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Pile Diameter Effects for Large Diameter Monopiles Using State-of-the-Art Force-Displacement and Moment-Rotational Springs to Represent All Possible Reactions on the Pile (8-spring model)

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1.0 Introduction

1.1 Scope:-

The resistance of piles to lateral loading is often modelled using lateral support curves or p-y springs. However, the large diameter and smaller length to diameter ratio (aspect ratio or L/D ratio) of monopiles often means that additional forms of soil resistance are available. These are often grouped together under term 'pile diameter effects'.

This short report aims to identify and split these additional contributions into their separate components. In addition, these effects can then be modelled using state-of-the-art force-displacement and moment-rotational springs to represent all the possible reactions on the pile.

1.2 Pile diameter effects:-

Pile diameter effects include the following contributions:

1. Pure pile diameter effects (i.e. that which effects p-y springs only).

2. Shear forces on bottom of monopile.

3. Moment due to side resistance on shaft of monopile.

4. Moment due to end bearing and gravity effects on bottom of monopile.

5. Depth effects on how p-y springs vary in top soil layers.

Items 1 and 5 relate primarily to the p-y springs and can be dealt with independently from the other effects.

Items 2 to 4 relate to a set of additional forms of soil resistance acting on the pile. These additional soil resistances are shown schematically in Figure 1.

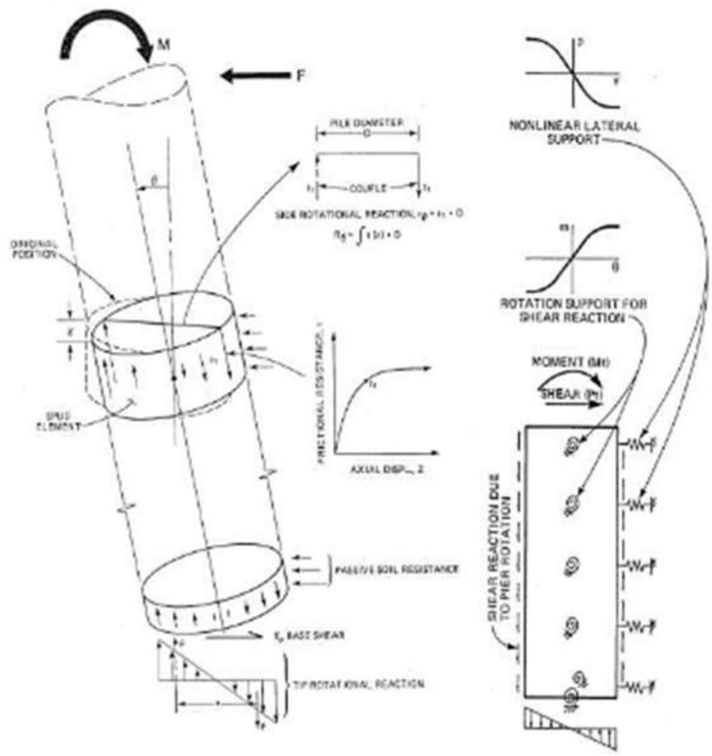


Figure 1: Soil resistances on monopile (FHWA RD-86-102 and Lam 2013).

These additional soil resistances can be modelled using additional force-displacement and moment-rotational springs.

<u>1.3 Aims of report:-</u>

This mini-report aims to:

1. Use the new force-displacement and moment-rotational springs to model all the soil reactions on the pile (i.e. both shaft and base).

2. Develop state-of-the-art formulations for the new force-displacement and moment-rotational springs. All these new formulations are non-linear or curved springs to most accurately represent the actual behaviour of the additional soil resistances.

3. Carry-out investigation of pile diameter effects using these new force-displacement and moment-rotational springs. Investigations have been carried out for typical 6MW monopile for L/D ratio from 3.5 to 6.

2.0 Soil Resistances on Pile

2.1 Representation as springs:-

All the soil resistances on the pile can be represented by force-displacement springs and moment-rotational springs. The various soil resistances on a pile are described below:

1 Force-displacement springs on shaft:-

a) Lateral resistance – commonly known as P-y springs.

b) Axial resistance – commonly known as T-z springs.

2 Moment-rotational springs on shaft:-

a) Torsional resistance – referred to as M-z springs in this report. Torsional resistance about vertical axis of pile acting on shaft.

b) Rotational or tilting resistance – new R-x springs created. Rotation of the shaft about the horizontal axis causes differential shear or frictional resistance to be induced across the diameter of the pile.

