NGI (Norwegian Geotechnical Institute) is a leading international centre for research and consulting in the geosciences.

NGI develops optimum solutions for society, and offers expertise on the behaviour of soil, rock and snow and their interaction with the natural and built environment.

NGI works within the oil, gas and energy, building and construction, transportation, natural hazards and environment sectors.

NGI is a private foundation with office and laboratory in Oslo, branch office in Trondheim and daughter company in Houston, Texas, USA. NGI was awarded Centre of Excellence status in 2002.

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Offshore wind turbine foundations

NGI Strategic Research Project SP2 2011-2013

Summary report, 19 November 2013

NGI report no. 20110001-R-01

Background

The Norwegian Geotechnical Institute (NGI) initiated a three-year (2011-2013) research programme with focus on geotechnical issues specific to the offshore wind energy sector. This research programme concentrated on advancing the current state of knowledge in the areas of site characterisation, geotechnical design and monitoring of offshore wind turbine foundations. This report presents the main results of the research program. A bibliography of the published papers is given in the last section of the report. Those who are interested in more detailed information are referred to these documents.

The Research Council of Norway and NGI provided funding for the research programme (total NOK 5.25 million, spread equally over the 3 years).

Organisation

The research programme was coordinated by NGI under the supervision of Vaughan Meyer. Technical guidance was provided by Knut H. Andersen (Technical Expert, Offshore Energy), Lars Andresen (Managing Director), Hans Petter Jostad (Technical Expert, Numerical Modelling), Karl Henrik Mokkelbost (Director, Offshore Energy), Per Magnus Sparrevik (Technical Expert, Subsea Technology) and James Strout (Head of Technology Development and Innovation).

The research team comprised:

- Per Magne Aas
- Lars Andresen
- Wystan Carswell (Ph.D student – University of Massachusetts Amherst)
- Gustav Grimstad
- Jörgen Johansson
- Hans Petter Jostad
- Amir Kaynia
- Thomas Langford
- Tom Lunne
- Finn Løvholt
- Christian Madshus
- Karin Norén-Cosgriff
- Ana Page
- Joonsang Park
- Morten Saue
- Knut Schjetne
- Per Magnus Sparrevik
- James Strout
- Hendrik Sturm
- Maarten Vanneste
- Inge Viken

An international external advisory panel provided industry input into the research programme and guidance of the research aims during the course of the programme. The advisory panel's contribution to the research programme is greatly appreciated.

The panel members were:

- Morten Liingaard (DONG Energy) - Denmark
- Pieter Mattelaer (GeoSea) - Belgium
- Henrik Mikkelsen (MT Højgaard) - Denmark
- Julian Osborne (East Anglia Offshore Wind / Vatenfall) – United Kingdom
- Knut Ronold (DnV) - Norway
- Marc Seidel (RePower) - Germany
- Pål Johannes Strøm (Statoil) - Norway
- Tor Inge Tjelta (Forewind / Statoil) - Norway

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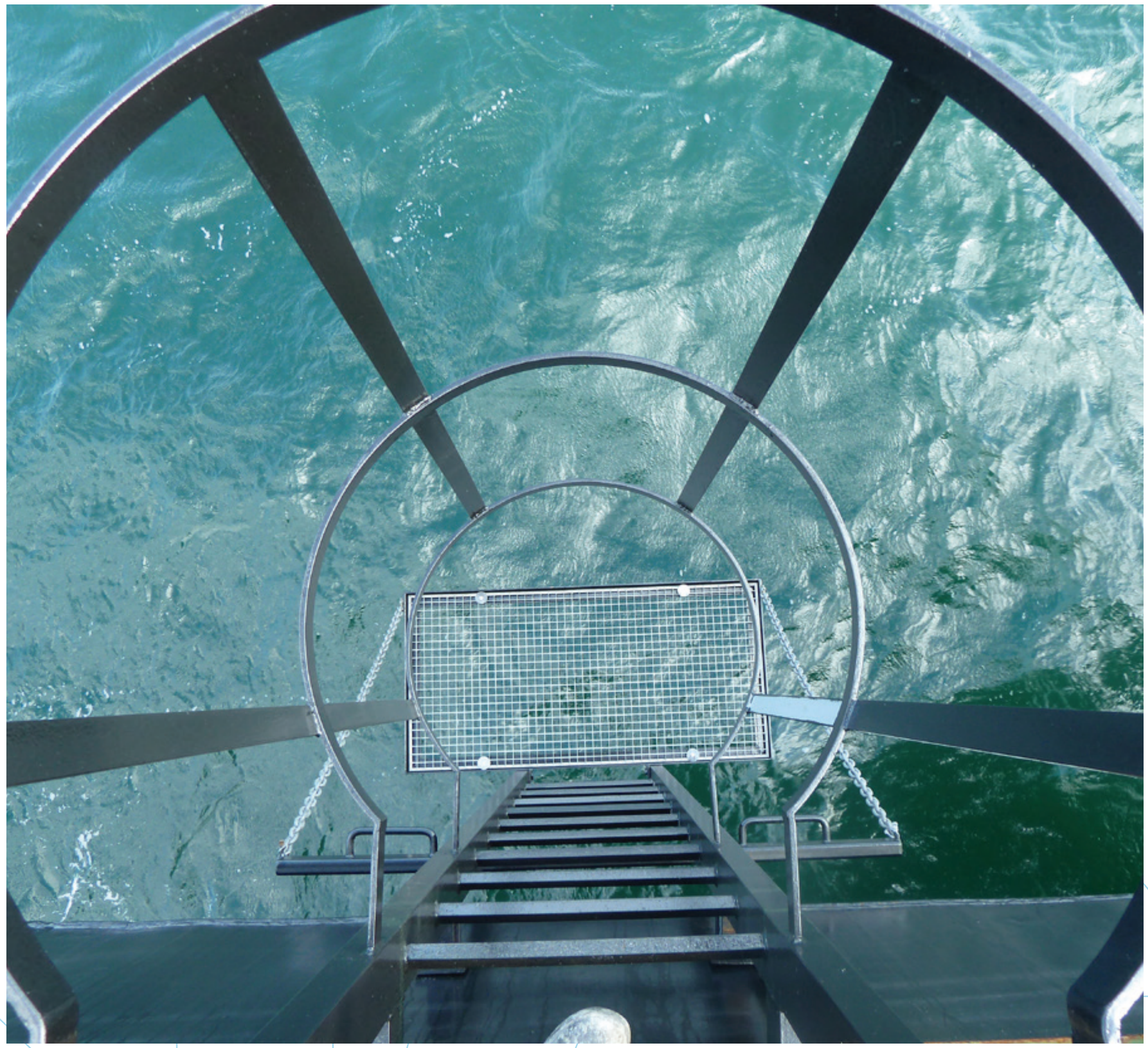
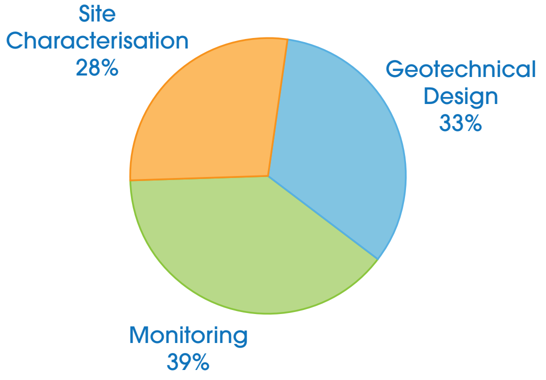


