carried out in a third phase with the information collected. During this phase, it was found that the expressions used until now for the sizing of these protections are based on variables like the pile diameter (D), omitting climatic variables such as wave height and wave period (H and T) that play an important role during the design phase.

The lack of criteria for the design of scour protections taking into account climatic variables, has been associated in a fourth study phase to research for formulas taking into account variables such as [13].

A recommendation has been made for the design of the extension of scour protections as a function of wave length (L) using this formulation and the data collected during the first phase.

4. Discussion

The following sections will describe in detail a study on the prediction of the scour phenomenon for the first and second phases, and the design analysis of its protections associated with the third and fourth phases.
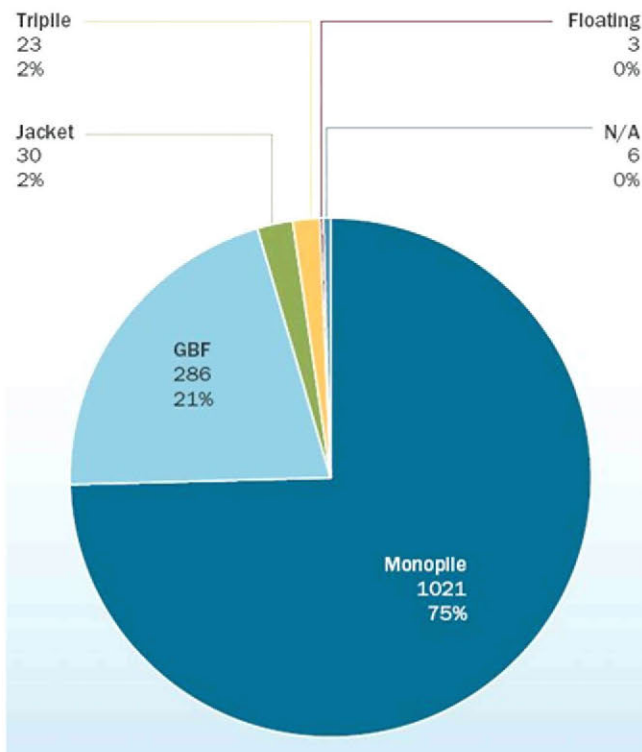
Fig. 2. Location of European wind farms studied. Own research.

4.1. Scour phenomenon

The scour phenomenon occurs around any structure under steady current conditions (e.g. flow in a river), or located in a marine environment, due to the increase in the sediment transport capacity by currents or by a combination of currents and waves.

Many authors, such as like [5,14,15] have studied this phenomenon around a slender circular pile foundation, under steady current, wave or combined wave and current conditions. However, there is less research related to piles located in marine environments, considering the effect of waves and current at the same time.

There are two main methods for taking scour into account when designing monopile foundations. One is characterized by considering the presence of scour protection. The other, which does not include the design of scour protection, takes structural measurements into account by increasing the foundation depth or the pile diameter.

To date, many of the offshore wind farms selected have been built without considering the design of scour protections. This allowed us to avail of real data on completely unprotected structures.

To characterize the way in which scour appears in the vicinity of a pile, it is necessary to know its maximum depth and extension around the structure. Accordingly, the investigations conducted to date have been directed towards numerically predicting these parameters.

The dimensionless scour depth (S/D, S = Scour depth and D = Pile diameter) is a parameter that allows non-dimensional studies on the scour process around a pile to be carried out. This depends on several dimensionless parameters like the KC number, the Shields parameter or the pile Reynolds number (see Ref. [15]).

Table 2 lists the most important formulations developed for predicting the maximum scour depth. These formulations were conducted taking into account different flow conditions (steady current only, waves only, steady current or waves or steady current and waves).

