Lowering costs by individual design of foundation structures

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1 Summary

For the development of offshore wind farms, it has up to now been common practice to design two-five standardised foundations structures to fit all positions irrespective of the number of turbines to be erected and irrespective of the variations in water depth and soil conditions within each group. For the 30 Vestas V90 3.0 MW turbines to be supported at the Kentish Flats Offshore Wind Farm in the outer Thames Estuary, Ramboll have made 30 individual foundation designs based on the actual site conditions at the individual positions. By designing the foundations individually and by applying a number of advanced analysis methods and innovative design decisions, Ramboll has succeeded in reducing the overall weight and fabrication costs of the 30 foundations.

2 Description

Kentish Flats Offshore Wind Farm has been constructed at a water depth of 6-8 m on the southern side of the outer Thames Estuary, 6 miles north of Herne bay at the Kent coast. The wind farm will consist of 30 Vestas V90 3.0 MW wind turbines connected to an onshore substation by three submarine cables. The project is carried out by Vestas Wind Systems as turnkey contractor with MT Hojgaard as the foundation subcontractor. Ramboll was chosen by MT Hojgaard to carry out the detailed design of the turbine foundation structures.

The foundation structure is a monopile with a grouted transition piece similar to the foundation structures installed by MT Hojgaard at Horns Rev, Denmark. The design was carried out as 30 individual foundation designs based on the actual site conditions at the individual positions, i.e. the actual soil profile and water depth at each location. In comparison with the tender design based on five standardised foundation types, the detailed design of the monopile and transition piece as well as the grouted joint included a number of design innovations and advanced analyses which lead to an overall weight reduction, as well as substantial savings on steel and grout material quality:

- By carefully analysing the load cases driving the foundation design and optimising the response of the turbine for these load cases, Vestas managed to minimise the design loads for the foundations.
- As a result of carrying out time domain fatigue analysis from simultaneous wind and wave loads from 12 geographical directions, fatigue lives well above the required were obtained for both steel and grout.
- By calculating the maximum scour at each position and including it in the pile design, the need for expensive scour protection was avoided.
- Through a detailed Finite Element Analysis of the grouted joint between pile and transition piece, it was demonstrated that the length of the necessary grout zone could be reduced to 1.4 times the pile diameter,

and that the grout material Ducorit S5 would provide adequate strength and fatigue life for the joint for the entire in-service life.

The paper will convey the first hands-on experience from designing in accordance with the new DNV standard for offshore wind turbine foundations DNV-OS-J101. In addition the paper will provide an insight in the detailed design process, technical information about the advanced analyses, and, last but not least, it will present valuable ideas of how to lower the overall costs of offshore wind farms by optimising the foundation design.

3 Introduction

Kentish Flats Offshore Wind Farm has been constructed at a water depth of 6-8 m on the southern side of the outer Thames Estuary, 6 miles north of Herne bay at the Kent coast. The wind farm will consist of 30 Vestas V90 3.0 MW wind turbines connected to shore by a number of buried submarine cables. The project is carried out by Vestas Wind Systems as turnkey contractor with MT Hojgaard as the foundation subcontractor. Ramboll was chosen by MT Hojgaard to carry out the detailed design of the turbine foundation structures.

The foundation structure is a monopile with a grouted transition piece similar to the foundation structures installed by MT Hojgaard at Horns Rev, Denmark.

4 Schedule

The foundations for the Kentish Flats Offshore Wind Farm were designed, fabricated and installed with an ultra tight schedule. The foundation subcontract was awarded to MTH and signed the last day of 2003 and on October 19th 2004 the last of the 30 foundations was successfully installed by MTH, nearly one month ahead of schedule, using the MPI Resolution.

Figure 1 MPI Resolution installing one of the thirty foundations at Kentish Flats.

5 Vestas V90 Wind Turbine

The Kentish Flats Offshore Wind Farm will be equipped with 30 Vestas V90-3.0 MW turbines, which is the latest and biggest commercially available turbine from Vestas. The V90-3.0 MW turbine design is extremely compact, resulting in a modest weight. The total weight of the nacelle and rotor is only about 110t and the weight of the tower is around 100t.

6 Design

The foundation concept for the Kentish Flats development is the well-proven monopile concept illustrated below.