Introduction

NGI involvement with offshore wind projects

With the greater emphasis placed on the development of renewable energy in recent years, NGI has experienced a significant increase in work for offshore wind farm projects.

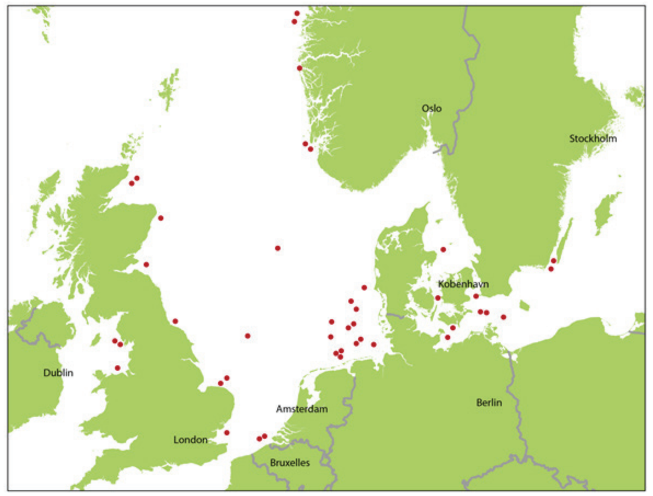
The nature of NGI's offshore wind activities can be roughly equally split into areas of site characterisation, geotechnical design and monitoring.



Nature of NGI offshore wind farm project work (2008 - 2011)

Offshore wind farms and the turbine structures themselves present particular geotechnical challenges, which include:

- site characterisation of large offshore areas (up to approximately 8 500 km^2) and associated spatial variability in geotechnical conditions
- the loading scenarios for geotechnical design of the foundations differ to those for other types of offshore structures
- foundation stiffness is important since the turbines are sensitive to motions as well as their frequency
- the level of industry experience with different foundation types varies
- the long-term behaviour of the different foundations is largely unproven
- there are uncertainties in the application of standard design approaches to some foundation types
- the foundations are a significant part of the overall structure cost, raising the prominence of the foundation design in the project
- given the large number of foundations to be installed, robust designs and efficient installation procedures are required
- environmental and code verification requirements may influence the chosen foundation design



NGI engagements on offshore wind farm projects in Europe (2008-2011)

Outline of research

The focus of the research programme was to:

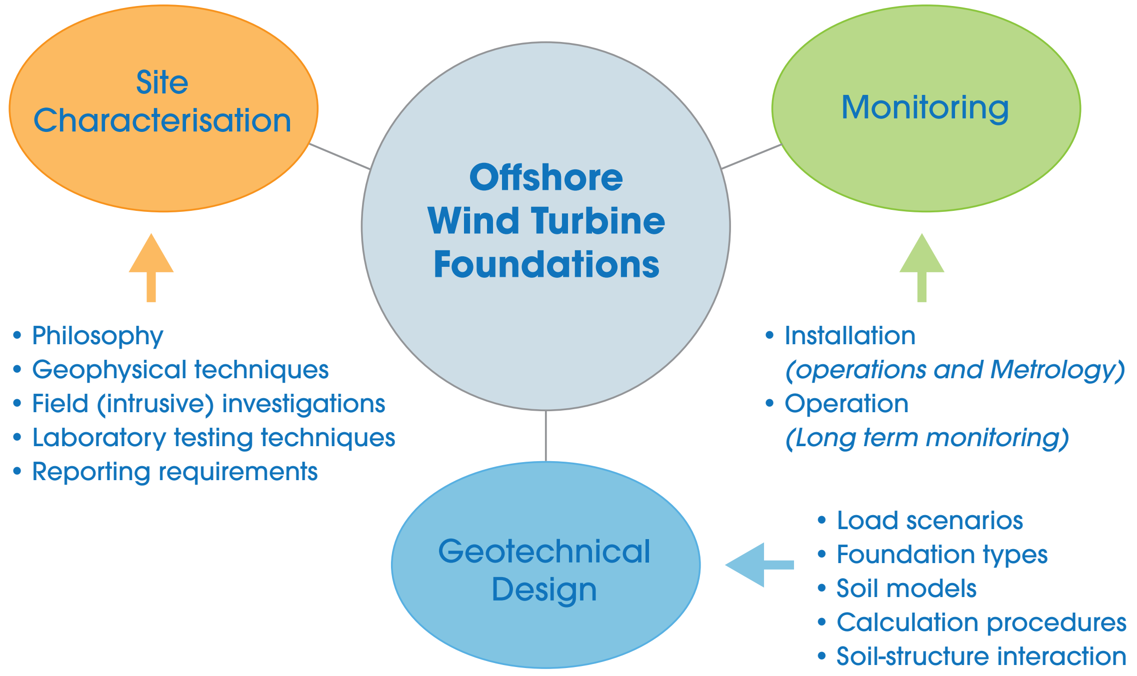
- identify areas where geotechnical-related research and development would be of benefit for offshore wind turbine foundations
- based on existing knowledge, improve existing methodologies and/or develop new techniques, focusing on the areas of site characterisation, geotechnical design and monitoring
- where possible, adopt an integrated approach to the research in conjunction with industry.

