FOREWIND

DOGGER BANK
TEESSIDE A & B

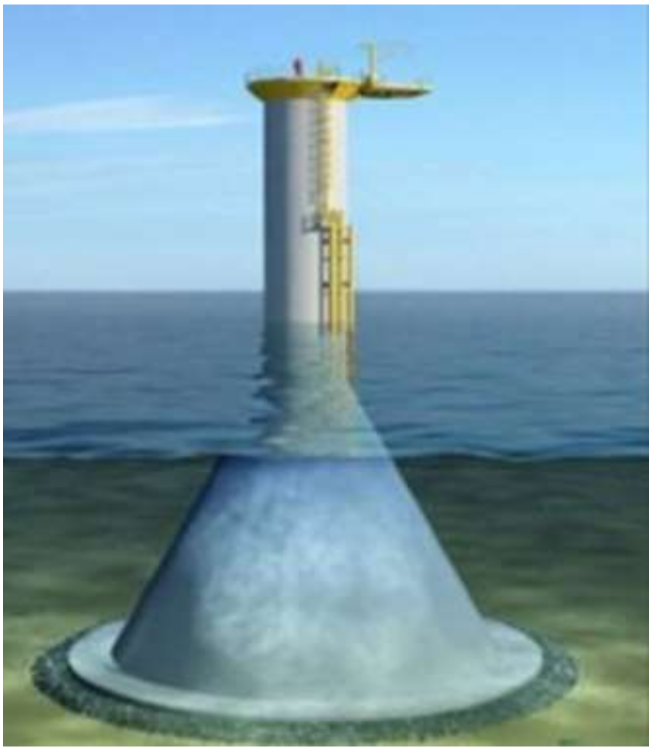
October 2013

Draft Environmental Statement
Chapter 5 Appendix B
Foundation Characterisation Study

Dogger Bank Offshore Wind Farm Development: Teesside Projects A & B

Foundation Characterisation Study - DRAFT

Version 5 – 14th October 2013



Contents

1. Background

During the operational phase of the Dogger Bank Offshore Wind Farm (OWF) development, changes will arise to the baseline tidal currents and wave regime due to the presence of foundation structures. These changes may, in the absence of scour protection and dependent on the sea bed sediment types, also cause scour to occur around the foundations.

Forewind has presented a range of foundation types and array layout arrangements within its Project Description for the Dogger Bank Teesside A & B projects. The effects on the baseline tidal currents and wave regime of particular worst case arrangements have been assessed as part of the Environmental Impact Assessment (EIA) process for the Dogger Bank Teesside A & B projects and reported in its Environmental Statement (ES). These worst case assessments were based on a 'necklace' of turbines placed at the closest spacings defined within the Project Description around the perimeter of each project area (750m and 1080m spacings for 6MW and 10MW layouts respectively) and the remainder of turbines evenly spaced throughout each project area to provide the maximum installed generating capacity stated within the Project Description. Meteorological stations were also included within the arrays at locations based on best present engineering-guided decisions. These assessments were performed for two scenarios:

- Scenario 1 – 200 no. 6MW turbines founded on worst case 6MW GBS foundations and 5 no. meteorological stations.
- Scenario 2 – 120 no. 10MW turbines founded on worst case 10MW GBS foundations and 5 no. meteorological stations.

Numerical modelling demonstrated the effects of both of these arrangements on the wave and hydrodynamic regimes to be relatively small in magnitude and relatively local in spatial extent. The ES concluded that no significant changes to the baseline wave and hydrodynamic conditions were identified.

Forewind now intends to specify its wind turbine and meteorological station foundation requirements for the Dogger Bank Teesside A & B projects based on a description of their hydrodynamic properties, as previously assessed within the EIA process. This approach will be used in preference to stating detailed structural dimensions within the consent documents in order to enable compliance with the 'worst case' assumptions that have already been robustly assessed while allowing more realistic foundation designs to be assessed, avoiding over-conservatism and allowing greater flexibility in final selection of foundation type, whilst still ensuring complete clarity of which foundation designs are permitted to be deployed.

This 'hydrodynamic description' is intended to demonstrate to regulators that the preferred foundation types sit within the 'threshold of impact' that has already been assessed within the ES and, therefore, that potential impacts on the physical environment will be less than those already assessed as part of the 'worst case'.