Nowadays, the formula developed by Ref. [6] has been used with a coefficient of 1.25 to obtain a best-fit, through Scroby Sands data. The investigation developed by Ref. [16], was carried out to find a formula for different flow conditions. The formula proposed by Refs. [17] and [18], seem that it could over predict shallow water scour depths, considering only the pile diameter parameter. The formula proposed by Ref. [19] can be used for live-bed scour and clear-water scour. The formula obtained by Ref. [5] improves that as proposed by Ref. [18] taking into account wave action. Measurements of scouring and the action of waves and/or currents recorded from different literature were used for the parameterization and verification of the formula proposed by Ref. [20].

Table 1
Characteristic wind farm information (NA: Information not available). Own research.

Name	Year installed	Type of foundation	Monopile diameter [m]	Number of turbines	Nominal capacity of turbines [MW]	Water depth [m]	Significant wave (H_s [m])	Peak period (T_p [s])	Peak current speed (U_m [m/s])
N7 (Germany)	1997	Monopile	6	1	NA	7	4.6	16.1	1.3
Horns rev (Denmark)	2002	Monopile	4.25	80	2	6−14	5.2	NA	NA
Scarweather sands (UK)	2002	Monopile	2.2	30	3.6	6	3.6	6	1.1
Otzumer balje inlet (Germany)	2003	Monopile	1.5	1	NA	11.7	NA	NA	1.4
North hoyle (UK)	2003	Monopile	4	30	2	7−11	4.78	6.8	1.17
Scroby sands (UK)	2004	Monopile	4.2	30	2	3−12	2.25	NA	1.65
Arklow bank (Ireland)	2004	Monopile	5	7	3.6	2-6	5.6	NA	2
Nysted (Denmark)	2004	Gravity based	10.5−16	72	2.3	6−9.5	NA	NA	NA
Kentish flats (UK)	2005	Monopile	5	30	3	3−5	4.88	NA	0.9
Barrow (UK)	2006	Monopile	4.75	30	3	12−18	4.9	NA	0.8
Thornton bank (Belgium)	2006	Gravity based	6.5−17	60	5	10−24	6.32	11.06	1.2
Egmond aan zee (Netherlands)	2007	Monopile	4.6	36	3	16−21	3.6	8	0.6
Lynn and inner dowsing (UK)	2007	Monopile	4.74	54	3.6	6−13	2.38	7.03	0.9
Princess amalia (Q7) (Netherlands)	2008	Monopile	4	60	2	19−24	7.7	9.7	1.3