Research methodology

NGI's approach to this research programme is based on over 40 years' experience with foundations for offshore structures. In this respect, it is important to note that the change in focus from the design and construction of a foundation for a single, large offshore structure, such as an oil and gas platform, to the foundations for an offshore wind farm, is much like the shift from **bespoke**, or **tailor-made** engineering, towards **mass production**.

The research methodology has concentrated on filling gaps in the existing knowledge base identified from the particular geotechnical challenges highlighted for offshore wind turbine foundations.

Research areas with subtopics



- Philosophy
- Geophysical techniques
- Field (intrusive) investigations
- Laboratory testing techniques
- Reporting requirements

- Installation
  (operations and Metrology)
- Operation
  (Long term monitoring)

- Load scenarios
- Foundation types
- Soil models
- Calculation procedures
- Soil-structure interaction

Comparison between an offshore platform and an offshore wind farm

Troll platform, Statoil

Alpha Ventus (www.alpha-ventus.de Photo: Mattias Ibeler)

- **Single structure (platform)**
- **Cyclic loads from waves dominate**
- **Big and robust structure**
- **Large return on investment**

- **Multiple structures (OWTs)**
- **Cyclic loads from wind and wave**
- **Slender structure (serviceability issues)**
- **Lesser return on investment**

TAILOR MADE → MASS PRODUCTION

(alters basis for site characterisation, design, fabrication & installation)

Research Programme

The research programme comprised a total of 17 individual research projects. Many of these projects represent a continuation of a particular research topic through the three-year programme. Results from most of these projects are summarised in this report.

Year	Research Area	Title	Project leader
2011	**Site characterisation**	Shallow Marine Surface Waves for Geotechnical Site Characterisation	Maarten Vanneste
	Geotechnical design	Developing a NGI procedure for analysis of cyclic load - time data	Karin Norén-Cosgriff
		Damping properties of soils	Finn Løvholt
		Dynamic soil-structure interaction	Jörgen Johansson
		Integrated simulation of offshore wind turbines	Hendrik Sturm
		Settlement of bucket and monopile foundations in clay	Morten Saue
		Cyclic ADP model	Gustav Grimstad
2012	**Site characterisation**	Attenuation from near-surface seismics	Maarten Vanneste
	Geotechnical design	Analysis of soil damping and stiffness for Offshore Wind Turbines	Finn Løvholt
		Load assessment, geotechnical design and serviceability of a skirted OWT foundation on sand	Hendrik Sturm
	Monitoring	Instrumentation and monitoring strategy for wind energy foundations	James Strout
2013	**Site characterisation**	MASW: Joint multi-modal inversion, attenuation and 2-3D effects	Maarten Vanneste
		Participation in the German FoU project: Offshore SI for GBS windmills	Tom Lunne
	Geotechnical design	A procedure for establishing soil springs for structural design	Hendrik Sturm
		Quantification of cyclic / dynamic load histories – Cycle Count	Karin Norén-Cosgriff
		Global damping and stiffness response from OWT foundations	Finn Løvholt
		Upgrading and improvement of PDCAM and UDCAM	Hans Petter Jostad

Quantitative shallow sub-surface characterization using seismics

Rationale

Shear wave velocity, dynamic stiffness and soil damping are essential parameters for design of offshore windfarms. Traditionally, they are determined through laboratory tests, which are influenced by sample disturbance. Mapping lateral sub-surface variations over larger areas requires integration of non-invasive seismic data with geotechnical boreholes. Complementing conventional seismics with surface waves can be beneficial for geotechnical and engineering applications, particularly when cyclic loading or vibrations play a role. Surface waves are dispersive, which allows establishing shear wave velocity profiles down to about one wavelength. At given frequencies, multiple propagation modes exist. Using these in inversion improves resolution, reduces uncertainty, and extends the investigation depth. Multi-modal inversion relies on novel forward modelling that accounts for the overlying water. In addition, the quality factors, being inversely proportional to material damping, can be determined from near-surface geophysics and can assist in soil characterization.

Main Objectives

- Evaluate marine surface wave data acquisition;
- Develop algorithms to obtain shear wave velocities from multi-modal surface waves;
- Estimate quality factors from near-surface seismics;
- Bridge the gap between geophysical and geotechnical parameters.

Survey design for high-quality surface waves

Using surface waves offshore requires specific conditions on survey design (source and receiver configurations). A feasibility study, combined with a unique field experiment at Gjøa (Socco et al., 2011; Vanneste et al., 2011), reveals that the optimum acquisition consists of seabed-coupled shear wave vibrators with densely-populated (e.g., 2.5 m spacing) seabed-coupled ocean-bottom cables (Figure 1). Data at long offsets increase the possibility of detecting higher modes. A seismic source emitting low frequencies over which surface waves stand out yields higher-quality results (Figure 2). Alternative to the seabed-coupled system, a towed streamer (hydrophones or 2C) is feasible, but one quickly loses resolution and data quality drops with towing height above the seabed (Figure 3).

