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REVIEW OF MODELLING APPROACHES FOR IRREGULAR, NON-LINEAR WAVE LOADING ON OFFSHORE WIND TURBINES AND THEIR RELEVANCE FOR FUTURE DESIGNS

Deliverable D4.3.1 (WP4: Offshore foundations and support structures)

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Abstract:

This document provides the recommendations from the work package 4 on modelling approaches for irregular, non-linear wave loading of offshore wind turbines. It does not provide new methods.

Acknowledgement

This report is the result of work jointly carried by several participants in the Task 4.3 “Enhancement of design methods and standards”. Contributions from the University of Stuttgart (M. Kühn, T. Fischer), DTU/Risø (J.D. Sørensen), Delft University of Technology (W. de Vries), DONG A/S (C. Mørch), GEGR-E (P.W: Cheng), Garrad Hassan (T. Camp), GL Wind (K. Argyriadis), RAMBOLL A/S (H. Carstens) and Shell bv (A. Ploeg) are kindly acknowledged

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STATUS, CONFIDENTIALITY AND ACCESSIBILITY									
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released			**R0**	General public	X		Private web site	
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S3	Draft for comments			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

This document gives a short review by WP4 in the UPWIND project of modelling approaches for irregular, non-linear wave loading on offshore wind turbines. I was decided that a consensus on the application and further development needs should be reached on basis of discussions rather than on simulations. This is justified by the following (see however Section 4 for an exception)

- irregular, non-linear waves are relevant for shallow water locations (below 20 m water depth) but only relevant for some extreme load cases at locations with larger water depth and the WP focuses on substructure and foundation issues for deeper water, i.e. 30-40 m and possibly more,
- engineering methods are still an open issue why a detailed investigation of the matter is not possible,
- it is unlikely that WP4 resources are sufficient to contribute to real scientific progress why only a review is conducted and not a development of practical yet better methods than what has already been proposed, and, importantly,
- other issues like soil-structure interaction and p-y curves of large piles is potentially more important for design improvement

2. The review process

The review process consisted in an evaluation, based on the WP member's present experience, of contemporary methods' relevance and, if relevant, their performance. This was done for a selected number of load cases and for a number of combinations of structures and site conditions. For instance: are nonlinear waves at all a relevant contributor to loads on a monopile in shallow water, or do 2nd order waves perform sufficiently accurate for nonlinear modelling in extreme conditions at future larger water depths? The evaluation matrix shown in Table 1 was developed. Each row represents a combination of site and structure to consider. The three first columns define the load cases to look at for each such structure and site and the fourth column serves for the evaluation of complexity of the method. To simplify the evaluation process and the following comparison of evaluation results the ranking '1' for 'simple', '2' for 'medium', and '3' for high was used in the complexity column and the ranking '+' for 'good', '0' for 'neutral', and '-' for 'bad' was used in the load case columns. It was agreed that each member willing to contribute should choose his preferred methods and fill in the matrix for each of them. For documentation the returned evaluation matrices are listed in the Appendix.

It was anticipated that there would of course be differences in opinion between the WP members. Therefore, after the filled in evaluation matrices were returned, a discussion in plenum took place where clarification of details was made and consensus was reached. The next sec-

Table 1: ***The evaluation matrix applied.***

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile				
	Shallow site Gravity foundation				
	Deep site Monopile				
	Deep site Frame structure				
Future sites	Deep site Gravity foundation				
	Deep site Compliant struct.				

tion reports on the consensus for a selected number of modelling approaches.