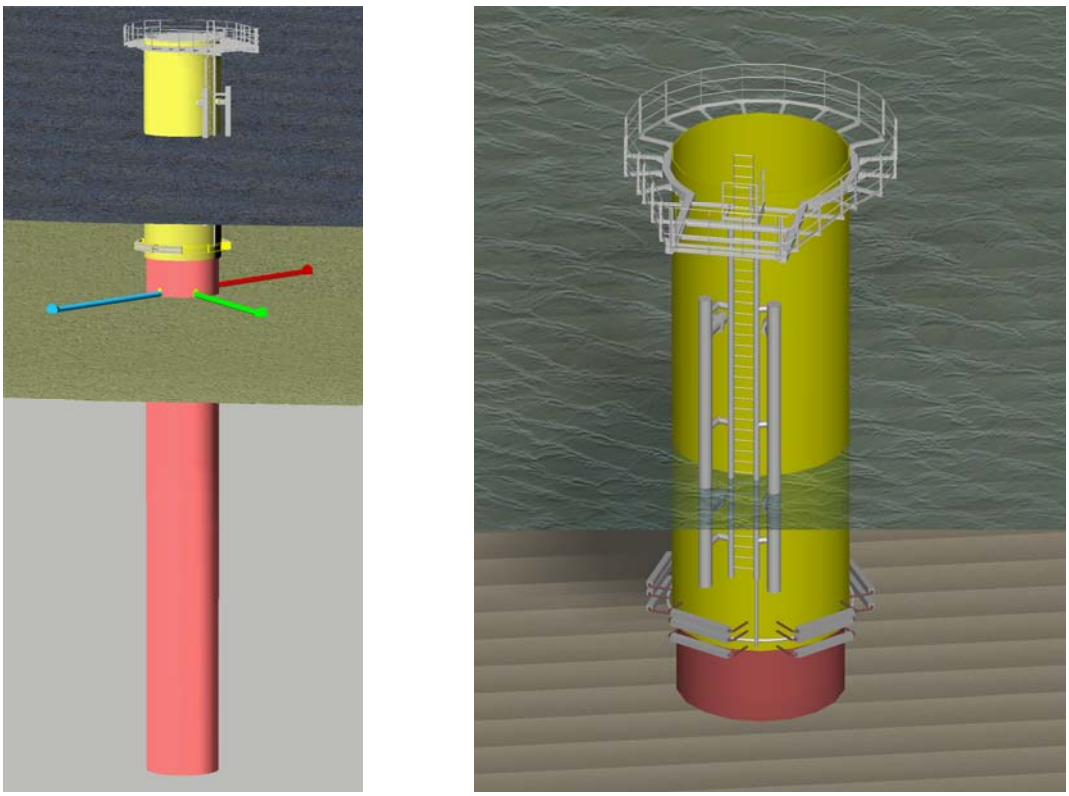

Figure 6.1. Foundation structure with secondary items

The monopile concept consists of a pile section (red) and a transition piece (yellow). The pile is fabricated without any attachments, with an elliptical cut-out for the J-Tube and driven to its target penetration by a large hydraulic hammer with 1.95m of the pile above mean water level. The outer pile diameter is 4300 mm and thereby a transition piece with an inner diameter of 4440 mm (70 mm grout annulus) is suitable.

After driving the pile, the larger diameter transition piece is installed, and the annulus of the 6 m long overlap zone between the outside of the pile and the inside of the transition piece is grouted by high performance Ducorit S5 grout.

All secondary structures, like boat landing, caged ladder etc. are supported on the outside of the transition piece and are not subjected to pile driving fatigue. The J-tubes are routed inside the transition pieces through elliptical holes in the piles just above mudline.

The design was carried out in accordance with the new DNV standard for offshore wind turbine foundations DNV-OS-J101 [1]. The standard, which was first issued in June 2004, is thorough and contains most of the technical guidance necessary for a designer to complete a detailed design for an offshore wind turbine foundation, such as extreme and fatigue load cases, load and safety factors, material quality selection and design acceptance requirements.

All of the technical solutions and analysis method described in this paper was carried out in accordance with and certified by DNV.

6.1 Computer Model

The monopile, transition piece and tower are modeled as one 3D-structure using Ramboll's ROSA program for each of the soil profiles. In Figure 6.2, one of these computer models is shown.