The requirements of this document are to:

1. Demonstrate that appropriate hydrodynamic coefficients or properties to characterise the wind turbine and meteorological station foundations have been identified;
2. Determine a method for calculating the selected coefficients;
3. Calculate these coefficients for the foundations to be described in the consents; and
4. Document the method in a step-wise manner, appropriate for use before future foundation procurement activities, to determine whether a foundation lies within the assessed EIA envelope.

2. Worst Case Generic Foundation Types

Following a review of generic foundation types, the conical Gravity Base Structures (GBS) were considered to have the greatest potential effects on tidal currents and the wave regime. This is based on two principal factors: (1) conical GBS have the greatest basal dimensions of all foundation types considered; and (2) conical GBS have the greatest extent of physical blockage within the water column of all foundation types considered.

In addition to these assessments, empirical formulae were used to demonstrate that conical GBS represented the 'worst case' foundation type also in terms of potential for scour hole development on the sea bed around the foundations.

The use of GBS as a 'worst case' foundation type in the physical processes assessments is further substantiated from the results of a review of 30 Environmental Statements associated with offshore wind farm developments, in both UK and overseas waters. This review covered the following OWF developments:

- Scarweather Sands
- Cromer
- Teesside
- Lynn
- Inner Dowsing
- Kentish Flats
- Gunfleet Sands
- North Hoyle
- Burbo Bank
- Westermost Rough
- Thanet
- Sheringham Shoal
- Greater Gabbard
- Lincs
- London Array
- Gwynt-y-Môr
- West Duddon
- Dudgeon
- Gunfleet Sands II
- Walney
- Humber Gateway
- Triton Knoll
- Firth of Forth
- East Anglia
- Beatrice
- Nysted
- Horns Rev 1
- Oriel
- Rodsand II
- Anholt

In those ES documents which directly compared different foundation types using analytical or modelling techniques, it was found that monopile foundations had the least effect on the tidal currents and wave regime, jackets and tripods had slightly greater effects, flat base GBS had greater still effect and greatest effect of all was caused by conical GBS. In terms of wave effects, this is principally because of their size and presence through a large proportion of the water column, which causes reflection and, in some cases, diffraction of incoming waves.

Quantitative assessments in the ES for the Dogger Bank Teesside A & B projects were therefore made using conical GBS as the worst generic type of foundation.

The methods presented in this paper are well suited to the assessment of different sizes and geometries of conical GBS and can also be used to assess the effects of flat base GBS foundations. This is because the WAMIT model used as the basis for assessments of effects of foundations on incoming waves inherently considers not only wave reflection but also processes of wave diffraction. These processes become important when the dimensions of the foundation are large with respect to the wavelength of the incident waves.

For monopole foundations or multileg structures such as tripods and jackets, wave diffraction will be insignificant because each structural member is very small compared to the incident wavelengths and only small energy losses through reflection will be encountered in respect of waves and only small and localised changes in flow will occur due to the slender size of the structural members.

The methods presented in this note are intended to ensure that the final design of any flat base or conical GBS foundations falls within the range of effects previously modelled within the ES as a 'worst case'. The effects of monopole and multileg foundations already fall well within the conservative assessments that have been made within the ES and do not require further investigation.

As discussed in Section 1, the effects of 5 no. meteorological stations and associated foundations, within each project area have been included in the assessments in the ES. Meteorological stations may be mounted on fixed structures similar to wind turbine foundations but of a smaller size, therefore it can be assumed that the effects of a meteorological station foundation can be modelled on a smaller version of a 6MW conical GBS foundation.

3. Selecting suitable hydrodynamic coefficients

Within the EIA process, the effect of conical GBS foundations on the wave and tidal regimes was assessed using numerical formulae and numerical modelling techniques. This approach used separate models to assess potential changes to tidal flows and potential changes to the passage of waves. An initial stage for each considered the near-field (local scale) effects, with a subsequent stage considering the far-field (wider scale) effects.

Tidal flows

For the near-field effects on tidal flows, basic continuity, energy and momentum equations were used to calculate the reduction of discharge flow due to the presence of a foundation, which introduces a drag force that modifies the fluid speed around the structure. This approach was adopted to enable ranking the relative near-field effect of six different GBS types identified by a market search and concept design studies, each suited to a 10MW turbine, located in a notional water depth of 35m Mean Sea Level, MSL. The 'worst case' foundation design in terms of its drag force coefficient was determined based on this modelling; ensuring the assessment envelope encompassed a wide range of available foundation options.