3. The recommendations

In this section the consensus on a selection among the evaluated wave models is presented. In the Appendix an overview of which models have been evaluated is given. These fall into two main groups: models for regular waves, and models for irregular waves. These groups may further be crudely divided into two subgroups: one for linear waves, and one for non-liner waves. Here only models for irregular waves are considered. Despite the title of this document, both linear and non-linear wave models are considered because it turns out that often linear wave models are sufficiently accurate for a number of site conditions and load cases – or they are the only practically applicable tool. So, it has boiled down to considering the following five methods:

1. Irregular Airy waves with Wheeler stretching
2. Irregular Airy waves simulated by use of the New wave approach and combined with Wheeler stretching
3. Irregular Airy waves with Wheeler stretching and an embedded appropriate cut-and-paste stream function wave
4. 2nd order irregular waves
5. Boussinesq irregular waves

Out of these methods the 3rd is not generally known but specific to the offshore wind turbine design community. Therefore a short presentation is given in Subsection 3.3.

Regarding the complexity, it has been discussed among the members whether the WP should concern complexity in application or complexity in implementation. It was found most natural that the review should focus on complexity in use, however, that very often also reflects complexity in implementation. Some remarks are made on the subject where appropriate.

3.1 Irregular Airy waves with Wheeler stretching

This method is the very basic method for simulating irregular waves [1] with the wheeler stretching [2] as a means for approximating the kinematics above SWL (still water level). Note that for gravity foundations larger diameters are often the case why special means to account for diffraction will be needed, McCamy-Fuchs corrections is a recommendable method [3]. The method is considered easy to apply because practically all wave software can simulate this kind of waves, and there are no tricks to setting input parameters of to interpret the output. It is also simple to implement. The method is *not* recommended for storm conditions because large time consumption makes it unsuitable, though the accuracy is fine for deep water sites.

Table 2: *Evaluation matrix for irregular Airy waves with Wheeler stretching*

<table>
<tr><th></th><th></th><th>Fatigue</th><th>Response extrapolation</th><th>Storm conditions</th><th>Complexity</th></tr>
<tr><td rowspan="4">Current sites</td><td>Shallow site
Monopile</td><td>0</td><td>0</td><td rowspan="6">Not recommended, though accuracy fine for deep waters</td><td>1</td></tr>
<tr><td>Shallow site
Gravity foundation</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Deep site
Monopile</td><td>+</td><td>+</td><td>1</td></tr>
<tr><td>Deep site
Frame structure</td><td>+</td><td>+</td><td>1</td></tr>
<tr><td rowspan="2">Future sites</td><td>Deep site
Gravity foundation</td><td>+</td><td>+</td><td>1</td></tr>
<tr><td>Deep site
Compliant struct.</td><td>+</td><td>+</td><td>1</td></tr>
</table>

3.2 Irregular Airy waves with New wave and Wheeler stretching

This method is a further development of the irregular Airy waves simulation method. It is much better fit for the storm situation – it has actually been developed for this purpose, as it guarantees the simulated time series will contain a wave of height H_{max} even though the time series will only be a few wave periods long [4]. It is still linear wave kinematics, why Wheeler stretching should be applied, and it is still an irregular wave train. It may be used for fatigue, but it is not its prime purpose. For that purpose the plain Airy wave model is recommended. The method may be corrected for diffraction, but it is not relevant in the storm situation because of the large wave lengths. Because the theory behind the method is not as straight-forward as for the plain irregular Airy wave model the method is considered somewhat more complex.

Table 3: *Evaluation matrix for irregular Airy wave with NewWave and Wheeler stretching*

<table>
<tr><th></th><th></th><th>Fatigue</th><th>Response extrapolation</th><th>Storm conditions</th><th>Complexity</th></tr>
<tr><td rowspan="4">Current sites</td><td>Shallow site Monopile</td><td colspan="4" rowspan="2">Not intended for use in these situations; see Table 2 for evaluation of accuracy of an appropriate alternative</td></tr>
<tr><td>Shallow site Gravity foundation</td></tr>
<tr><td>Deep site Monopile</td><td colspan="2" rowspan="4">Not intended for use in these situations, though accuracy fine for deep waters</td><td>+</td><td>2</td></tr>
<tr><td>Deep site Frame structure</td><td>+</td><td>2</td></tr>
<tr><td rowspan="2">Future sites</td><td>Deep site Gravity foundation</td><td>+</td><td>2</td></tr>
<tr><td>Deep site Compliant struct.</td><td>+</td><td>2</td></tr>
</table>