Caisson
H/ΔD < 1

Rubble mound breakwater
H/ΔD = 1 - 4

S-shaped breakwater
H/ΔD = 3 - 6

Berm breakwater
H/ΔD = 3 - 6

Rock beach
H/ΔD = 6 - 20

Dune erosion (sand beach)
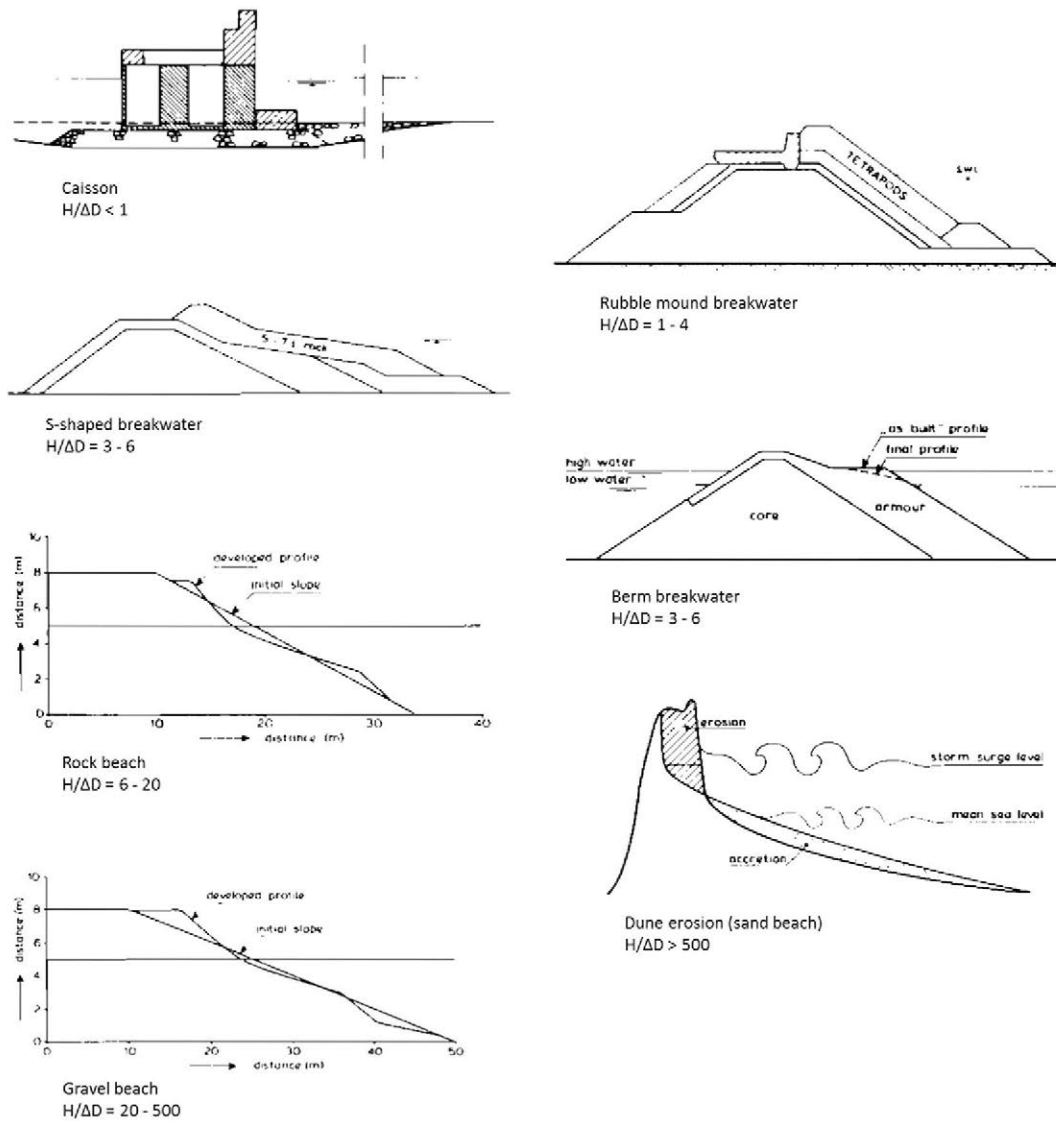H/ΔD > 500

Gravel beach
H/ΔD = 20 - 500

Fig. 3. Structure classification. Reproduced from Ref. [12].

Table 2
Scour depth prediction, main formulae. Own research.

Authors	Year	Flow conditions	Maximum scour depth prediction
Breusers et al. [6]	1977	Steady current	$\frac{S}{D}\text{max} = 1.5 \cdot D \cdot \tanh\left(\frac{h}{D}\right)$
Zanke [16]	1982	Steady current or waves	$\frac{S}{D}\text{cmax} = 2.5 \cdot \left(1 - 0.5 \cdot \frac{uc}{u}\right)$
			$\frac{S}{D}\text{wmax} = KC - 6$
Melville et al. [17]	1988	Steady current	$\frac{S}{D}\text{cmax} = 2.4$
Sumer et al. [18]	1992	Steady current or waves	$\frac{S}{D}\text{cmax} = 1.3$
			$\frac{S}{D}\text{wmax} = 1.3 \cdot (1 - \exp(-0.03(KC - 6)))$
Richardson and Davis (HEC-18) [19]	1995	Steady current	$\frac{S}{h}\text{cmax} = 2 \cdot K1 \cdot K2 \cdot K3 \cdot \left(\frac{b}{h}\right)^{0.65} \cdot Fr^{0.43}$
Sumer et al. [5]	2002	Steady current and waves	$\frac{S}{D}\text{cwmax} = 1.3 \cdot (1 - \exp(-A(KC - B)))$
Zanke et al. [20]	2011	Steady current and waves	$\frac{S}{D}\text{cwmax} = 2.5 \cdot \left(1 - 0.5 \cdot \frac{uc}{u}\right) \cdot xrel$

Table 3
Different recommendations on the parameters of the scour extension Equation (4.1.1) [25].