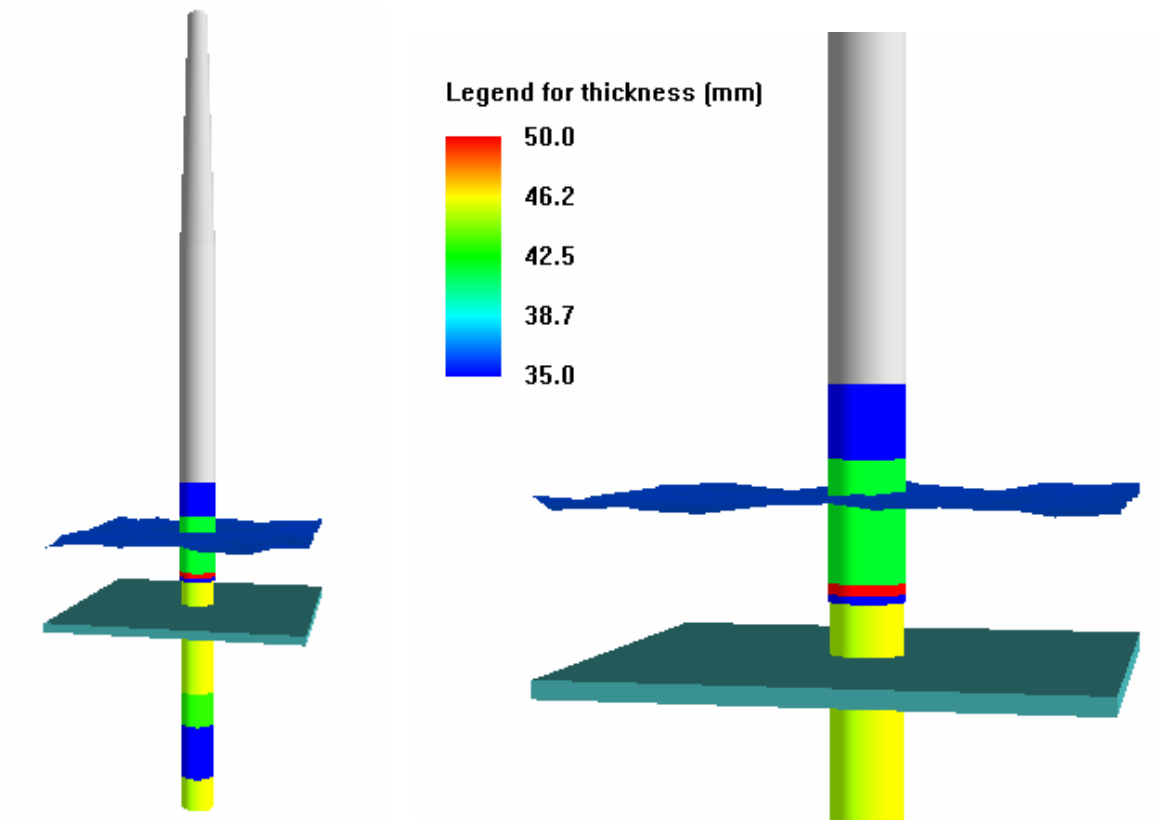

Figure 6.2 Wind turbine foundation ROSA model

In addition to the structural elements, a number of modeled appurtenances ensure the correct weight distribution and wind and wave load areas for equipment and secondary items, i.e. nacelle, rotor, ladders, boat landing etc.

The soil is modelled by means of a set of non-linear springs, denoted P-Y, T-Z and Q-W springs, representing the lateral and axial soil strength and stiffness. The pile-soil interaction model is shown in principal in Figure 3 below.