3.3 Irregular Airy waves with embedded stream function wave

This section gives a short description of a method consisting in the simulation of an irregular Airy wave train with Wheeler stretching followed by embedment of an appropriate stream function wave. It aims at shallow water sites and the storm load case. It is appreciated that the method is an engineering approach consisting in a non-physical blend of two methods that has not yet been subject to a scientific investigation. The method is appealing in the sense that it

Table 4: *Evaluation matrix for irregular Airy waves with embedded stream function wave*

<table>
<tr><th></th><th></th><th>Fatigue</th><th>Response extrapolation</th><th>Storm conditions</th><th>Complexity</th></tr>
<tr><td rowspan="4">Current sites</td><td>Shallow site Monopile</td><td rowspan="6">Not intended for use in this situation</td><td rowspan="2">Not intended for use, but might be used</td><td>+</td><td>2</td></tr>
<tr><td>Shallow site Gravity foundation</td><td>+</td><td>2</td></tr>
<tr><td>Deep site Monopile</td><td colspan="2" rowspan="4">Not intended for use in these situations, though it might be used in storm conditions, but it is not worth the effort</td><td>2</td></tr>
<tr><td>Deep site Frame structure</td><td>2</td></tr>
<tr><td rowspan="2">Future sites</td><td>Deep site Gravity foundation</td><td>2</td></tr>
<tr><td>Deep site Compliant struct.</td><td>2</td></tr>
</table>

contains a stream function wave with the appropriate kinematics, on the one side, and, on the other side, it produces irregular waves fit for the examination of the effect of dynamical amplification. These two effects are covered with a small computational effort. At the end of this section a short description of the method is given. From this it is seen that the implementation of the method is not very complicated. However the interpretation of results can be a little tricky. Because of the non-physical mix care shall be taken when interpreting loads. If wave loads are drag dominated the loads are generated at the wave crest well away from the point where the stream function kinematics and the irregular Airy kinematics are over-lapped. For inertia dominated loads trouble may emerge because these loads are generated not so long from the merging zone. All taken into consideration the method has been assigned medium complexity.

As mentioned the method is not intended for deep water sites, though it might of course be used in the storm situation, but it is not worth the effort, especially when seen in the light of the unknown accuracy. Regarding the unknown uncertainty it should be appreciated that the real sea is 3-deminsional, so already applying long crested wave models uncertainty is introduced.

Description of the method
An irregular surface wave time series can roughly be divided into two parts, parts with waves of low steepness which can be approximated well by the linear approximation and steep waves where the linear approximation is insufficient. In this approach a linear irregular time series is generated with an option of replacing the highest wave crest with a nonlinear wave form, i.e. a stream function wave or a fifth order Stokes wave over typically one wave length with a wave height equal the 50-yr max wave height. To avoid discontinuities a smooth transition between the linear irregular time series and the replacement wave is then obtained by either a linear or a cosine transition over typically another quarter of a wave length in each end of the replaced part. Thus, typically, in total one and a half wave lengths of the original time series is manipulated with.

3.4 2nd order irregular waves

This method provides a means to simulate irregular waves that are slightly non-linear [5]. Thus it aims at operational sea states at shallow waters, i.e. fatigue. It is questionable if the wave loads change enough to justify the extra effort of applying this method. Investigations have shown [6] that the fatigue loads change only little from the linear wave models. The reasons are that wind loads are still dominating, and the second order effect does not come into play until higher wind speeds where only a minor part of the fatigue consumption takes place. For deep

Table 5: *Evaluation matrix for 2nd order irregular waves*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+ for h < 25m 0 otherwise	-	-	>2 and <3
Current sites	Shallow site Gravity foundation	-	-	-	>2 and <3
Current sites	Deep site Monopile	Not intended for use in these situations			
Current sites	Deep site Frame structure				
Future sites	Deep site Gravity foundation				
Future sites	Deep site Compliant struct.				