3 Force-displacement springs on base:-

a) Axial resistance – commonly known as Q-w springs.

b) Shear resistance – referred to as S-v springs in this report. This additional resistance is often included in the design of drilled shafts, etc.

4 Moment-rotational springs on base:-

a) Rotational resistance due to end bearing and gravity effects – new R-u springs created. Rotation of the base of the pile about the horizontal axis causes the end reaction (including self-weight of material within pile if applicable) to shift by an eccentricity to create a resisting moment. Initially the end reaction is uniform, then trapezoidal, and ultimately triangular, etc.

b) Torsional resistance – referred to as M-w springs in this report. Torsional resistance about vertical axis of pile acting on base.

The use of P-y springs, T-z springs, and Q-w springs to represent the lateral and axial resistance of a pile is very common. The S-v springs are often included in the design of piles with low L/D ratio. Torsional springs M-z and M-w are included for completeness, but torsion does not often govern design of monopiles. However, the use of rotational resistances of R-x springs on the shaft and R-u spring on the base is relatively unknown. It is the aim of this report to include these additional resistances directly, rather than indirectly for example by use of p-y modifiers to the p-y curves, etc.

The shear resistance on the base (S-v springs) and new rotational resistances (R-x and R-u springs) can add significantly to the resistance of lateral loads. However, as we shall see some of these resistances are not developed at the same rate or displacement of the other springs. Careful coupling of all the springs is necessary in order to adequately quantify the benefits of these additional resistances at all load-levels, including serviceability loads.

Figure 2 below shows the spring axis and naming convention used for the force-displacement and moment-rotational springs.

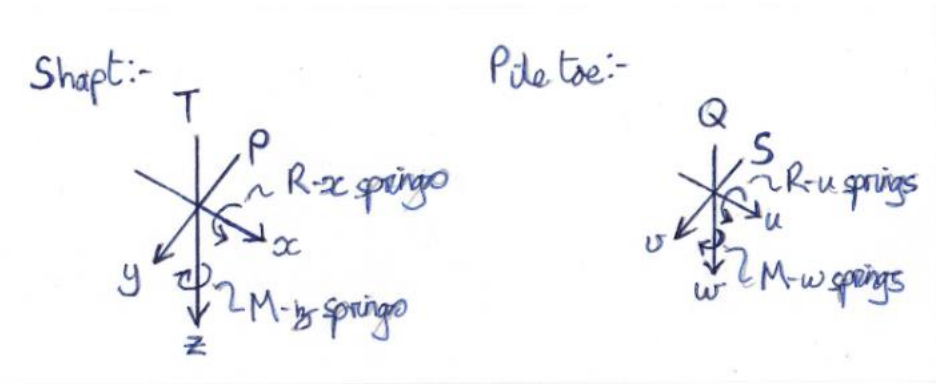


Figure 2: Spring axis and naming convention.

2.2 Construction and application of springs:-

Further details of how the various force-displacement and moment-rotational springs along the pile are constructed are presented in Section 4. In addition, description of the analytical method used to simultaneously apply the various springs to the pile is described in Section 5.

3.0 Preliminary Results

3.1 Brief description of investigation:-

An investigation has been carried out for a typical 6MW monopile in a central or southern North Sea site. The monopile has a 6.5 metre diameter by 100mm wall thickness, i.e. to suit water depth of 20 to 25 metres. Further details of the model are presented in Appendix B.

The investigation has been carried out for an aspect ratio of L/D = 3.5, L/D = 4.5, and L/D = 6. The loading for each L/D ratio has been kept the same such that L/D = 4.5 can be thought of as ‘the right pile length’, L/D = 3.5 can be thought of as ‘too short’, and L/D = 6 can be thought of as ‘too long’.

In addition, the investigation has been carried out for 5№ or 6№ load-levels. It is important to also investigate various load-levels as the pile diameter effects are non-linear and vary significantly between serviceability loads and ultimate loads.

3.2 Ratio of pile head displacements:-

The results of the investigation for various aspect ratios and load levels are presented in Table 1 below. Results are expressed as the ratio of lateral deflection at the pile head with all soil resistances included versus lateral deflection at pile head without additional soil resistances included.