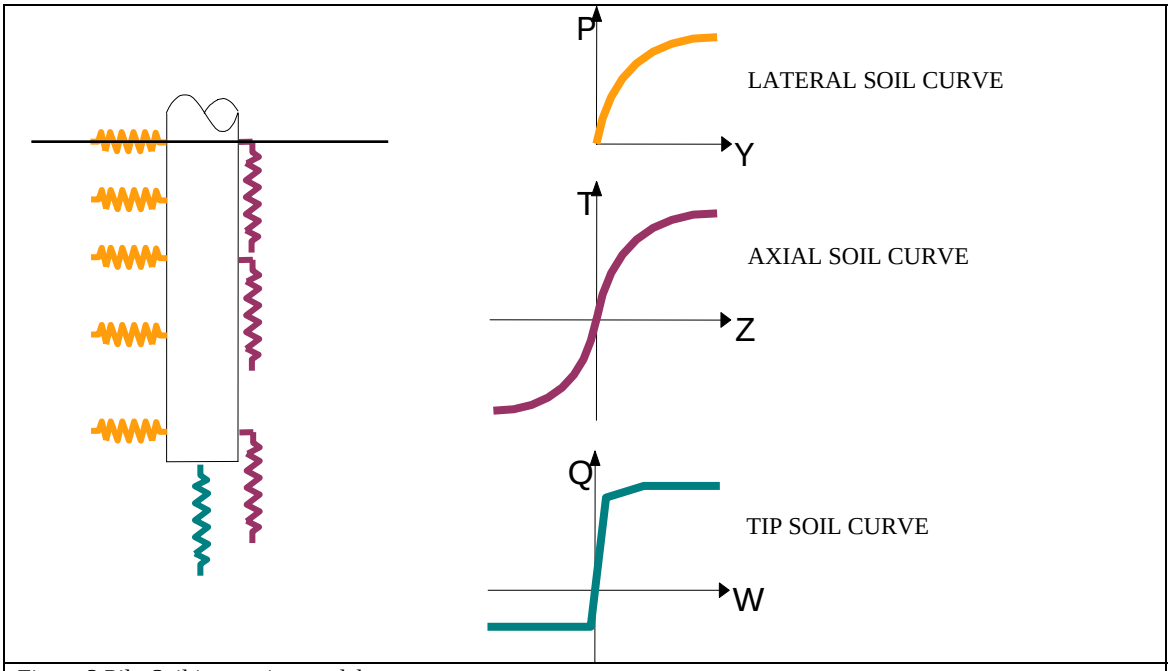

Figure 3 Pile-Soil interaction model

When the wind, wave and gravity loads are applied to the structure, equilibrium is determined by the program based on the soil stiffness and capacity along the pile. If an equilibrium can not be reached, the penetration of the pile needs to be increased. An example of such an equilibrium is shown in the figure below. The size of each of the coloured discs represents lateral reaction in the soil layer and the colour of the disc shows the utilisation ratio of the soil capacity, i.e. the percentage of maximum capacity at a given layer necessary to obtain equilibrium. Please note that there is no reaction in the soil layers close to the undisturbed mudline due to the presence of scour in the calculation model. Further it can be seen that in this load case the pile is rotating around the level of zero reaction about three quarters down the pile where the disc is dark blue.

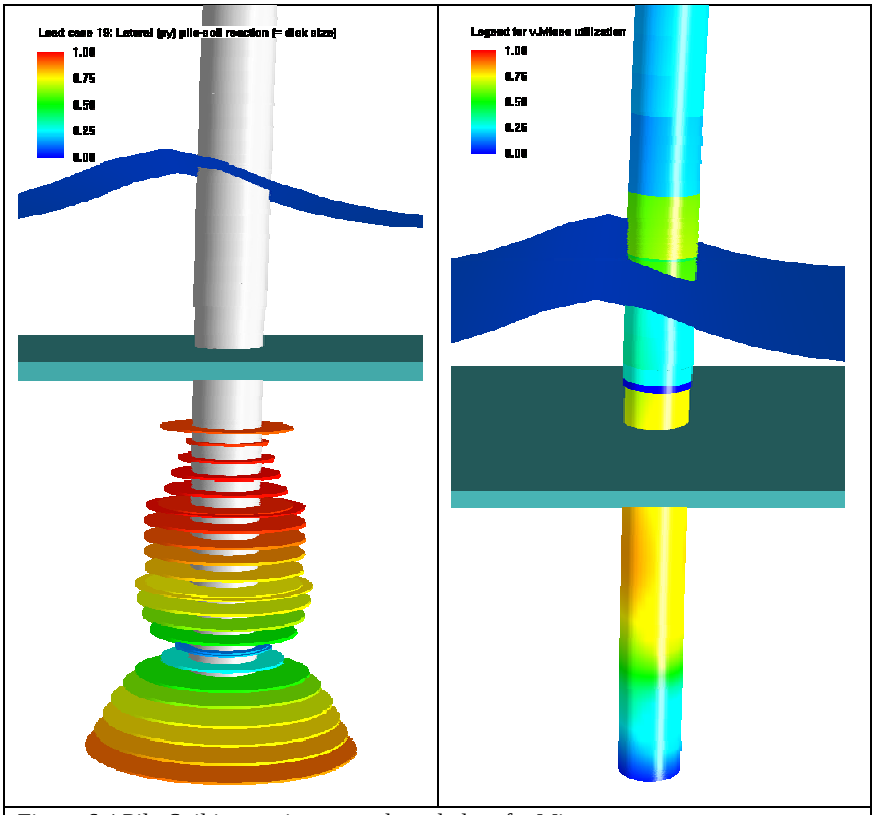

Figure 6.4 Pile-Soil interaction example and plot of v.Mises stresses..