Author	Recommendation
Hoffmans and Verheij, 1997 [23]	$\propto_{up} \approx \varnothing$(angle of internal friction)
	$\propto_{down} \approx \frac{1}{2} \propto_{up}$
Sumer and Fredsoe, 2002 [5]	$\propto_{down} \approx 25°$

Different standards and recommendations have been followed for years in these formulations. One of the most important references is Det Norske Veritas (DNV), which, in the Offshore standard [21] uses the equations developed by Ref. [18] for the calculation of scour depth. The Coastal Engineering Manual (CEM) [22], recommends the use of formulations developed by Refs. [19] and [5].

The maximum extension of scour around the pile has been studied and characterized by different authors such as [23], [5] or [24].

The scour process shape around a circular pile is known to be similar to a frustum. Thus, scour extension is defined in Ref. [25] as:

$$Ls = D + Se \cdot (\cot(\propto_{up}) + \cot(\propto_{down})) \tag{4.1.1}$$

where S_e is the scour depth in equilibrium, and $\propto_{up}$ and $\propto_{down}$, are the slopes of a scour hole.

Table 3 shows some authors' main recommendations on the Equation (4.1.1).

Authors such as [26] presented formulations for estimating the maximum scour extension, where the maximum scour depth (S_e) and the angle of internal friction ($\varnothing$) of sediment were present (see Equation (4.1.2)).

$$Ls = Se \cdot (\cot \varnothing) \tag{4.1.2}$$

4.2. Scour protection design

Nowadays, there are different scour protection systems used in offshore wind farms like dumped stone riprap, stone or concrete pitching, soil-cement bagging or grouted fabric mattress [27], with the positioning of a horizontal collar/deflector [23]. The most common scour protection consists of rocks and stones (dumped stone riprap) placed around the offshore turbines. This is due to the low cost of this material and its ready availability, although it presents problems such as its installation and susceptibility to damage by currents and waves, as mentioned in Ref. [27]. In order to characterize these protections, it is important to define the stone size (D_{50}) and the extension and thickness of the protection layers. Scour protection mostly has two different layers, a filter and an armour layer.

The weight of the stone is important in order to prevent its displacement. The relationship between stone diameter D_{50} and average weight W_{50}, is defined in Ref. [28] as:

Table 4
Stone size (D50) and thickness of filter and armour layers present in different wind farms. Own research.

Name	D_{50} [m]	Thickness [m]
North hoyle	0.3	Unknown
Egmond aan zee	0.4	1.4 (armour)
Thornton bank	0.35	0.7
Horn rev	0.2 (filter), 0.4 (armour)	0.5 (filter), 1 (armour)
Scroby sands	0.15	Unknown
Arklow bank	0.425	Unknown

Table 5
Recommendations for calculating the extension of riprap scour protections. Own research.

Author	Scour protection extension (L_{ext})
Bonasoundas (1973) [29]	2.5D–4.5D
Hjorth (1975) [30]	2.5D
Breusers and Raudkivi (1991) [31]	3D–4D
Hoffmans and Verheij (1997) [23]	2.5D–4D
Melville and Coleman (2000) [32]	3D–4D
May (2002) [33]	2D

$$D_{50} = \left(\frac{W_{50}}{\rho_s}\right)^{1/3} \tag{4.2.1}$$

Table 4 shows the stone size (D_{50}), and the thickness of filter and armour layers present in wind farms on which scour protection data is available.