	Ratio of lateral deflection at pile head with all soil resistances included versus lateral deflection at pile head without additional soil resistances included.		
Load case	Pile length:- L = 3.5D	Pile length:- L = 4.5D	Pile length:- L = 6D
Case#1b Mean fatigue load e.g. 22.5% extreme load	0.94	0.94	0.94
Case#2b 2 x mean fatigue load e.g. 45% extreme load	0.84	0.92	0.92
Case#3c Maximum operating load e.g. 70% extreme load	0.65	0.91	0.92
Case#4b Unfactored extreme load	0.51	0.82	0.92
Case#5b Factored extreme load (i.e. load factor 1.35)	0.48	0.71	0.92
Case#6b Global FOS – 2.25 x extreme load	N/a	0.61	0.91

Table 1: Reduction in pile head deflection.

Further details of results and comparison with other methods are given in Appendix A.

3.3 Conclusions:-

A preliminary investigation into the pile diameter effects has been carried out. The results indicate that potentially significant benefits can be realised by including all the soil resistances on the pile. The preliminary conclusions are as follows:

1. For long monopiles (e.g. L > 6D) and shorter piles at very low load-levels the benefit is generally less than 10%. However, it appears this benefit can always be applied even for the longest piles and lowest load-levels.

2. For very short piles (e.g. L ≤ 4.5D) and very high load-levels the benefit can be substantial, e.g. up to 50%, or capacity of the laterally loaded pile is effectively doubled. However, significant rotation is required to develop all of these additional resistances.

3. For intermediate L/D ratios and intermediate load-levels the benefits vary between 10% and 50%; i.e. a significant improvement. The actual benefit will depend on the characteristics of each site, load-level, and details of monopile, etc. The proposed method can consistently calculate the benefit for each application.

4. A single p-y modifier applied only to the p-y springs to try and explain the pile diameter effects (as proposed by some parties) is not recommended as the benefit depends so much on the coupling effects, load-level and L/D ratio.

5. For monopiles any benefits need to be used with caution, as many aspects of the wind turbine (e.g. natural frequency, foundation stiffness, and cyclic degradation) occur at SLS loads where the benefits may be minimal.

More comprehensive discussion, recommendations, and conclusions are available upon request.

3.4 Some comments on advantages:-

Some comments on the advantages of the proposed methodology of using force-displacement and moment-rotational springs to represent all soil resistances along the pile are as follows:

1. The incorporation of pile diameter effects for shorter piles is a simple extension of the p-y spring methodology already well-established for long piles.

2. Pile diameter effects can be determined easily for different L/D ratios and any load-levels, i.e. both serviceability and ultimate loads. Displacement criteria and monopile lengths can be optimised in minutes.

3. The pile diameter effects can be split into their different components, e.g. shear on base or additional rotational resistance. Each component is represented by a non-linear curve; this most accurately represents the behaviour of real soils. The curves representing each component can be independently improved upon or revised at any time. The accuracy and sensitivity of each component can be tested by use of alternative springs and/or comparison with real site data.

4. By way of comparison, 3D finite element software that utilise linear elements can in fact be rather inaccurate as they assume the soil behaves linearly up to yield failure. The whole point of laterally loaded piles is that the load-displacement behaviour is non-linear.

5. In addition, 3D finite element software that utilise linear elements can often only be accurate for one load-level, i.e. different stiffness values need to be run for each load-level. Even then the results will be compromised as not all layers of the soil down the pile will be at same stress/strain level.

More comprehensive advantages and disadvantages of system, including comparison and limitations of other methods, are available upon request.

For other articles on geotechnical aspects including limitations of 3D finite element modelling and black-box technology refer to Section 6.

3.5 Comparison with field test measurements:-

Research using this methodology has shown good comparison with field test measurements (e.g. reference FHWA RD-86-102) and natural frequency measurements of as-built structures (e.g. wind turbine foundations).

4.0 Derivation of Force-Displacement and Moment-Rotational Springs

4.1 General:-

It is important when using this methodology to accurately represent the behaviour of the soil resistances. A brief description of how each force-displacement spring and moment-rotational spring has been derived is given in following sub-Sections.

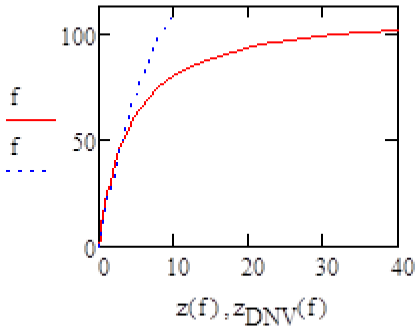
4.2 P-y springs:-

The p-y springs used in this investigation have been derived from standard literature. The Reece p-y curves for stiff clay (w/o freewater) have been used in this investigation to suit a clay site and were generated using the proprietary software LPILE. However, any p-y curve appropriate to any site, geotechnical conditions, and loading can be used, e.g. clay, sand, rock, and with or without cyclic degradation, etc. It is advantage of this methodology that any soil resistance component can independently be revised or substituted with alternative versions, e.g. in order to increase accuracy and/or test sensitivity, etc.