sites it is not worth the effort to apply 2^{nd} order irregular waves because the contribution from the 2^{nd} order terms is vanishing. The method has been marked as not suited for gravity foundations in shallow waters because of large diameter issues. The complexity of implementing the methods is considered higher than the methods presented so far. More important is the complexity in use. The second order contributions are computed with input from the first order waves, which in turn are computed from the spectrum inputted to the method. Thus the spectrum of the waves simulated will have more power than the spectrum inputted. To reach a certain output spectrum care must be taken that the input spectrum is down-scaled accordingly. This makes the use of the method less than straight-forward. The method has been rank with respect to complexity to be somewhere between 2 and 3.

3.5 Boussinesq irregular waves

This method is not an engineering approach. None of the members could identify commercial available codes that can perform the simulations, nor do the WP members know of non-commercial codes fit for engineering use. The procedure has been used for design basis purposes in a number of cases. The simulation technique, based on the Boussinesq equations, aims at producing waves at shallow sites [7], however breaking waves cannot be modelled. The procedure is very slow. Therefore it is only recommended for cases where nonlinear kinematics are severe that computationally cheaper methods cannot serve the purpose. One way to apply the method would be to develop a library of time series to pick from. Implementation is considered very involved and its use similarly challenging requiring special skills. Therefore the complexity is considered much higher than 3.

Table 6: *Evaluation matrix for Boussinesq irregular waves*

<table>
<tr><th></th><th></th><th>Fatigue</th><th>Response extrapolation</th><th>Storm conditions</th><th>Complexity</th></tr>
<tr><td rowspan="4">Current sites</td><td>Shallow site
Monopile</td><td>+</td><td>+</td><td>+</td><td>>>3</td></tr>
<tr><td>Shallow site
Gravity foundation</td><td colspan="4">Can it be applied for large diameter structures?</td></tr>
<tr><td>Deep site
Monopile</td><td colspan="4" rowspan="4">Not intended for these cases</td></tr>
<tr><td>Deep site
Frame structure</td></tr>
<tr><td rowspan="2">Future sites</td><td>Deep site
Gravity foundation</td></tr>
<tr><td>Deep site
Compliant struct.</td></tr>
</table>

4. Recommendation on future needs

From the two last rows in the evaluation matrices indications about future needs can be read, and much has already been said in the introduction regarding the needs for nonlinear wave models in the future.

However, in addition to this, for shallow sites, the specification of design load cases, for instance in the extreme load cases as they are presently defined in the IEC 61400-3 CDV [9], could be significantly clearer if one had an engineering tool with proper simulation of irregular non-linear waves. Presently these load cases specify that one dynamical analysis, where linear wave models are allowed, and two types of quasi-static analyses with non-linear wave kinematics, shall be carried out unless it can be document that one can do better, which will seldom be the case. Specification of such a load case would be significantly clearer, the computations would be eased, the results would be significantly more transparent, and there will thus be potential for less conservative design, if an engineering tool with proper simulation of irregular non-linear waves would be available.

5. Conclusion for UPWIND

For the further work in WP4 the conclusion that can be drawn from the above review is that the methods presented in sections 3.1 and 3.2 will be the preferred ones because the focus will be on deep waters. As already stressed in the Introduction irregular, non-linear waves are relevant for shallow water locations (below 20 m water depth) and possibly only for some extreme load cases at locations with larger water depths. Since the WP focuses on substructure and foundation issues for deeper water, i.e. 30-40 m and possibly more, the two methods 'Irregular Airy waves with Wheeler stretching' and 'Irregular Airy waves with New wave and Wheeler stretching' are sufficiently complex to provide the needed accuracy and furthermore they are well established within the traditional offshore community implying that results can easily be compared with experience in offshore sector.