Forward modelling vs. inversion of multi-modal surface waves

Inversion relies on proper forward models. Conventional forward models ignore the effect of the water column which results in erroneous shear wave velocities (Figure 4). Multi-modal inversion schemes that take this into account were not available when this R&D project started. Inverting multiple modes implies that the process becomes more data driven, and will yield improved results with lower uncertainties. We addressed these shortcomings by rewriting our in-house full-wavefield forward model Laysac to extract the kinematic solutions for multi-modal surface waves (Rayleigh, Scholte, Love), and implemented it into our inversion scheme (Figure 5).

Survey design - Data examples

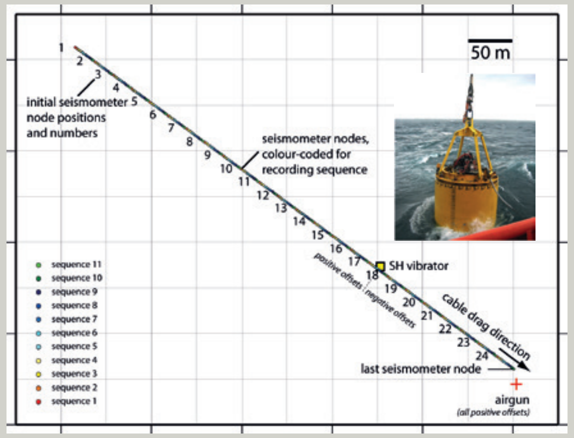


Figure 1. Gjøa field survey design for multi-component shear wave profiling (see Vanneste et al., 2011).

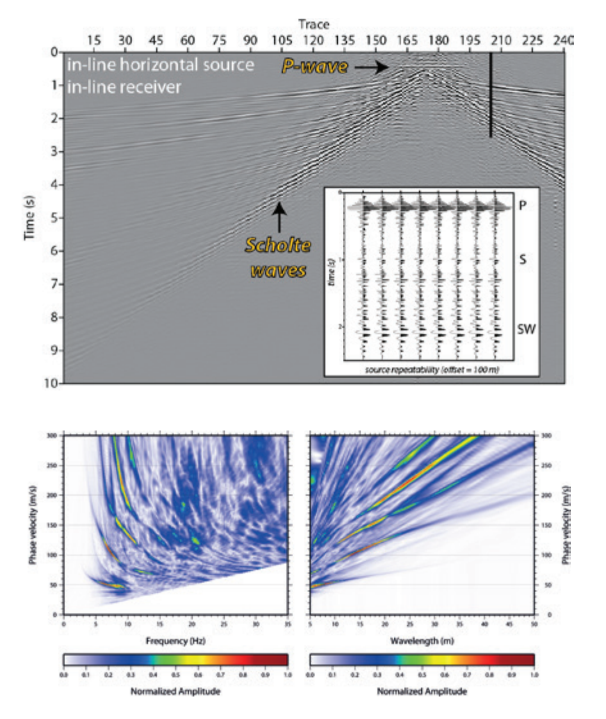


Figure 2. Gjøa shear wave data. (Top) Stacked shot gather. (Bottom) Spectral images converted into phase velocity vs. frequency or wavelength. High-amplitude events are surface wave modes.

Application 1: High-resolution shear wave velocities and anisotropy

The Gjøa field (North Sea, 360 m water depth) was the scene of a unique shear wave experiment (Statoil and NGI, 2007). The resulting multi-component seismic data, with 240 4C receivers at 2.5 m spacing (Figure 2, top) remain the only marine shear wave data available worldwide. Spectral images (Figure 2, bottom) reveal the fundamental and 4 higher surface wave modes. This is the only data set – both offshore and onshore – showing high-quality multi-modal surface waves, which makes it an ideal test case for forward modelling and inversion.

The data acquisition with different source and receiver orientations (in-line, cross-line) allows recording both Scholte and Love waves, which have particle motion in the vertical and horizontal plane, respectively. With the newly implemented inversion algorithm, we obtain larger penetration depths, and smaller uncertainties on the best-fit model. Combining the results by constraining the layer thickness in the inversion provides information on anisotropy, a feature typically ignored in site investigations. Our results indicate that shear wave velocity anisotropy can be up to 15%.

Application 2: shear wave attenuation

Seismic wavefield propagation also depends on damping, expressed as the inverse property, the quality factor Q. Soil damping is a driver for fatigue, particularly in monopile structures, but is difficult to determine. Soil damping consists of large-strain non-linearity and small-strain attenuation. The latter part can be determined by seismic data and can therefore be used to improve the prediction of soil damping. There is, generally, little known on attenuation values in shallow soils from geophysical measurements.

One approach, based on the half-power bandwidth method in frequency-wavenumber domain, measures the attenuation coefficient from the width of the spectral peak. The method can be applied to both the fundamental and higher-order modes. The widths of the spectral peaks are largely controlled by the highest damping in the layered structure and less by its vertical variations.

From comparison of the spectral images of the Gjøa data with tuned full-waveform forward modelling, S-wave damping is less than 1% for the soft deepwater soils. The attenuation coefficient for the fundamental mode increases linearly as a function of frequency, indicating that damping is largely viscous rather than due to hysteresis (Figure 7).