4.3 T-z springs:-

The derivation of the t-z springs assumes much more importance when the all the soil resistances are included as they also form the basis of the rotational moment (R-x springs) and torsional moment springs (M-z).

Therefore hyperbolic t-z springs have been used in this investigation based on the latest state-of-the-art research. Hyperbolic stress-strain models have been found to reasonably represent the nonlinear behaviour of most soils and nonlinear load-transfer functions of piles. A typical hyperbolic t-z curve compared with the DNV t-z curve is shown below:



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The advantages of hyperbolic t-z curves are that they have a much less stiff asymptote near the ultimate stress. This is important in order to avoid overestimating the capacity of some of the additional soil resistances at the higher load-levels. However, any t-z curve can be used in the analysis, e.g. DNV OS J101 or API RP 2A.

4.3 Q-w springs:-

The q-w springs used in this investigation have been derived from standard literature, e.g. API RP 2A.

4.4 S-v springs:-

The shear on the base is often included in the design of drilled shafts and pylon foundations. It is also included as an option in the proprietary software LPILE. The shear force on the base can be determined from cohesion and/or friction due to the end bearing force and treating this shear force as an additional p-y spring acting on the toe of the pile.

4.5 R-x springs:-

The moment versus rotation curves for the base of the pile are one of the most important as they can contribute additional soil resistances at both low load-levels and at high deformations. The rotational moment on the shaft is derived by integration of the t-z springs acting at a lever-arm from the centreline of the pile. It is assumed the shear stresses vary linearly from the neutral axis of the pile.

As the R-x springs are directly based on conventional skin-friction or adhesion versus displacement curves, it is important the t-z curves used in the derivation of the R-x springs are as accurate as possible. Hence it is recommended hyperbolic curves or similar are used to represent the t-z springs.

4.6 R-u springs:-

The moment versus rotation curves for the base of the pile are probably the most complex to determine. However, the response of the pile is probably least sensitive to the R-u springs as their resistance is mainly developed only at the higher deformations. The R-u curve has been split into three sections; the first part is based on elastic half-space theory, the second part is based on resultant triangular loading with an eccentricity, and the asymptote part is based on development of knife-edge load. The soil weight within the monopile is included where applicable.

4.7 M-z and M-w springs:-

The torsion on the shaft is derived by integration of the t-z springs acting around the circumference of the pile. The torsion on the base of the pile is derived in a similar fashion.

5.0 Coupling and Interaction of Soil Resistances

5.1 Method of analysis:-

The method of combining all the various soil resistances is very important as all the soil resistances are not mobilised at the same rate or at the same deformations. For example, the shear on the base will only be mobilise when the pile toe starts to move (which may not occur under low load-levels and/or long piles) and axial loading and moment rotation of the base are generally only mobilised at higher deformations, etc. In addition, pile head conditions, e.g. fixity or presence of 'pile extension' will also affect the relative development of the soil resistances at the top of the pile.

Therefore it is necessary to combine all the soil resistances in proportion to their relative movements appropriate to each load-level being investigated, rather than simply adding their ultimate resistances together.

In this investigation all the soil resistances have been represented by non-linear curves and analysed using the finite element program GTStrudl. Key features and advantages of using GTStrudl are as follows:

- 6№ non-linear springs are applied to every joint below the seabed to represent all possible soil reactions on the pile, e.g. 3№ force-displacement springs and 3№ moment-rotational springs. Joints are normally located every 1.0m to 2.5m down the pile.
- All curves are non-linear or curved to most accurately represent the behaviour of the actual soils. Different soil resistances will develop their resistances at different rates and at different deformations.
- The soil reaction (force/moment) for each soil resistance component is automatically calculated depending on the load-level, soil-structure stiffness, and magnitude of displacement/rotation of each joint, etc. Pile diameter effects, displacement criteria, and optimisation of monopile length for each load-level can therefore be investigated in minutes.
- Individual soil resistance components, e.g. p-y springs or t-z springs, can be varied to suit site conditions and turbine location. Soil resistance components can be upgraded and/or replaced with alternative versions in order to increase accuracy and/or test sensitivity.
- Interaction between soil resistance components, e.g. axial load and moment rotation of shaft (which both depend on t-z springs) can be addressed by modifying springs or by applying a 'preload' to the non-linear springs, etc.