The far-field effects of this 'worst case' foundation type for tidal currents were then assessed using a numerical model based on the MIKE-3 FM computational software. A foundation was represented at each turbine location using a sub-grid structure represented by seven cylinders of different heights and diameter. Where necessary, the foundation design was conservatively scaled up or down in size to suit the water depths across the Dogger Bank developable area. The modelling first considered an array of 10MW turbines within the Dogger Bank Teesside A & B projects. The process outlined above was then repeated for the 'worst case' conical GBS foundation design suited to a smaller, 6MW, turbine, with an array of these turbines within the Dogger Bank Teesside A & B projects.

Waves

For the near-field effects on the passage of waves, numerical modelling was undertaken using the WAMIT (Wave Analysis Massachusetts Institute of Technology) software to determine a coefficient that represented the relative loss of energy due to processes of reflection and diffraction-induced wave spreading. This so-called 'reflection factor' was calculated for the same six different 10MW GBS foundation types under wave periods ranging from 2 to 25 seconds, using 1 second increments, for a defined 'design condition' water depth of 35m. By integrating the results across the measured site average wave energy spectrum, a single 'representative value' was defined for purposes of ranking the effect of the foundation types on the wave regime. The worst case value for waves was associated with the same foundation identified as a worst case for the tidal flow impacts. Having determined this, further WAMIT modelling was undertaken to determine the reflection coefficient of the foundation for five different water depths, ranging from 20m to 50m in 7.5m increments, under the same range of wave periods from 2 to 25 seconds, using 1 second increments. This process was undertaken for 'worst case' foundation sizes suited to both 10MW and 6MW turbines.

Within each array, flexibility is required by Forewind in final layout arrangements and due to this a coefficient was calculated under each wave period increment for the minimum developable depth in each project area. For Dogger Bank Teesside A this is a water depth of 22m MSL and for Dogger Bank Teesside B this is a water depth of 23.25m MSL. Calculating the transmission coefficient for each minimum developable water depth under each wave period increment was undertaken for purposes of use in the ES based on linear interpolation between the values derived for the five different water depths from WAMIT, resulting in a 'worst case' wave reflection coefficient for each of the Dogger Bank Teesside A & B projects. The use of a minimum developable water depth wave reflection coefficient for each project is the conservative method and foundations in deeper water would be compared against this worst case value.

The far-field effects on the wave climate were then assessed using the Mike21-SW modelling software. The 'worst case' wave reflection coefficients for the minimum developable depths within each project area were used to represent each structure within that project area, irrespective of actual depth at the turbine location. This was undertaken to be conservative in the approach adopted and allow considerable flexibility in the movement of turbines from an evenly spaced array to a more concentrated arrangement within shallower areas if required, with the minimum spacing between adjacent turbines still being in accordance with the Project Description. The far-field runs were performed for the same two array layout scenarios previously described for the tidal flow modelling and there was found to be no significant difference in effect between the two scenarios.

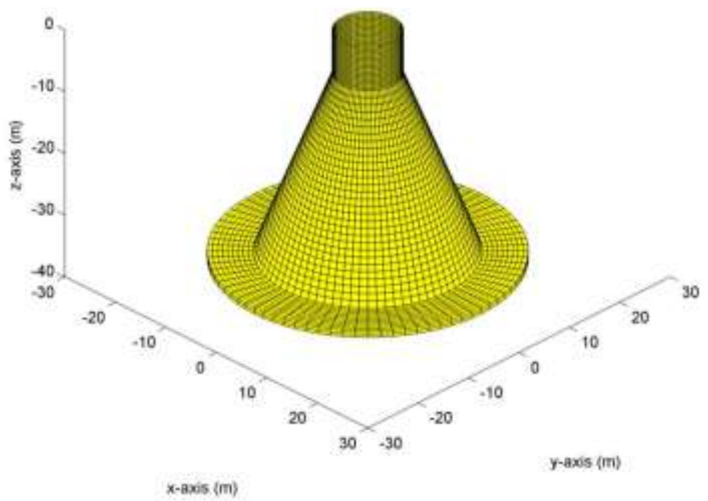
As the effects of a 'worst case' layout and foundation on the tidal currents and wave regime have been assessed using drag and reflection coefficients in the ES, it is suggested that these parameters could suitably form the basis of any hydrodynamic description of foundation type. However, in order to make the description as simple as possible whilst still remaining meaningful, it is argued that only the wave reflection coefficient should be used. This is because baseline tidal currents are very low across the project areas and the changes in tidal currents reduce to insignificant levels within a very short distance of the developable area. In contrast, baseline wave processes are far more important in the stirring of sediments from the sea bed and in the creation of scour around the foundation bases. Furthermore, the drag coefficient approach was used in the ES purely for the purposes of ranking the worst case foundation type for effect on tidal currents, with the far-field modelling including the foundations using a sub-grid structural representation. In contrast, the wave reflection coefficient was used in the ES to: (i) rank the near-field effect of different GBS foundation types; (ii) determine how water depth and wave period affects the coefficient; (iii) determine how different foundation geometries (i.e. for 6MW and for 10MW) affect the coefficient. It has also quantitatively been determined that the worst case foundation type for waves is also the worst case for currents. Separate scour assessments using empirical formulae have also identified this same foundation type to be the 'worst case' for scour hole formation and therefore its use in the ES as a worst case is fully justified.