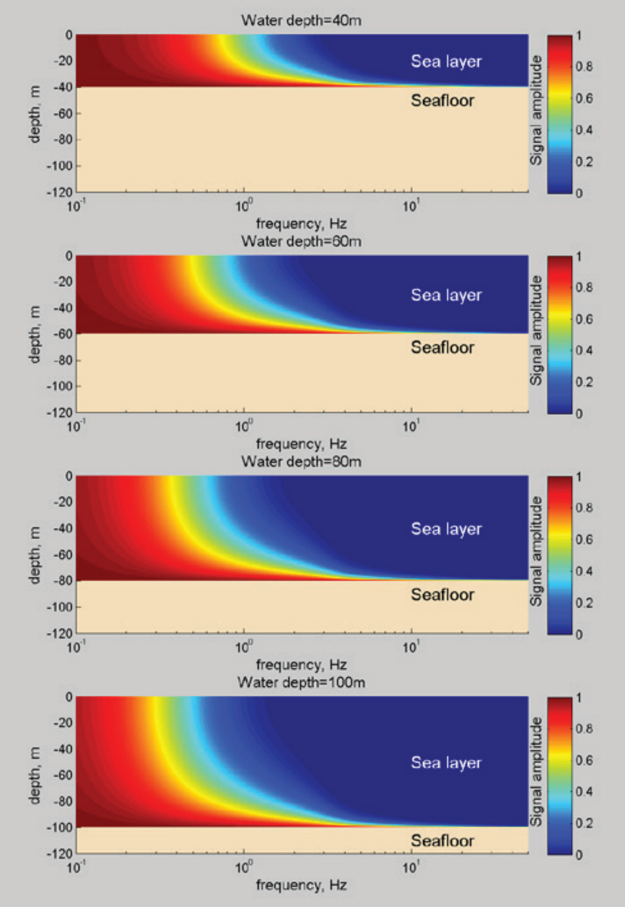


Figure 3. (left): Normalised fundamental mode shape in the water column for a simple soil model and various water depths. This figure illustrates that both the receiver and source should – ideally – be coupled to the seabed to record surface waves over larger frequency range. Shear wave velocity is 0 m/s in the water and 100 m/s in the top soil (10 m). In the half-space underneath, shear wave velocity is 200 m/s.

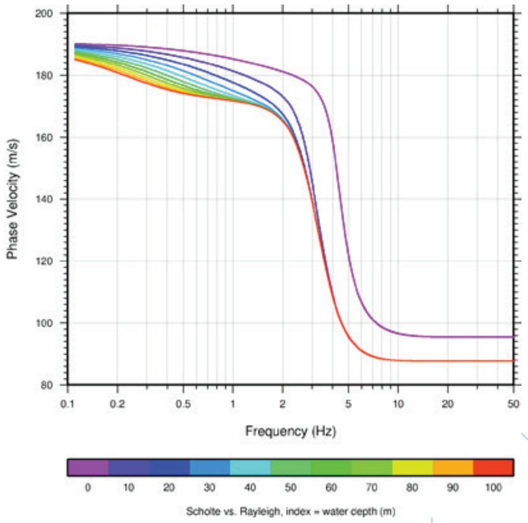


Figure 4. Dispersion curve for fundamental Rayleigh (pink) vs. Scholte wave mode (other colours), illustrating the effect of the water layer (depth given in figure legend), for the same soil model as above.

Dissemination of results / Further reading

Further reading is given in the bibliography. NGI also hosted a workshop on attenuation in 2012, with participants from the University of Southampton, the Norwegian Geological Survey, the University of Oslo, Duke University, and NORSAR.

Acknowledgements

The Gjøa field data were collected in collaboration with Statoil. We also acknowledge the SEABED project C-Dog for additional data and testing.

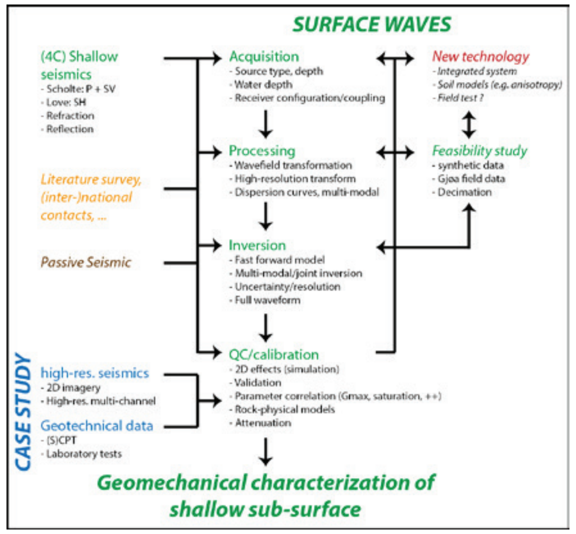


Figure 5. Flow charts for surface wave acquisition, processing and inversion in order to obtain high-resolution shear wave velocity with depth.

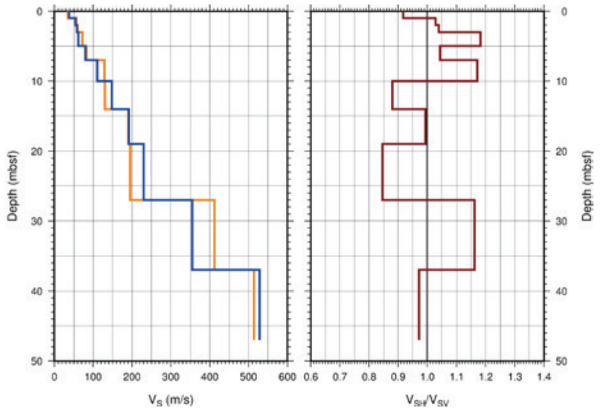


Figure 6. (Left) Results from multi-modal Scholte (blue) and Love (orange) wave inversion, with constrained layer thickness. (Right) Ratio of horizontal and vertical velocities, as an indication of anisotropy (up to 15%) in the shallow sub-surface.

Note: Surface wave forward models and inversion typically assumes a 1D layered soil structure, whereas the subsurface is essentially 3D. This assumption is acceptable as long as sub-surface structural variations remain limited over the spatial scale of the measurements.