5.2 Other benefits of GTStrudl:-

Other benefits of GTStrudl are as follows:

- GTStrudl is able to automatically calculate the natural frequency of the structure with any number of non-linear soil springs as supports. The consequence of this is that the natural frequency of the structure will vary between load cases (i.e. the soil springs become softer with increasing load). Appendix A shows results of this variation of natural frequency with load-level. Most other software needs to have depth to fixity predetermined in some way; this is often one reason why natural frequencies measured in the field are slightly higher than design values.

6.0 Other Articles by Matt Bristow

6.1 Geotechnical articles (offshore wind farms):-

1. Pile Displacement Criteria – comprehensive list of recommended displacement criteria from serviceability loads to ultimate loads.

2. P-y Spring Comparison – comparison and recommendations for p-y curves.

3. Determination of Geotechnical Parameters for Weak Rocks and IGM's – state-of-the-art method for fractured and weathered materials.

4. Determination of Stiffness Parameter ε_{50} (Epsilon-50) – best estimate determination of ε_{50} from soil strength parameters, geophysical surveys, and triaxial test results, etc.

5. Cyclic Degradation of Soils – methods for the determination and prevention of cyclic degradation of soils.

6.2 Other geotechnical articles:-

1. Natural Frequency Measurements – thirty reasons why the natural frequency of as-built structures is often higher than design values.

2. Limitations of 3D finite element software – limitations of 3D finite element software and black-box technology when used for the design of monopiles.

3. T-z Springs – state-of-the-art method for determination of T-z springs for large diameter piles.

6.3 Structural articles (offshore wind farms):-

1. Methods for Optimisation of Monopile Design – how to save 10 to 20% or more on the weight of the monopile.

2. Alternative Method for Design of Grouted Connections – alternative method to DNV OS J101 (May 2014).

Appendix A Additional Detailed Results

Results of soil resistance investigation and pile diameter effects for L/D = 3.5, L/D = 4.5, and L/D = 6D for typical offshore monopile of 6.5 metre diameter are given in Tables A1, A2, and A3 below:

	LPILE #104[1]	LPILE #***	GTStrudl #204	GTStrudl #206	GTStrudl #209	GTStrudl #208	MathCAD #***	Other methods
Analysis method	Proprietary software for analysis of laterally loaded piles.	Proprietary software.	Finite element software with soil resistances modelled as non-linear springs.	Finite element software.	Finite element software.	Finite element software.	Worksheet with all soil resistances analysed from first principles.	Proprietary software for analysis of drilled shafts and/or short piers.
Pile length (multiple of pile diameter)	L = 4.5D (29.25m)	L = 4.5D	L = 4.5D (29.25m)	L = 4.5D	L = 4.5D	L = 4.5D (29.25m)	L = 4.5D (29.25m)	L = 4.5D
Model features	P-y springs only.	P-y springs and shear on base.	P-y springs only to resist lateral loads.	P-y springs and shear on base only to resist lateral loads.	P-y springs and rotational moments only to resist lateral loads.	All additional soil resistances included.	All additional soil resistances (except torsion) included.	Name of software or alternative method:
Soil resistances included (force-displacement and moment-rotational springs)	P-y	P-y S-v	P-y T-z Q-w M-z	P-y T-z Q-w S-v M-z	P-y T-z Q-w R-x R-u M-z M-w	P-y (lateral force) T-z (axial force) Q-w (end bearing) S-v (shear base) R-x (rotation shaft) R-u (rotation base) M-z (torsion shaft) M-w (torsion base)	P-y T-z Q-w S-v R-x R-u	i) PYLON – all additional soil resistances included (except torsion). ii) S-Shaft (SWM or strain wedge method) – all additional soil resistances included. iii) EPRI software – all soil resistances included.
Lateral displacement and rotation at pile head (mm & °):- Case#1b (Mean fatigue load) Case#2b (2 x mean fatigue load) Case#3c (Max operating load) Case#4b (Extreme load) Case#5b (Factored extreme load) Case#6b (Global FOS)	 δ_x = 1.44mm, θ_z = 0.016° δ_x = 4.82mm, θ_z = 0.043° δ_x = 11.5mm, θ_z = 0.085° δ_x = 28.5mm, θ_z = 0.169° δ_x = 67.3mm, θ_z = 0.319°		 δ_x = 1.51mm, θ_z = 0.018° δ_x = 5.21mm, θ_z = 0.047° δ_x = 12.3mm, θ_z = 0.092° δ_x = 30.9mm, θ_z = 0.182° δ_x = 69.1mm, θ_z = 0.335° δ_x = 416mm, θ_z = 1.50°	 δ_x = 1.51mm, θ_z = 0.018° δ_x = 5.21mm, θ_z = 0.047° δ_x = 12.2mm, θ_z = 0.091° δ_x = 29.3mm, θ_z = 0.176° δ_x = 61.6mm, θ_z = 0.309° δ_x = 352mm, θ_z = 1.26°	 δ_x = 1.41mm, θ_z = 0.017° δ_x = 4.79mm, θ_z = 0.045° δ_x = 11.2mm, θ_z = 0.087° δ_x = 26.3mm, θ_z = 0.165° δ_x = 52.7mm, θ_z = 0.280° δ_x = 289mm, θ_z = 1.04°	 δ_x = 1.41mm, θ_z = 0.017° δ_x = 4.79mm, θ_z = 0.045° δ_x = 11.2mm, θ_z = 0.087° δ_x = 25.2mm, θ_z = 0.162° δ_x = 49.1mm, θ_z = 0.267° δ_x = 252mm, θ_z = 0.95°		Parametric formula methods: i) LPILE - Parametric formula for use with LPILE. ii) GTStrudl – Parametric formula for use with GTStrudl (p-y springs only).
Lateral displacement and rotation at pile toe (mm & °):- Case#1b Case#2b Case#3c Case#4b Case#5b Case#6b						 δ_x = 0.002mm, θ_z = 0.00015° δ_x = 0.006mm, θ_z = 0.0005° δ_x = 0.047mm, θ_z = 0.0012° δ_x = 1.75mm, θ_z = 0.011° δ_x = 9.20mm, θ_z = 0.051° δ_x = 98.9mm, θ_z = 0.57°		
Natural frequency (Hz)[2]:- Zero load Case#1b Case#2b Case#3c Case#4b	N/a.	N/a	 f_1 = 0.321Hz f_1 = 0.301Hz f_1 = 0.295Hz f_1 = 0.285Hz f_1 = 0.264Hz	 f_1 = 0.321Hz f_1 = 0.301Hz f_1 = 0.295Hz f_1 = 0.286Hz f_1 = 0.268Hz	 f_1 = 0.321Hz f_1 = 0.303Hz f_1 = 0.296Hz f_1 = 0.289Hz f_1 = 0.271Hz	 f_1 = 0.321Hz f_1 = 0.303Hz f_1 = 0.296Hz f_1 = 0.290Hz f_1 = 0.276Hz	N/a	

Table A1: Results of soil resistance investigation and pile diameter effects for L/D = 4.5.

Key:-

δ_x	Lateral deflection at pile head (mudline) or toe of pile
θ_z	Rotation at pile head or toe of pile
f_1	Natural frequency of complete structure (first mode only)
D	Diameter of pile (6.5 metres all models)
L	Embedment depth of pile (varies)

Description of soil resistances:-

P-y	Force-displacement	Lateral force on shaft
T-z	Force-displacement	Axial force on shaft
Q-w	Force-displacement	End bearing on base
S-v	Force-displacement	Shear force on base
R-x	Moment-rotational	Rotational moment/tilting on shaft
R-u	Moment-rotational	Rotational moment/tilting on base
M-z	Moment-rotational	Torsion on shaft
M-w	Moment-rotational	Torsion on base

Load cases:-

Case#1b	Mean fatigue load, e.g. 22.5% extreme load
Case#2b	2 x mean fatigue load, e.g. 45% extreme load
Case#3c	Max operating load, e.g. 70% extreme load
Case#4b	Unfactored extreme load
Case#5b	Factored extreme load (i.e. load factor 1.35)
Case#6b	Global FOS - 2.25 x extreme load

Footnotes:-

(1) The lateral deflection for LPILE#104 is slightly less than GTStrudl#204 as the former does not include shear deformation of the pile.

(2) Note the natural frequency will vary with load case as all soil resistances are non-linear (i.e. soil springs become softer with increasing load). This is often one reason why natural frequencies measured in field are slightly higher than design values.