As shown, the size of riprap (D_{50}) present in different scour protection layers (armour and filter layers) is not the same, with a smaller size being used in the filter layers.

Information available on offshore wind farms confirmed that the armour layer thickness of scour protections is usually accepted as being at least twice the average stone size D_{50} (see Table) as [23] recommends, although finding information on this characteristic of scour protections was quite difficult.

Table 5 shows recommendations for calculating the extension of riprap scour protections researched by different authors to date. Formulae have mostly been designed with steady current conditions.

The figures given in Table 5 for the maximum extension of scour protection are expressed according to the pile diameter (D), whilst omitting climate variables such as wave height and wave period that play an important role in the design of these structures.

Other authors, such as [26] and [34] have developed methods for calculating the optimal dimension of scour protections taking into account the maximum scour depth (S_{max}), the angle of internal friction ($\varnothing$) on the seabed and a safety factor (F_s), defining the scour protection extension as:

$$L_{ext} = F_s \cdot S \cdot \cot \varnothing \tag{4.2.2}$$

Offshore standard [21] recommends the following Formula (4.2.3) for estimating the scour protection extension in the design of offshore wind farms.

Table 6
Values of maximum scour estimations by the application of different formulae (from Refs. [6] and [21]) and available scour data of European wind farms studied (from Refs. [35–38]). Own research.

Name	Monopile diameter [m]	Estimated scour [m]		Available scour data [m]	
		S_{max} (Breusers) [6]	S_{max} (S&F, DNV) [21]	S_{max}	S_{max}
N7	6	7.41	7.80	1.05D	6.30
Scarweather sands[a]	2.2	3.30	2.86	0.59D	1.30
Otzumer balje inlet[a]	**1.5**	**2.25**	**1.95**	**1.47D**	**2.21**
North hoyle	4	5.87	5.20	0.125D	0.50
Scroby sands	**4.2**	**5.96**	**5.46**	**1.66D**	**6.97**
Arklow bank	5	6.25	6.50	0.86D	4.00
Kentish flats	5	7.10	6.50	0.46D	2.30
Barrow	4.75	7.10	6.18	1.21D	5.74
Egmond aan zee	4.6	6.90	5.98	0.48D	2.2
Princess amalia (Q7)	4	6.00	5.20	1.075D	4.30

[a] Met Mast data.

Table 7
Extension of scour protections recommended for different authors in European wind farms studied. Own research.

Name	Monopile diameter (m)	L_{ext} (m)					
		4D ([23,29,31,32])	Cartens (Equation 4.2.2)	DNV (Equation 4.2.3)	Löffler (Equation 4.2.4)	$L/4$	$L/2$
N7	6	24	30.62	15.83	40	32.75	65.50
Scarweather sands	2.2	8.8	13.64	6.82	14.22	12.10	24.21
North hoyle	4	16	24.26	12.16	17.06	13.88	27.76
Lynn and inner	4.74	18.96	28.34	16.33	14.25	14.77	29.55
Egmond aan zee	4.6	18.4	28.50	14.24	23.82	21.75	43.5
Princess amalia (Q7)	4	16	24.80	13.40	34.61	29.82	59.64

Table 8
Values of H_0 of European wind farms studied. Own research.

Name	Monopile diameter [m]	H_s [m]	D_{50} [m]	$H_0 = \dfrac{H_s}{\Delta * D_{50}}$
Horns rev	4.25	5.20	0.40	8.20
North hoyle	4	4.78	0.30	10.05
Scroby sands	4.2	2.25	0.15	9.46
Arklow bank	5	5.60	0.42	8.31
Thornton bank	6.5–17 (GBS)	6.32	0.35	11.39
Egmond aan zee	4.6	3.60	0.40	5.68

$$L_{ext} = \frac{D}{2} + S_{max} \cdot \cot \varnothing \qquad (4.2.3)$$

During the fourth phase of the research, formulations were analysed where climatic variables such as wave height and wave period have been considered. This made it possible to assess flow–structure interaction through these parameters.