Recommendation: The hydrodynamic properties of the foundation should be represented by the wave reflection coefficient, with consideration given to foundation size and water depths.

4. Method for determining the wave reflection coefficient of foundation types

Detailed computational simulations of the wave field around a single foundation should be undertaken using the WAMIT (Wave Analysis Massachusetts Institute of Technology) numerical modelling software. This is available from http://www.wamit.com.

WAMIT is a wave radiation/diffraction panel program developed for linear analyses of the interaction of surface waves with marine and offshore structures. It is widely recognised to be an industry standard for the analysis of floating and fixed structures and was developed at the Department of Ocean Engineering at Massachusetts Institute of Technology. An example of the representation of a conical GBS foundation in WAMIT is shown below for all elements below the water surface.



The WAMIT modelling is intended to demonstrate that the wave reflection coefficient of the foundation structure is less than, or equal to, the values tested within the Environmental Statement for the Teesside A and B projects. If this is the case, then the foundation will have an impact on the wave regime no greater than that which has already been tested and therefore will be suitable for use within the existing consents.

Step 1 – Develop a WAMIT model of the foundation structure being considered using the following input conditions / assumptions:

- Flat and frictionless sea bed
- Foundation structure geometry discretized into quadrilateral panels

If the foundation design varies according to water depth across the project areas, then a model will be needed for the minimum developable depth in each project area (assuming that scaling rules for different water depths apply in accordance with those set in the Project Description).

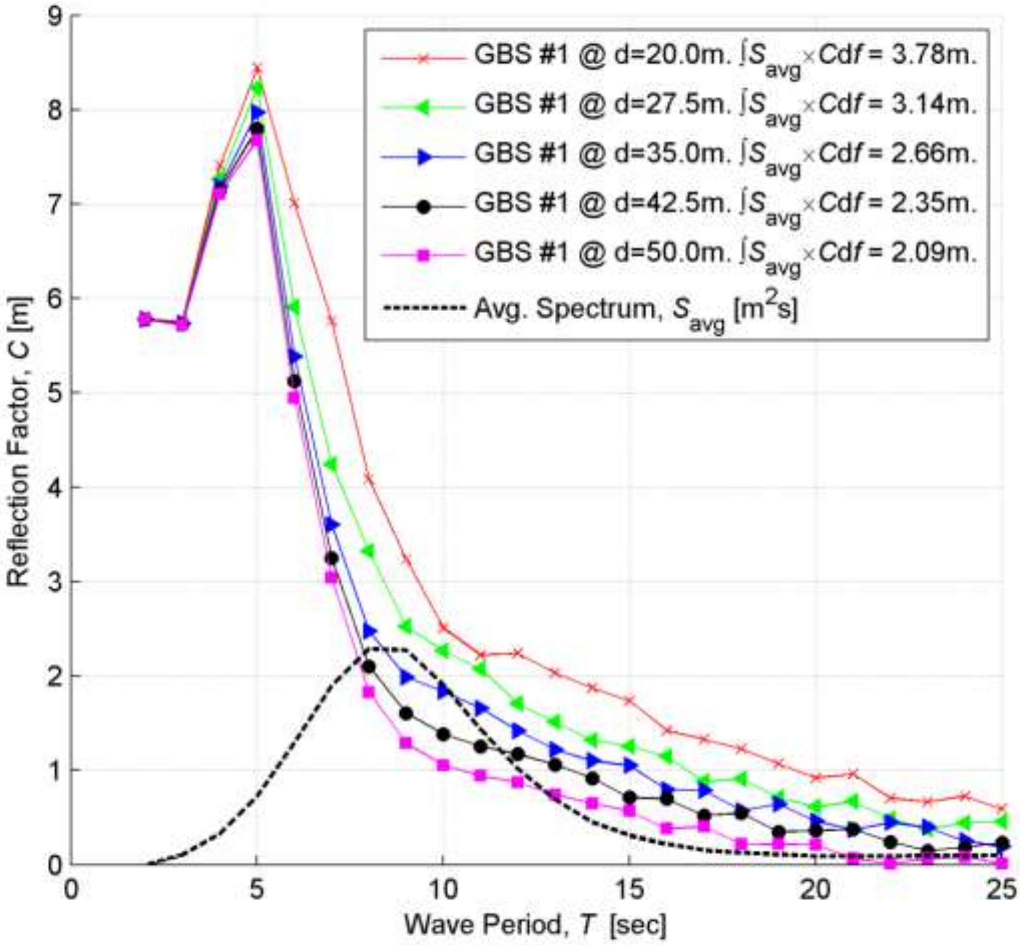
Step 2 – Run the WAMIT model(s) to determine a 'worst case' reflection coefficient for the structure(s) (under the minimum developable depth in each project area) and for various wave period conditions and populate results into the 'insert' spaces in the table below.