	GTStrudl #241	GTStrudl #242	GTStrudl #243	GTStrudl #240	
Analysis method	Finite element software with soil resistances modelled as non-linear springs.	Finite element software.	Finite element software.	Finite element software.	
Pile length (multiple of pile diameter)	L = 3.5D (22.75m)	L = 3.5D	L = 3.5D	L = 3.5D (22.75m)	
Model features	P-y springs only to resist lateral loads.	P-y springs and shear on base only to resist lateral loads.	P-y springs and rotational moments only to resist lateral loads.	All additional soil resistances included.	
Soil resistances included (force-displacement and moment-rotational springs)	P-y T-z Q-w M-z	P-y T-z Q-w S-v M-z	P-y T-z Q-w R-x R-u M-z M-w	P-y (lateral force) T-z (axial force) Q-w (end bearing) S-v (shear base) R-x (rotation shaft) R-u (rotation base) M-z (torsion shaft) M-w (torsion base)	
Lateral displacement and rotation at pile head (mm & °):- Case#1b (Mean fatigue load) Case#2b (2 x mean fatigue load) Case#3c (Max operating load) Case#4b (Extreme load) Case#5b (Factored extreme load) Case#6b (Global FOS)	 δ_x = 1.51mm, θ_z = 0.018° δ_x = 5.92mm, θ_z = 0.050° δ_x = 22.6mm, θ_z = 0.138° δ_x = 112mm, θ_z = 0.527° δ_x = 367mm, θ_z = 1.59° N/a.	 δ_x = 1.51mm, θ_z = 0.018° δ_x = 5.46mm, θ_z = 0.048° δ_x = 19.1mm, θ_z = 0.120° δ_x = 88.8mm, θ_z = 0.415° δ_x = 285mm, θ_z = 1.20° N/a.	 δ_x = 1.42mm, θ_z = 0.018° δ_x = 5.18mm, θ_z = 0.047° δ_x = 16.3mm, θ_z = 0.110° δ_x = 67.1mm, θ_z = 0.338° δ_x = 221mm, θ_z = 0.98° N/a.	 δ_x = 1.42mm, θ_z = 0.018° δ_x = 4.95mm, θ_z = 0.046° δ_x = 14.8mm, θ_z = 0.102° δ_x = 56.7mm, θ_z = 0.287° δ_x = 174mm, θ_z = 0.76° N/a.	
Lateral displacement and rotation at pile toe (mm & °):- Case#1b Case#2b Case#3c Case#4b Case#5b Case#6b				 δ_x = 0.007mm, θ_z = 0.0006° δ_x = 0.22mm, θ_z = 0.0034° δ_x = 3.32mm, θ_z = 0.026° δ_x = 21.6mm, θ_z = 0.163° δ_x = 79.3mm, θ_z = 0.59° N/a.	
Natural frequency (Hz):- Zero load Case#1b Case#2b Case#3c Case#4b	 f_1 = 0.320Hz f_1 = 0.301Hz f_1 = 0.286Hz f_1 = 0.232Hz f_1 = 0.152Hz			 f_1 = 0.321Hz f_1 = 0.302Hz f_1 = 0.293Hz f_1 = 0.265Hz f_1 = 0.206Hz	

Table A2: Results of soil resistance investigation and pile diameter effects for L/D = 3.5.