An example of this is the study [13] which shows that the extent of pressure distribution on the berm (L_{pb}) calculated by the Sainflou theory is:

Caisson
$H/\Delta D < 1$

Rubble mound breakwater
$H/\Delta D = 1 - 4$

S-shaped breakwater
$H/\Delta D = 3 - 6$

Berm breakwater
$H/\Delta D = 3 - 6$

Rock beach
$H/\Delta D = 6 - 20$

Turbine Foundation

Scour Protection
$H/\Delta D = 6-20$

Gravel beach
$H/\Delta D = 20 - 500$

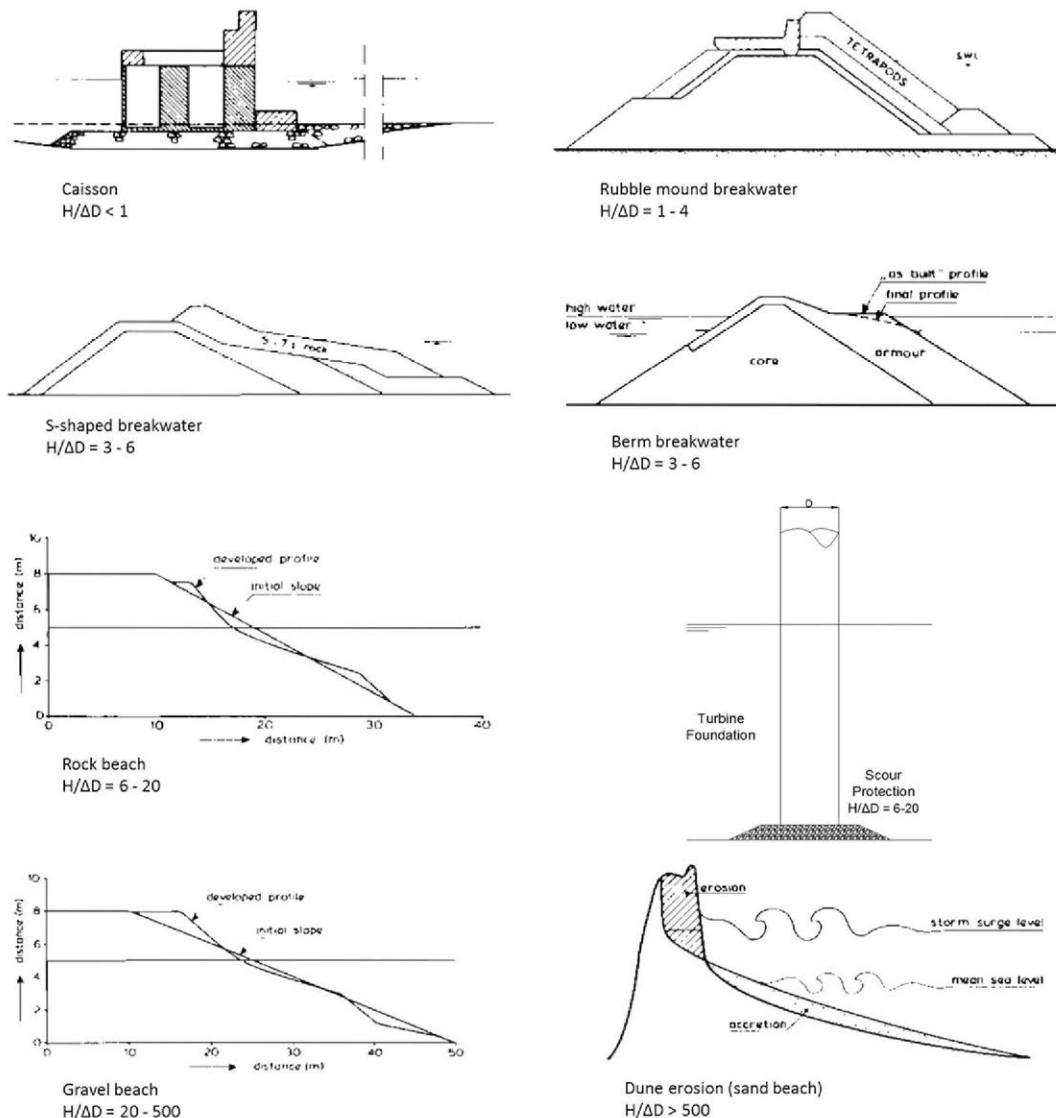Dune erosion (sand beach)
$H/\Delta D > 500$