6. References

1.	O.M. Faltinsen, "Sea Loads on Ships and Offshore Structures", Cambridge University Press, 1990 (or any other basic textbook on offshore structures)
2.	J.D. Wheeler, "Method for Calculating Forces Produced by Irregular Waves", Journal of Petroleum Technology, March 1970.
3.	R.C. MacCamy & R.A. Fuchs, "Wave forces on piles: A diffraction theory", U.S. Army Corps of Engineers, Beach erosion board, Technical Memorandum No. 69, December 1954
4.	P. Tromans, A. Anaturk & P. Hagemeijer, "A New Model for the Kinematics of Large Ocean Waves – Application as a Design Wave", *Proceedings of the first International Offshore and Polar Engineering Conference, Edinburgh, UK,*1991.
5.	J. Sharma & R.G. Dean, "Second-order directional seas and associated wave forces", OTC paper no 3645, The 11th annual Offshore Technology conference in Houston. Tex., April 30-May 3,1979
6.	H.F. Veldkamp & J. van der Tempel, "Influence of wave modelling on the prediction of fatigue for offshore wind turbines", *Wind Energy* (2004), vol. 8, Issue 1, pp. 49 - 65
7.	P.A. Madsen, H.B. Bingham & Hua Liu, "A new Boussinesq method for fully nonlinear waves from shallow water to deep water", *J. Fluid Mech.* (2002), *vol.* 462, pp. 1-30.
9.	International Electrotechnical Commission: IEC 61400-3 Ed. 1. CDV, "Wind turbine - Part 3: Design requirements for offshore wind turbines", dated 2007-08-10

7. Appendix: The filled-in evaluation matrices

In this appendix the filled in matrices returned by a number of the work package members is are listed for reference. The Table 7 and Table 8 give an overview of the methods evaluated - regular and irregular methods, respectively, of which the latter are of main interest here. On the following pages you find the individual matrices organised by member – not by method.

Table 7: *Regular wave models evaluated*

<table>
<tr><th>Kimon Agyriadis
Germanisher Lloyd</th><th>Po Wen Cheng
General Electric</th><th>Jan v. d. Tempel
T.U. Delft</th><th>Tim Camp
Garrad Hassan</th></tr>
<tr><td>Airy, regular</td><td></td><td></td><td>Regular Airy</td></tr>
<tr><td>Airy, regular, Wheeler</td><td></td><td></td><td></td></tr>
<tr><td>Stokes 5^{th} order regular wave</td><td>Stokes 5^{th} order regular wave</td><td rowspan="2">Non-linear, according to ISO standards</td><td></td></tr>
<tr><td>Stream function regular</td><td>Stream function regular</td><td>Regular stream function</td></tr>
<tr><td>First order (solitary) regular</td><td></td><td></td><td></td></tr>
</table>

Table 8: *Irregular wave models evaluated*

Kimon Agyriadis Germanisher Lloyd	**Po Wen Cheng** General Electric	**Jan v. d. Tempel** T.U. Delft	**Tim Camp** Garrad Hassan
Airy irregular, Wheeler, linear superposition		Airy irregular, Wheeler, linear superposition	Airy irregular, Wheeler, linear superposition, no diffraction
			Irregular Airy with constrained NewWave
Airy – wheeler stretching, embedded stream function regular wave			Irregular Airy with 'cut & paste' extreme stream function wave
Stokes 2^{nd} order irregular waves, superposition	Second Order Wave (Stanford)		
Boussinesq irregular waves	Boussinesq irregular waves		Boussinesq irregular waves

7.1 Kimon Agyriadis (Germanisher Lloyd)

It is noted that

- Boussinesq is not a standard tool at GL
- Gravity foundations are assumed to be large foundations compared to wave length. The analysis is performed using potential theory or Green functions.
- The “storm conditions” case considers hydrodynamic action only

Table 9: *Airy, regular*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	-	1
	Shallow site Gravity found.	0	-	-	1
	Deep site Monopile	0	0	-	1
	Deep site Frame structure	0	0	-	1
Future sites	Deep site Gravity found.	0	0	-	1
	Deep site Compliant struc.	0	0	-	1