	GTStrudl #221	GTStrudl #222	GTStrudl #223	GTStrudl #220	
Analysis method	Finite element software with soil resistances modelled as non-linear springs.	Finite element software.	Finite element software.	Finite element software.	
Pile length (multiple of pile diameter)	L = 6D (39.0m)	L = 6D	L = 6D	L = 6D (39.0m)	
Model features	P-y springs only to resist lateral loads.	P-y springs and shear on base only to resist lateral loads.	P-y springs and rotational moments only to resist lateral loads.	All additional soil resistances included.	
Soil resistances included (force-displacement and moment-rotational springs)	P-y T-z Q-w M-z	P-y T-z Q-w S-v M-z	P-y T-z Q-w R-x R-u M-z M-w	P-y (lateral force) T-z (axial force) Q-w (end bearing) S-v (shear base) R-x (rotation shaft) R-u (rotation base) M-z (torsion shaft) M-w (torsion base)	
Lateral displacement and rotation at pile head (mm & °):- Case#1b (Mean fatigue load) Case#2b (2 x mean fatigue load) Case#3c (Max operating load) Case#4b (Extreme load) Case#5b (Factored extreme load) Case#6b (Global FOS)	 δ_x = 1.51mm, θ_z = 0.018° δ_x = 5.20mm, θ_z = 0.047° δ_x = 12.1mm, θ_z = 0.091° δ_x = 25.9mm, θ_z = 0.166° δ_x = 42.8mm, θ_z = 0.248° δ_x = 106mm, θ_z = 0.51°	 δ_x = 1.51mm, θ_z = 0.018° δ_x = 5.20mm, θ_z = 0.047° δ_x = 12.1mm, θ_z = 0.091° δ_x = 25.9mm, θ_z = 0.166° δ_x = 42.8mm, θ_z = 0.248° δ_x = 105mm, θ_z = 0.50°	 δ_x = 1.41mm, θ_z = 0.017° δ_x = 4.79mm, θ_z = 0.045° δ_x = 11.2mm, θ_z = 0.087° δ_x = 23.9mm, θ_z = 0.157° δ_x = 39.5mm, θ_z = 0.236° δ_x = 98.6mm, θ_z = 0.48°	 δ_x = 1.41mm, θ_z = 0.017° δ_x = 4.79mm, θ_z = 0.045° δ_x = 11.2mm, θ_z = 0.087° δ_x = 23.9mm, θ_z = 0.157° δ_x = 39.5mm, θ_z = 0.236° δ_x = 97.2mm, θ_z = 0.48°	
Lateral displacement and rotation at pile toe (mm & °):- Case#1b Case#2b Case#3c Case#4b Case#5b Case#6b				 δ_x = 0.0017mm, θ_z = 0.00058° δ_x = 3.08mm, θ_z = 0.010°	
Natural frequency (Hz):- Zero load Case#1b Case#2b Case#3c Case#4b	 f_1 = 0.321Hz f_1 = 0.301Hz f_1 = 0.294Hz f_1 = 0.287Hz f_1 = 0.281Hz			 f_1 = 0.321Hz f_1 = 0.303Hz f_1 = 0.296Hz f_1 = 0.290Hz f_1 = 0.283Hz	

Table A3: Results of soil resistance investigation and pile diameter effects for L/D = 6.

Appendix B Model Details

Some details of the investigation models are included below for information.

Turbine details:-

Wind turbine rating: 6.0 MW.
Rotor diameter: 126 metres
Mean wind speed: 10m/s.
50 year wind speed: 50m/s.
Hub-height relative to seabed: 114.6 metres
Interface level relative to seabed: 43.3 metres
Minimum target natural frequency: 0.285Hz
Tower bottom diameter: 5.5 metres.

Monopile and TP details:-

Monopile diameter: 6.5 metres (all L/D ratios).
Transition piece diameter: 5.5 to 6.88 metres (with conical section).
Overall length of transition piece: 24.6 metres.
Length of grouted connection: 9.4 metres.
Plate thickness TP: 75mm to 80mm.
Plate thickness monopile above seabed: 85mm to 100mm.
Plate thickness monopile below seabed: 100mm.

A constant thickness of monopile below seabed has been used in the investigation for all L/D ratios.

Site conditions:-

Water depth (LAT): 25.0 metres (without scour hole)
Water depth (HSWL): 30.4 metres
50 year wave height: 13.6 metres.
50 year wave period: 14.4 seconds.
50 year current: 1.4m/s.

Ground conditions:-

Seabed to depth: Very stiff clay.
Cohesion: c_u = 250kPa all depths.
Stiffness parameter: ε_{50} = 0.004.

Ground conditions in the investigation have been assumed to be constant with depth in order to try and avoid disproportionate variation in pile deflection characteristics with changes in pile length, etc.

Typical target lateral deflection at mudline due to extreme loads: 0.5% ±0.1% x pile diameter.

Loading at mudline:-

The following loading at the mudline has been used for the various load cases:

Load case	Loading	
Case#1b Mean fatigue load e.g. 22.5% extreme load	M = 60200kNm Q = 1220kN	N = 16700kN T = 3850kNm

Case#2b 2 x mean fatigue load e.g. 45% extreme load	M = 125,000kNm Q = 2680kN	N = 16300kN T = 7700kNm
Case#3c Maximum operating load e.g. 70% extreme load	M = 208,000kNm Q = 4740kN	N = 15500kN T = 12000kNm
Case#4b Unfactored extreme load	M = 324,800kNm Q = 7780kN	N = 14600kN T = 17100kNm
Case#5b Factored extreme load (i.e. load factor 1.35)	M = 439,800kNm Q = 10490kN	N = 13600kN T = 23100kNm

Table B1: Loading at mudline for each load case.

Non-linear effects (e.g. P-delta effects) have been turned off in the analysis in order to keep loading constant between models. Terms such as "mean fatigue load" are meant to be indicative and have been rounded to nearest percentage, etc.

Fatigue loads at mudline: 78100kNm @ 10^7 cycles.