Fig. 4. Proposed classification for offshore wind turbine foundations. Modified from Ref. [12].

$$L_{pb} = \frac{L}{2\pi} \cdot arcos\left(\frac{-\pi \cdot H}{L} \cdot \coth L \cdot \tanh\left(\frac{2 \cdot \pi \cdot h}{L}\right)\right) \qquad (4.2.4)$$

Considering this formula from a conservative approach would be reasonable to design scour protections with larger dimensions of L_{pb}.

5. Results

Available data on technical reports and publications with regard to scour processes in European wind farms, such as [35–38], enabled the main formulations (see Table) for estimating maximum scour depth to be evaluated.

Table 6 shows the maximum calculated scour data from different formulations used in standard and technical recommendations ([21]) for the design of offshore wind farms compared with available scour data found in technical reports. As observed, the maximum scour was less than estimated in most offshore wind farms studied. Only two displayed greater scour (see Table 6, bold).

Table 7 shows the extension for scour protections recommended by different authors calculated in offshore wind farms with sufficient available data.

Results obtained applying the maximum extension recommended by different authors (4D) were more conservative than used by DNV standards.

As observed, the figures obtained by the Formula (4.2.4) were between $L/4$ and $L/2$.

Table shows H_0 values calculated for each European offshore wind farms where environmental actions (H_s, T_p) and scour protection (D_{50}) information were available and known, where $\Delta = (\rho_r/\rho_w) - 1$, $\rho_w = 1025$ kg/m^3 and $\rho_r = 2650$ kg/m^3 (average value of mass density for a general rock protection, rubble mound and riprap).

Table 8 shows all H_0 data except the Egmond Aan Zee figure between 6 and 20. The value close to 6 of Egmond Aan Zee may be due to the correlation between H–T. In this offshore wind farm, the value of the peak period is low due to the wind, which is a subject that should be studied and taken into account in designing future offshore wind farms.

In his PhD Thesis [12], Van der Meer considered that for rock slopes and beaches where the diameter of the rock is relatively small, H_0 is between 6 and 20.

We therefore propose that offshore wind farms with monopile or gravity based structure foundations, may belong to this group, with H_0 between 6 and 15. Generally, dynamic scour protections present an average riprap diameter between 0.3 and 0.4 m.

Fig. 4 shows the classification proposed for offshore wind farms.

6. Conclusions

The design of scour protection must be integrated into the foundations design. In order to carry out an effective design, sediment properties, the seabed's geotechnical characteristics, environmental parameters (H_s, T_p, etc.), the turbine specifications (diameter, shape of pile, etc) must be taken into account and must accurately predict the maximum scour that would occur in the absence of this protection.

In the actual data used, difficulties in obtaining wave variables and their correlation between significant wave height (H_s), peak period (T_p) or half wave period (T_m), or significant wave height of wave spectrum (H_{m0}), mean period (T_{02}) are noted for operating farms.

This research proposes an indicator for the value of the dimensionless monomial wave height that enables scour protection of offshore wind farms to be designed as a function of extreme metocean parameters.

Taking the first adjustments set in the design of scour protections, it would be advisable to size these structures with extensions between $L/4$ and $L/2$, with granular material with a dimensionless wave height parameter (H_0) between 6 and 15.

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