Table 10: *Airy, regular, Wheeler*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	0	0	-	1
	Shallow site Gravity found.	0	0	0	1
	Deep site Monopile	0	0	-	1
	Deep site Frame structure	0	0	-	1
Future sites	Deep site Gravity found.	+	+	0	1
	Deep site Compliant struc.	+	+	-	1

Table 11: *Stokes 5th order regular wave*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	0	1
	Shallow site Gravity found.	-	-	-	-
	Deep site Monopile	-	-	+	1
	Deep site Frame structure	-	-	+	1
Future sites	Deep site Gravity found.	-	-	-	-
	Deep site Compliant struc.	-	-	+	1

Table 12: *Stream function regular*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	+	2
	Shallow site Gravity found.	-	-	-	-
	Deep site Monopile	-	-	+	2
	Deep site Frame structure	-	-	+	2
Future sites	Deep site Gravity found.	-	-	-	-
	Deep site Compliant struc.	-	-	+	2

Table 13: *First order (solitary) regular*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	+	1
	Shallow site Gravity found.	-	-	0	-
	Deep site Monopile	-	-	-	-
	Deep site Frame structure	-	-	-	-
Future sites	Deep site Gravity found.	-	-	-	-
	Deep site Compliant struc.	-	-	-	-

Table 14: *Airy irregular, Wheeler, linear superposition*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	0	0	-	1
	Shallow site Gravity found.	+	+	0	1
	Deep site Monopile	+	+	-	1
	Deep site Frame structure	+	+	-	1
Future sites	Deep site Gravity found.	+	+	0	1
	Deep site Compliant struc.	+	+	0	1

Table 15: *Airy – wheeler stretching, embedded stream function regular wave*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	0	0	+	1
	Shallow site Gravity found.	-	-	-	-
	Deep site Monopile	0	0	+	1
	Deep site Frame structure	0	0	+	1
Future sites	Deep site Gravity found.	-	-	-	-
	Deep site Compliant struc.	0	0	+	1

Table 16: *Stokes 2nd order irregular waves, superposition*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+	+	-	2
	Shallow site Gravity found.	+	+	0	2
	Deep site Monopile	+	+	0	2
	Deep site Frame structure	+	+	0	2
Future sites	Deep site Gravity found.	+	+	0	2
	Deep site Compliant struc.	+	+	0	2

Table 17: *Boussinesq irregular waves*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+	0	+	3
	Shallow site Gravity found.	-	-	-	3
	Deep site Monopile	+	+	+	3
	Deep site Frame structure	+	+	+	3
Future sites	Deep site Gravity found.	-	-	-	3
	Deep site Compliant struc.	+	+	+	3

7.2 Po Wen Cheng (General Electric)

It is noted that

- Some of the methods evaluated the evaluator has some experience with, while others are simply from literature review.

Table 18: *Stokes 5th order regular wave*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	-	1.5
Current sites	Shallow site Gravity found.	-	-	-	1.5
Current sites	Deep site Monopile	+	0	0	1.5
Current sites	Deep site Frame structure	+	0	0	1.5
Future sites	Deep site Gravity found.	-	0	0	1.5
Future sites	Deep site Compliant struc.	+	0	0	1.5

Table 19: *Stream function regular*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+	+	+	2
Current sites	Shallow site Gravity found.	-	-	-	2
Current sites	Deep site Monopile	0	0	0	2
Current sites	Deep site Frame structure	0	0	0	2
Future sites	Deep site Gravity found.	-	0	0	2
Future sites	Deep site Compliant struc.	-	0	0	2

Table 20: *Second Order Wave (Stanford)*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+	0	0	2.5
	Shallow site Gravity found.	-	-	-	2.5
	Deep site Monopile	0	0	0	2.5
	Deep site Frame structure	0	0	0	2.5
Future sites	Deep site Gravity found.	-	-	-	2.5
	Deep site Compliant struc.	0	0	0	2.5