6.2 Design Optimisation

In order to minimise the overall cost of the project in general and the foundation subcontract in particular the design was carried out in parallel with an optimisation process, which focused on minimising the material costs, fabrication and installation costs as well as minimising the anticipated maintenance costs for the expected 20 years of operation.

In order to obtain a substantial reduction in the material and fabrication cost it was necessary to optimise every aspect in the design process, from the applied wind and wave loads over the conditions at the site to the analysis methods applied.

The individual analyses which were carried out at a more advanced level than it has been common practice for offshore wind turbine foundations are briefly described in the following as well as the pros and cons regarding individualised design.

Owing to the tests, that was carried out in order to confirm the design of the grouted connection at Horns Rev, the common design practice for monopile/transition piece connections has been to use the Ducorit D4 high performance grout from Densit and an overlap length of 1.5xOD of the pile. However, by performing a detailed FE analysis of the grouted connection as illustrated below and analysing the capacity with respect to extreme and fatigue capacity, it was possible to demonstrate that an overlap length of 1.4xOD and the less expensive Ducorit material S5 was sufficient to satisfy the requirements set forth.

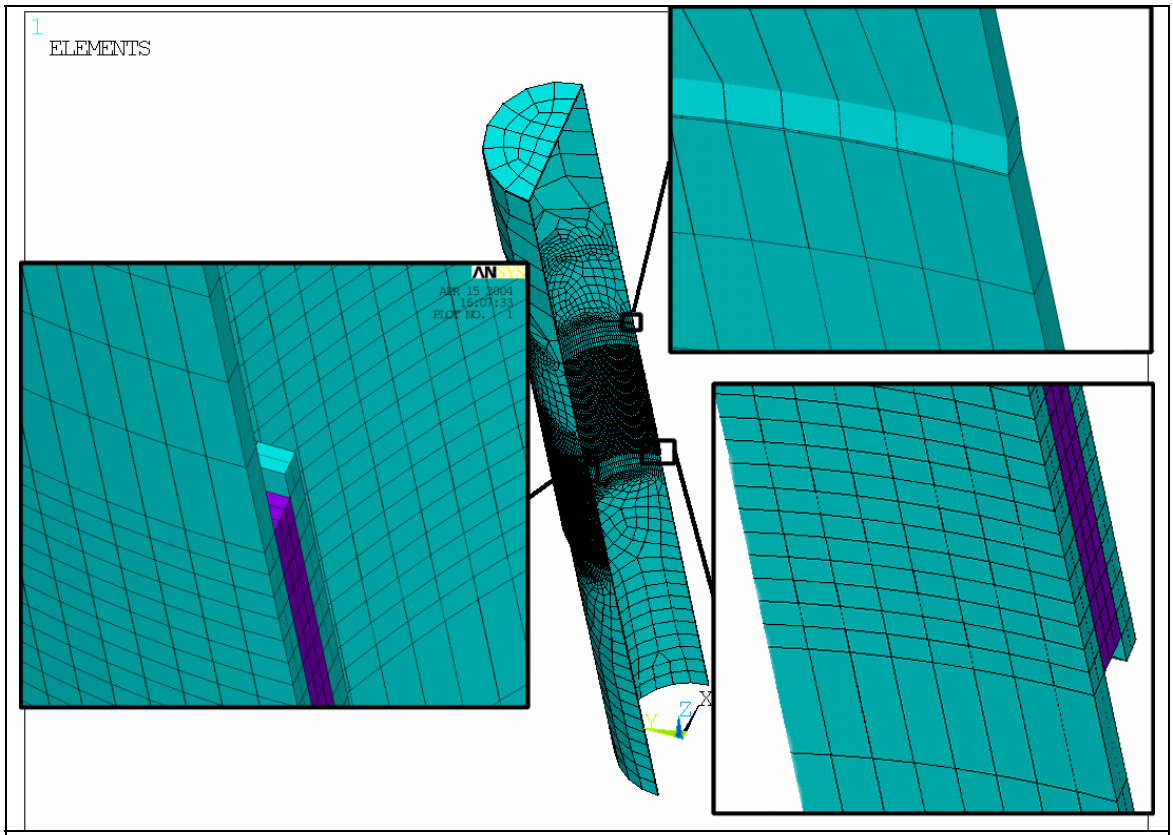

Figure 6.5 Ansys model of the grouted connection.