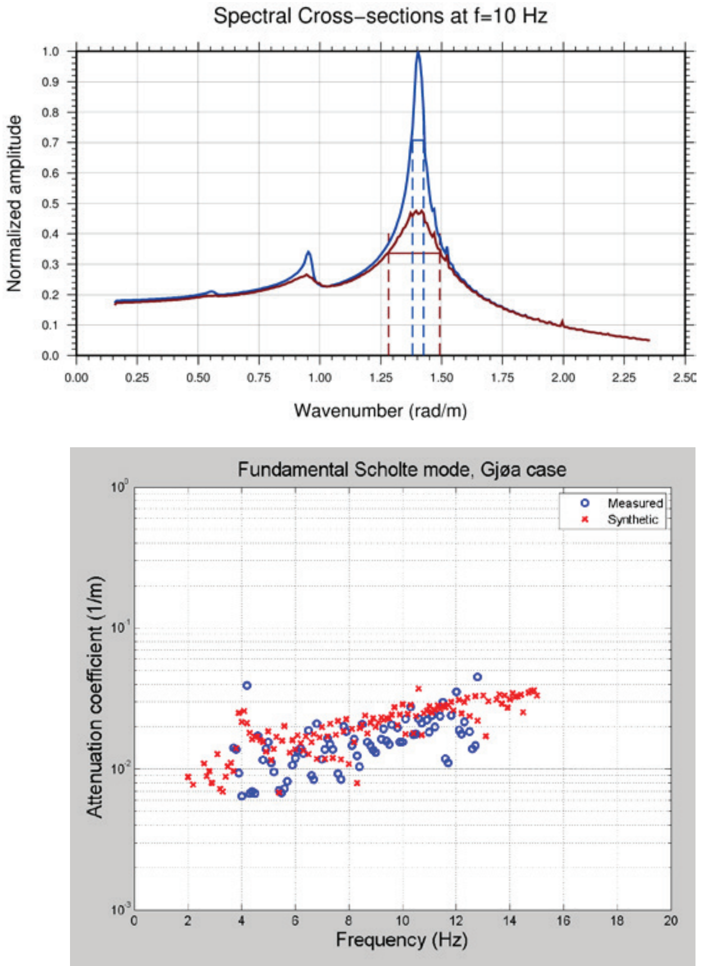


Figure 7. (Top) Cross-section of spectral image to determine attenuation from surface waves. (Bottom) Attenuation coefficients for fundamental Scholte waves from Gjøa field data (blue) and tuned synthetic data (red).

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Quantification of cyclic/dynamic load histories – cycle counting

New method

A new method has been developed that can transfer general, often highly irregular wave and wind load data, to standard input format for soil cyclic degradation calculations. This transformation is to a single frequency load with separation of average and cyclic components and counting & grouping of loads into parcels of increasing amplitude and mean value.

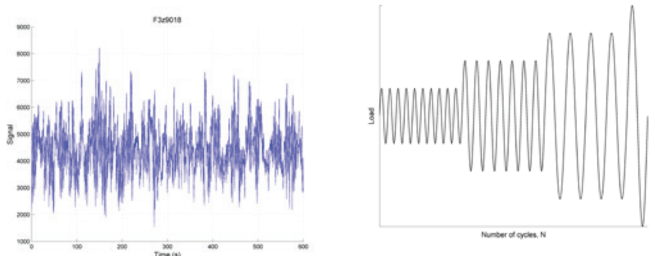

Figure 1. Converting load time series to standard input format for soil cyclic degradation calculations

Rain flow counting is often used in fatigue analysis of structures. In the rain flow method, all peaks are identified and counted. However, the method allows amplitudes to be determined from local maxima and minima belonging to different cycles, which may lead to overestimation of amplitudes, see Figure 2. As soil experiences kinematic and not isotropic hardening, the rain flow method is probably not so well suited for soil analysis.

In the new method, the amplitude of each half cycle is determined from adjacent local maxima and minima. The drawback is that the method requires operator input and is therefore more sensitive to operator judgement. One example is shown in Figure 3. The signal can either be counted as one cycle with a high amplitude disregarding the smaller internal cycles, or it could be counted as many cycles with lower amplitudes. The new method gives the operator the ability to override the maxima and minima identified by the program and define cycles interactively on the screen.

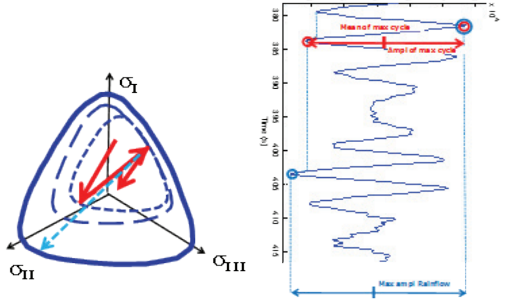

Figure 2. Rain flow method versus NGI's approach

In order to evaluate the effect of different ways to define cycles on soil shear strain accumulation, the method uses NGI's in-house program ACCUMUL to calculate resulting equivalent number of cycles for different cycle definitions.

The new method has been tested on a simulated load time series and the result compared with that obtained from a rain flow analysis on the same load time series. The comparison shows that the deviations between the two methods are considerable, in terms of both the identified number of cycles in the time series and the calculated equivalent number of cycles. Correct definition of load cycles is very important for design of the structure and foundation.