Table 21: *Boussinesq irregular waves*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+	+	+	3
	Shallow site Gravity found.	0	0	0	3
	Deep site Monopile	0	0	0	3
	Deep site Frame structure	0	0	0	3
Future sites	Deep site Gravity found.	0	0	0	3
	Deep site Compliant struc.	0	0	0	3

7.3 Jan v. d. Tempel (T.U. Delft)

It is noted that

- At Delft normally Airy linear wave theory with Wheeler stretching is used for fatigue and extremes. Only for detailed design, SESAM is used to perform a non-linear wave model according to the wave height / water depth / wave period ratios, following ISO.
- It is not felt that extension of wave models is required for offshore wind turbine support structure design.
- It was checked to additional information that Dick Veldkamp's thesis could offer, but his main conclusions have remained the same as the paper by him and Tempel. He found that the greatest uncertainty for fatigue of the support structure is not the modelling but the SN-curves and the Miner rule application.

Table 22: *Non-linear, according to ISO standards*

Non-linear, according to ISO standards		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	+	2
	Shallow site Gravity found.	-	-	+	2
	Deep site Monopile	-	-	+	2
	Deep site Frame structure	-	-	+	2
Future sites	Deep site Gravity found.	-	-	+	2
	Deep site Compliant struc.	-	-	+	2

Table 23: *Airy irregular, Wheeler, linear superposition*

Airy		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	+	+	0	1
	Shallow site Gravity found.	NA	NA	NA	NA
	Deep site Monopile	+	+	0	1
	Deep site Frame structure	+	+	0	1
Future sites	Deep site Gravity found.	NA	NA	NA	NA
	Deep site Compliant struc.	+	+	0	1

7.4 Tim Camp (Garrad Hassan)

There was no additional remarks.

Table 24: *Regular Airy*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	-	1
	Shallow site Gravity found.	-	-	-	1
	Deep site Monopile	-	-	0	1
	Deep site Frame structure	-	-	0	1
Future sites	Deep site Gravity found.	-	-	0	1
	Deep site Compliant struc.	-	-	0	1

Table 25: *Regular stream function*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	+	2
	Shallow site Gravity found.	-	-	0	2
	Deep site Monopile	-	-	+	2
	Deep site Frame structure	-	-	+	2
Future sites	Deep site Gravity found.	-	-	+	2
	Deep site Compliant struc.	-	-	+	2

Table 26: *Airy irregular, Wheeler, linear superposition, no diffraction*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	?	-	-	1
	Shallow site Gravity found.	?	-	-	1
	Deep site Monopile	+	-	-	1
	Deep site Frame structure	+	-	-	1
Future sites	Deep site Gravity found.	+	0	0	1
	Deep site Compliant struc.	+	0	0	1

Table 27: *Irregular Airy with constrained NewWave*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	-	-	2
	Shallow site Gravity found.	-	-	-	2
	Deep site Monopile	+	+	+	2
	Deep site Frame structure	+	+	+	2
Future sites	Deep site Gravity found.	+	+	+	2
	Deep site Compliant struc.	+	+	+	2

Table 28: *Irregular Airy with 'cut & paste' extreme stream function wave*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	-	+?	+?	2
	Shallow site Gravity found.	-	+?	+?	2
	Deep site Monopile	-	+	+	2
	Deep site Frame structure	-	+	+	2
Future sites	Deep site Gravity found.	-	+	+	2
	Deep site Compliant struc.	-	+	+	2

Table 29: *Boussinesq irregular waves*

		Fatigue	Response extrapolation	Storm conditions	Complexity
Current sites	Shallow site Monopile	0	+ but slow	+ but slow	3
	Shallow site Gravity found.	0	+ but slow	+ but slow	3
	Deep site Monopile	0	-	-	3
	Deep site Frame structure	0	-	-	3
Future sites	Deep site Gravity found.	0	-	-	3
	Deep site Compliant struc.	0	-	-	3