The most common approach when analysing the fatigue capacity of the Monopile foundation is to assume a mono directional load, representing the wind load by some sort of damage equivalent load and add the stresses arising from the wave load. However, this approach can be rather conservative and it is difficult to relate to any physical measures. Consequently, in order to strip the design of unnecessary conservatisms and be able to penetrate the internal J-Tube through the monopile without excessive wall thickness or fatigue damage, a multi directional time domain fatigue analysis with simultaneous load series of wind and waves was carried out as illustrated in the figure below.

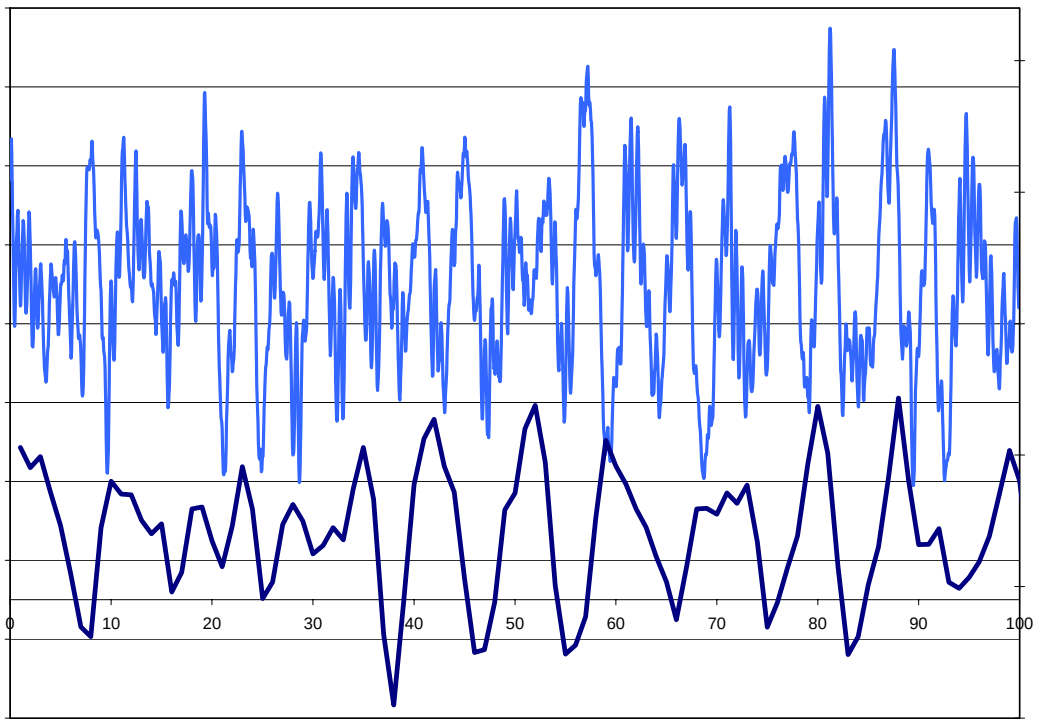

Figure 6 Example of wind and load processes at a wind speed of 24 m/s

By running time domain fatigue analysis from multiple directions it becomes possible to assess the individual contributions to the overall fatigue damage and thereby reach a thorough understanding of which wind and wave conditions have the greatest impact on the overall fatigue damage. The result from the individual directions is illustrated below.

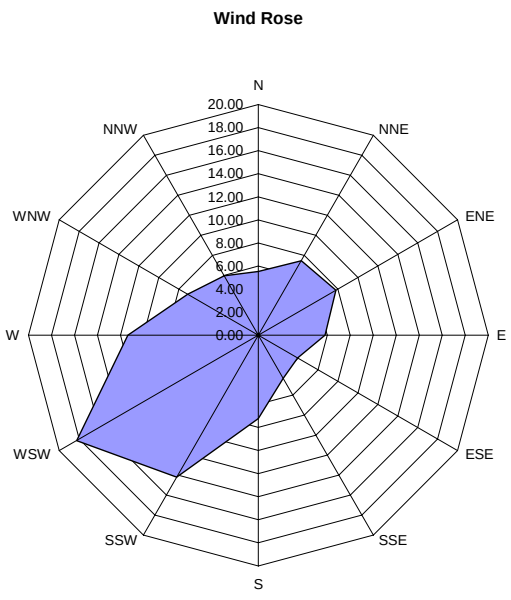

Figure 6.7: Probability of wind directions.