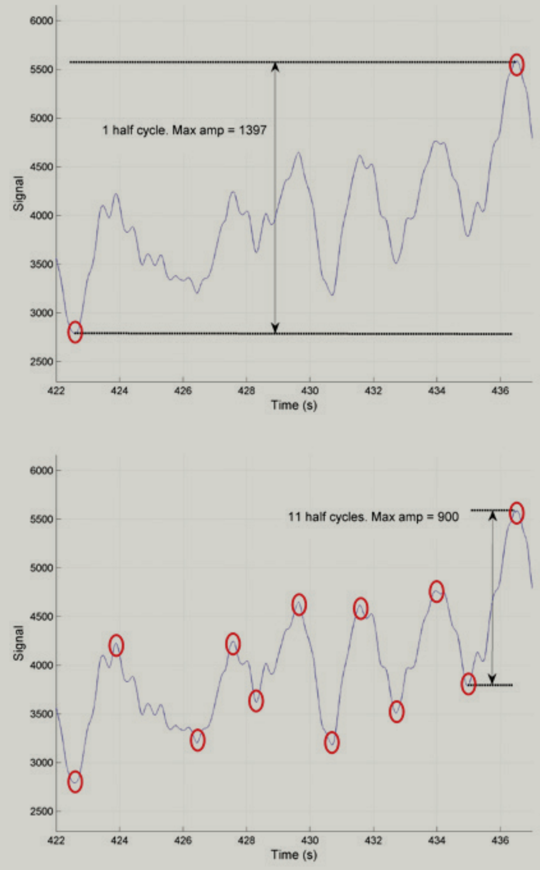

Figure 3. Different ways to define cycles affects the determined amplitudes

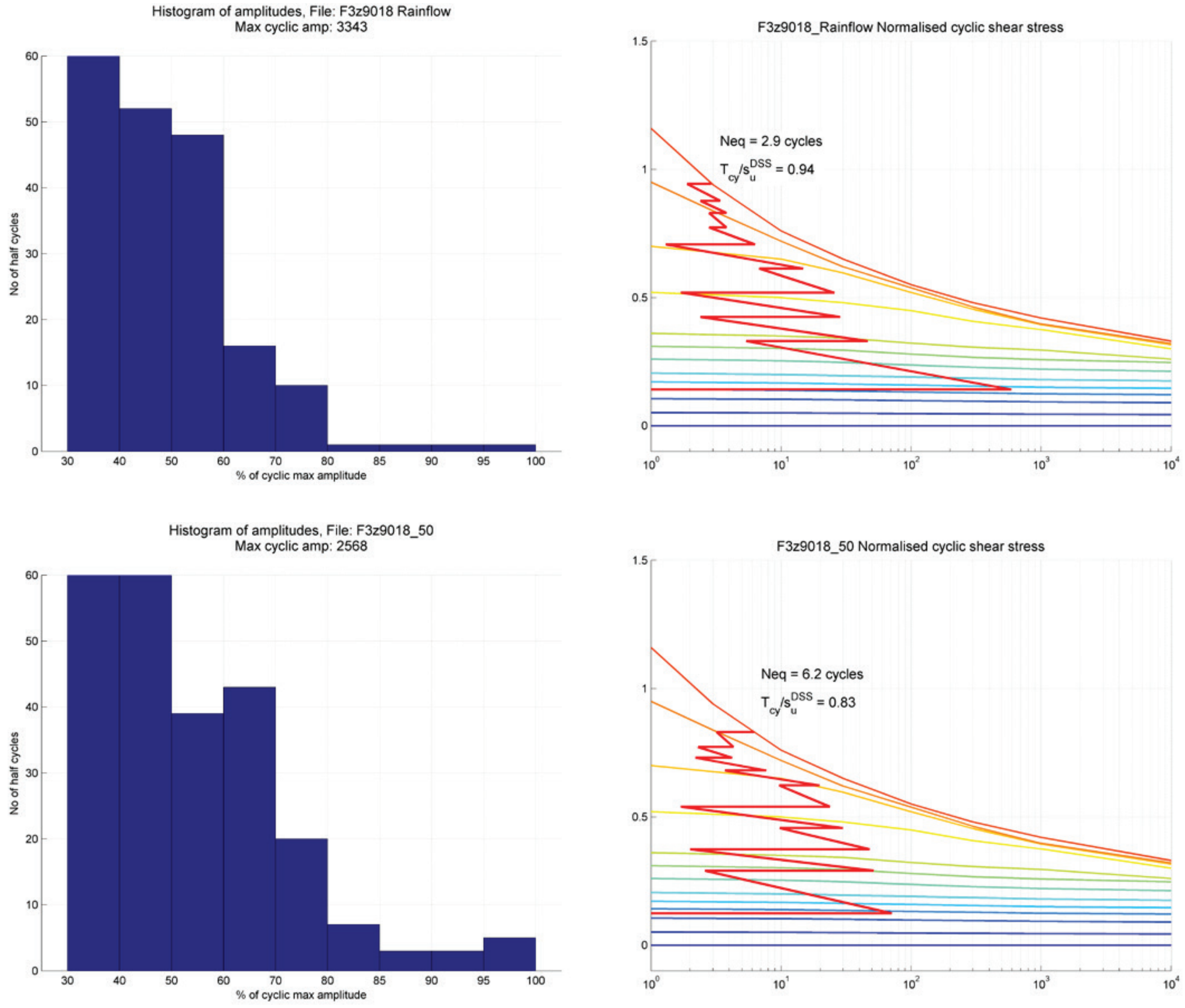

Figure 4. Comparison between the new method (above) and the rain flow method (below).

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Nonlinear Stiffness and Damping of Soils and Foundations

The periodic forces from wind, surface waves and swells acting on offshore installations, such as OWTs, lead to cyclic motion of the foundation soils. The damping characteristics of the soil results in energy dissipation, which in turn alters the cyclic response of the structure. Understanding damping is therefore important for the cost-effective design of structures. OWT foundation damping has not been widely studied, and consequently the influence of soil damping on OWT structural response is poorly understood. Research undertaken by NGI provides a step forward towards a better understanding and improved interpretation of stiffness and damping parameters for soils and foundations.