Wave period (s)	Average Spectral Density (m^2s)	Average Spectral Density (normalized)	'Worst Case' Reflection Coefficient	
			Teesside Project A	Teesside Project B
2.0	0	0.0000	INSERT	INSERT
3.0	0.1082	0.0068	INSERT	INSERT
4.0	0.3269	0.0206	INSERT	INSERT
5.0	0.7241	0.0456	INSERT	INSERT
6.0	1.29	0.0812	INSERT	INSERT
7.0	1.8952	0.1193	INSERT	INSERT
8.0	2.2857	0.1439	INSERT	INSERT
9.0	2.275	0.1432	INSERT	INSERT
10.0	1.9044	0.1199	INSERT	INSERT
11.0	1.4348	0.0903	INSERT	INSERT
12.0	1.018	0.0641	INSERT	INSERT
13.0	0.6924	0.0436	INSERT	INSERT
14.0	0.4503	0.0283	INSERT	INSERT
15.0	0.3106	0.0196	INSERT	INSERT
16.0	0.2183	0.0137	INSERT	INSERT
17.0	0.1514	0.0095	INSERT	INSERT
18.0	0.127	0.0080	INSERT	INSERT
19.0	0.1086	0.0068	INSERT	INSERT
20.0	0.0914	0.0058	INSERT	INSERT
21.0	0.0919	0.0058	INSERT	INSERT
22.0	0.0923	0.0058	INSERT	INSERT
23.0	0.0941	0.0059	INSERT	INSERT
24.0	0.0962	0.0061	INSERT	INSERT
25.0	0.0983	0.0062	INSERT	INSERT

The numerical formulae used to calculate the reflection coefficients from the WAMIT output are provided in Annex A.

The average spectral density data presented in the table were obtained from the wave buoy measurements taken at the 'Northern Dogger' location between 6th November 2010 and 10th August 2011, covering a total of 13,117 half-hourly measurements.

Step 3 – Use the tabulated outputs to plot reflection coefficient versus wave period for each of the water depths. Also plot the average wave spectrum. An example is provided below but the graph will only show the values for two lines, i.e. worst case condition for the two project areas.



Step 4 – Integrate the frequency-dependent reflection factors across the average wave energy spectrum to provide a single representative reflection coefficient for the foundation for each of the five water depths considered.

This is a simple calculation that sums the frequency-dependent reflection coefficients (inserted by the WAMIT modeller) multiplied by the fraction of the total wave energy at this particular frequency (the normalised spectral density).

An example for the Dogger Bank Teesside A project (22.0m MSL minimum developable water depth) is shown below. The sum total of Column C provides the single representative reflection coefficient for the foundation at the minimum developable water depth for the project.

COLUMN A	COLUMN B	COLUMN C
Average Spectral Density (normalized)	'Worst Case' Reflection Coefficient	Sum of Average Spectral Density and 'Worst Case' Reflection Coefficient
0.0000	INSERT	COL. A x COL. B
0.0068	INSERT	COL. A x COL. B
0.0206	INSERT	COL. A x COL. B
0.0456	INSERT	COL. A x COL. B
0.0812	INSERT	COL. A x COL. B
0.1193	INSERT	COL. A x COL. B
0.1439	INSERT	COL. A x COL. B
0.1432	INSERT	COL. A x COL. B
0.1199	INSERT	COL. A x COL. B
0.0903	INSERT	COL. A x COL. B
0.0641	INSERT	COL. A x COL. B
0.0436	INSERT	COL. A x COL. B
0.0283	INSERT	COL. A x COL. B
0.0196	INSERT	COL. A x COL. B
0.0137	INSERT	COL. A x COL. B
0.0095	INSERT	COL. A x COL. B
0.0080	INSERT	COL. A x COL. B
0.0068	INSERT	COL. A x COL. B
0.0058	INSERT	COL. A x COL. B
0.0058	INSERT	COL. A x COL. B
0.0058	INSERT	COL. A x COL. B
0.0059	INSERT	COL. A x COL. B
0.0061	INSERT	COL. A x COL. B
0.0062	INSERT	COL. A x COL. B
	SUM OF COLUMN C	**∑ =**