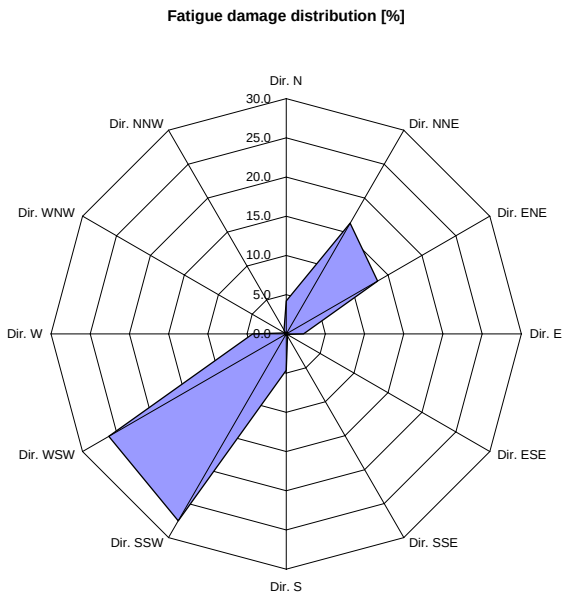

Figure 6.8: Distribution of fatigue damage.

The above figures illustrate the probability of the individual wind directions and the percentage of fatigue damage from the individual directions at the hot-spot with the lowest fatigue life. It can be seen that the WNW, NNW, ESE & SSE directions do not contribute to the fatigue damage even though the accumulated probability of wind from the

directions is about 20%. Equally, the wind comes from the North, East, South and West directions about 30% of the time but has a very limited impact on the lowest fatigue life in the monopile. Consequently, had the fatigue design been carried out as a mono-directional analysis, the calculated fatigue lives might have been close to half and would therefore have required a heavier wall thicknesses.

For a number of given conditions that contribute to the fatigue damage, such as standard production or start and stop conditions. The probability of the condition (maroon), the damage at equal probability (crème) and the combined damage found when multiplying the damage from a condition with the probability of the condition (cobalt) is shown. It can be seen that although the start and stop conditions impose a far larger damage to the structure when they occur, the probability of the condition over a 20 year period factors the overall damage down to insignificant. The reverse is true for the production conditions at lower wind speeds where the probability of them occurring are relatively high but the damage generated is very low. In turn most of the fatigue damage to the structure stems from the production load cases where the turbine operates at or close to rated power where neither the damage nor the probability of the condition is insignificant.

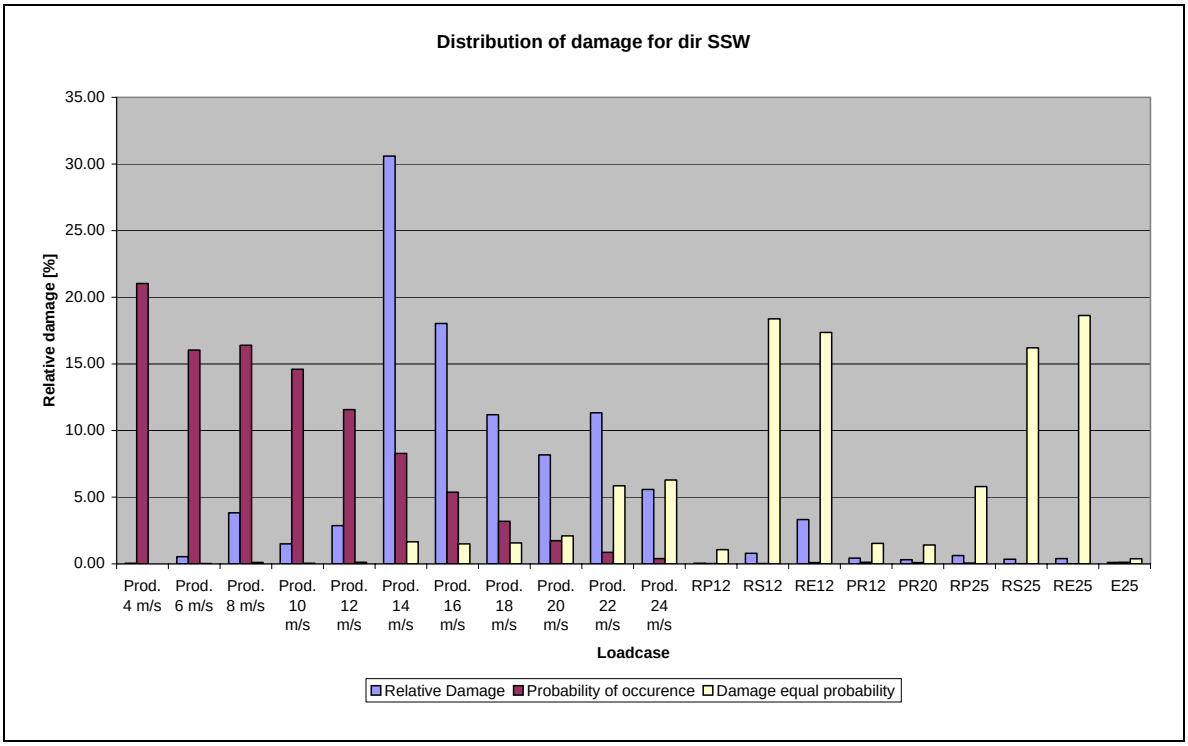

Figure 6.9: Distribution of fatigue damage for wind speed for the hotspot with maximum fatigue damage.

6.3 Individualised Design

Up to now, the approach to foundation design of an offshore wind farm has been to design three or five generic foundations to fit the soil and metocean conditions for all, up to 80, positions. However, this approach necessitates a conservative design where the largest water depth is combined with the weakest soil profile and worst scour conditions within any given group in order for the design to fit all positions. Depending on how homogeneous the soil conditions are and the variation in water depth, this approach is more or less conservative.

As soil investigation, by means of a combination of soil borings and CPT tests, existed for more than half of the positions at the beginning of the design, and as the remaining positions would be available prior to procurement of main steel, it was decided to design each of the 30 foundations individually based on the actual soil conditions and water depth at each position.

The soil conditions at Kentish Flats vary significantly, primarily due to a Paleocene channel which passes through the site and due to the variation in the height and strength of the overburden

The design was carried out assuming no scour protection, i.e. the expected scour depths for the individual positions have been assessed and taken into account in the soil profiles for the design. The scour for the individual positions varies from 1.0 m up to 5.6 m depending on the depth to the London clay and the overlaying sediment.

7 Fabrication and Installation

Concerns were raised that 30 individually designed foundations would intensify the complexity of fabrication and installation and therefore could yield higher risk of misplacement or increased cost of installation. However, since MTH was of the opinion that it was necessary to keep track of each monopile and transition piece anyway in order to ensure traceability of the primary steel plates, it was decided to proceed with the idea. In retrospect, after installation of 30 foundations in 60 days, it can be concluded that the individual designs did not complicate the installation unnecessary and that all 30 monopiles and transitions pieces were installed at the correct positions – one month ahead of schedule.

The installation on sea commenced august 23, and the pile driving, lift-on of transition piece and the grouting is made in one go from one position of the installation vessel “Resolution” which also transported the components in batches of 6 foundations from Hoboken in Belgium.

Finally, in another operation by another set-up, the internal positioned J-tube is brought in position for receiving the sub sea cable from shore.

The 30 piles with their transition piece were ready for the turbines October 20, in the 2004 season, well ahead of schedule.

8 Conclusions

The foundations for the Kentish Flats Offshore Wind Farm have been successfully designed, certified, fabricated and installed in less than one year and well ahead of schedule.

By designing the foundations individually and by applying a number of advanced analysis methods and innovative design decisions, Ramboll has succeeded in minimising overall weight and fabrication costs of the 30 foundations without compromising the required safety level or accepting increased inspection and maintenance costs in the operation of the wind farm.

9 Acknowledgements

The authors wish to thank Vestas Wind Systems, MTHojgaard and Ramboll for allowing the publication of this paper.

10 References

[1] DNV-OS-J101. Design of Offshore Wind Turbine Structures, Det Norske Veritas, June 2004.

[2] Rambøll Offshore Structural Analysis Program Package, version 3.8, December 2003.