Step 5 – Compare the single representative reflection coefficient for each foundation against the values in the table below.

Project area	Minimum developable water depth (m)	Previously assessed reflection coefficient		
		Meteorological station foundations	6MW turbine foundations	10MW turbine foundations
Teesside A	22.00	2.42	2.84	3.61
Teesside B	23.25	2.34	2.75	3.50

(a) If the reflection coefficient for foundations within each project area falls below the value stated in the table, then the foundation is acceptable in terms of its effect on the wave climate if the foundations are no closer than the spacings defined in the Project Description for the Dogger Bank Teesside A & B projects, namely 750m for 6MW turbines and 1,080m for 10MW turbines.

(b) If the reflection coefficient for foundations within each project area exceeds the value stated in the table, then the foundation type falls beyond the range of previously assessed impacts and more detailed far-field assessments may be required to satisfy the regulator in terms of effects on the wave regime. In this case, it may also be necessary to satisfy the regulator that effects on the tidal regime are also negligible through further near-field and far-field studies.

5. Other considerations

Wave period

In addition to minimum developable water depth, the ES also considered wave period when selecting the appropriate wave reflection coefficient for each foundation within the model domain. However, the above approach integrates the wave reflection coefficients across the whole measured wave spectrum and therefore provides a useful and effective relative comparison of any foundation design against those modelled within the ES based on a single representative value for each minimum developable water depth considered.

Annex A – Calculation of Wave Reflection Coeffcients

Methodology

The undisturbed wave energy flux over a plane bed is found from the following general expression:

$$E_f = \frac{1}{T}\int_0^T \int_{-h}^{\eta} \left(p^+ + \frac{1}{2}\rho(u^2 + v^2)u\right) dzdt \tag{8.1}$$

Where p^+ is the excess pressure, u and v is the horizontal and vertical velocity components, T the wave period, h the water depth. This expression is valid under the assumption of irrotational flow.

Using 1st order approximation the expression can be reduced to the following:

$$E_f = \frac{1}{T}\int_0^T \int_{-h}^{\eta} p^+ u \, dzdt \tag{8.2}$$

The energy flux in incoming waves can be found to be:

$$E_f = \frac{1}{16}\rho g H^2 c \left(1 + \frac{2kh}{\sinh(2kh)}\right) \tag{8.3}$$

Where ρ is the density, g gravitational acceleration, H the wave height, c the wave celerity, k the wave number ($k = 2\pi/L$), and h the depth.

The energy that is reflected is equal to the incoming flux minus the transmitted flux. The transmitted flux can be found by integrating from the foundation surface to infinity perpendicular to the wave direction.

$$\hat{E}_{f,transmitted} = \int_{CL}^{\infty} \left[\frac{1}{T}\int_0^T \int_{-h}^{\eta} p^+ u \, dzdt\right] ds \tag{8.4}$$

Where $\hat{E}_{f,transmitted}$ is the integrated wave energy flux from the CL (y = 0) to infinity.

In the case of a cylindrical foundation the energy that is reflected is related to the incoming energy multiplied by the diameter of the foundation, D (noting that the result is divided by half the diameter as only one half plane has been used in the above integration).

$$f = \frac{E_f Y - \hat{E}_{f,transmitted}}{\frac{1}{2} D E_f} \tag{8.5}$$

where $Y = \int_{CL}^{\infty} dy$ represents the integration area.

f is the fraction of the incoming energy that is reflected from a cylinder with diameter D, i.e. the reflection coefficient. This can also be expressed in terms of an equivalent blocking width, or reflection factor, over which all energy is reflected. The reflection factor for the cylindrical foundation is given by $C = f \cdot D$.

The reflection factor in the general case is expressed by

$$C = 2\frac{E_f Y - \hat{E}_{f,transmitted}}{E_f} \tag{8.6}$$

Note that the results are multiplied by 2 since only half the plane is included in the calculation.