Intrinsic soil damping under combined permanent and cyclic load

OWT foundations are typically subject to combinations of cyclic and average loads from wind and waves. In addition, the different loads may have different frequencies and approach from different directions. Hysteretic soil damping enters only through the cyclic part of the stress-strain curve during a load cycle, but often an average load is also present, leading to strain accumulation. Figure 1 shows a typical cyclic stress-strain curve, as well as an example laboratory measurement including both cyclic and average stresses. This strategic R&D program has shown that the measured hysteretic soil damping is influenced by the accumulated strain, and that this must be properly accounted for to interpret the soil damping correctly in OWT foundation design.

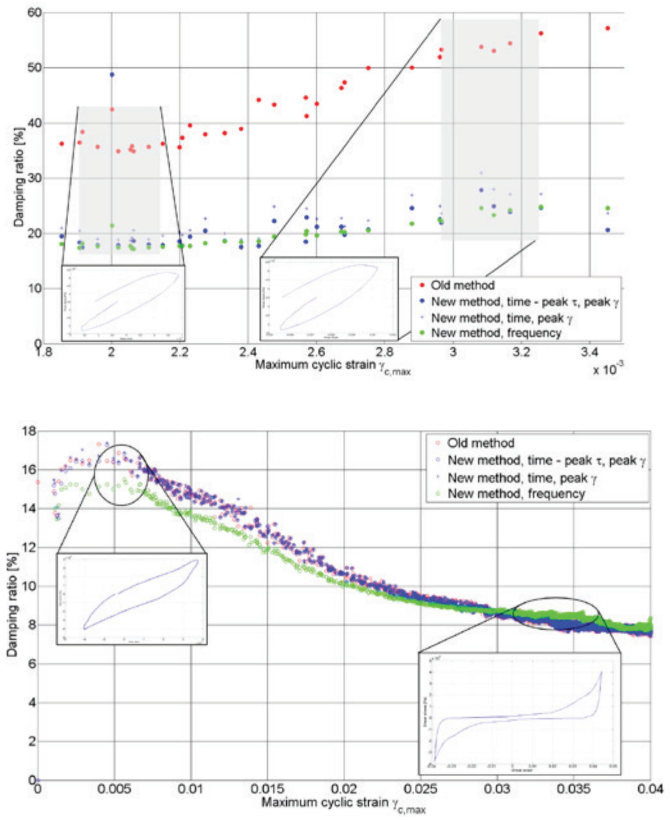

Figure 2. Upper panel, damping ratios and examples of cyclic curves for a clay sample. Lower panel, damping ratios and examples of cyclic curves for a sand sample. The insets show examples of single load cycles at a given strain level.

Figure compilation:

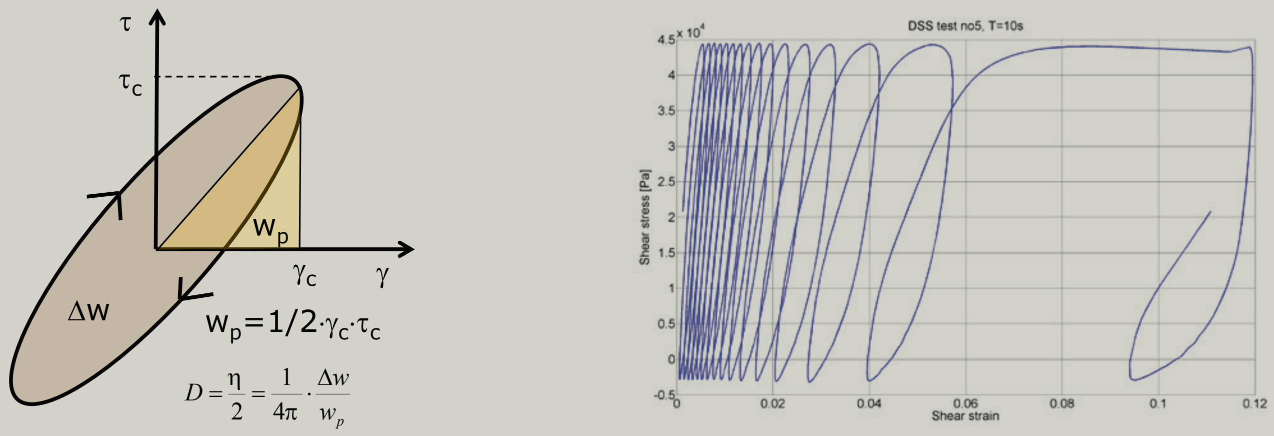

Figure 1. Left panel, simplified sketch of the relation between cyclic stress and cyclic strain for pure cyclic loading. The damping factor D is based on the area of the stress strain curve (external work) over the total potential energy. Right panel, real laboratory measurement data combining permanent and cyclic loads.

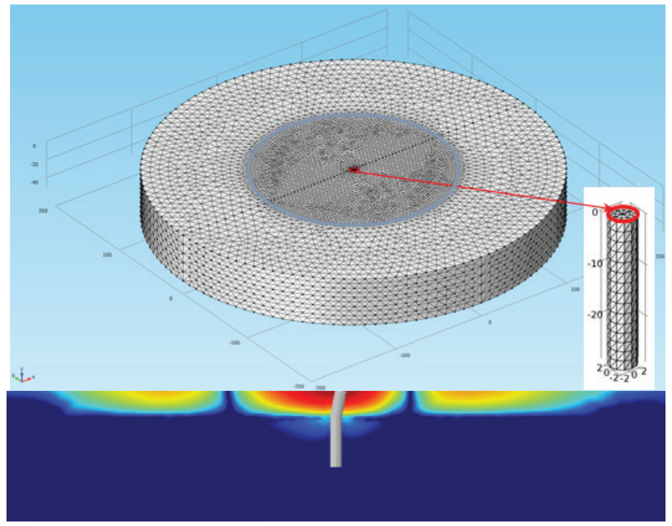

Figure 3. 3D model for evaluating dynamic response of foundation

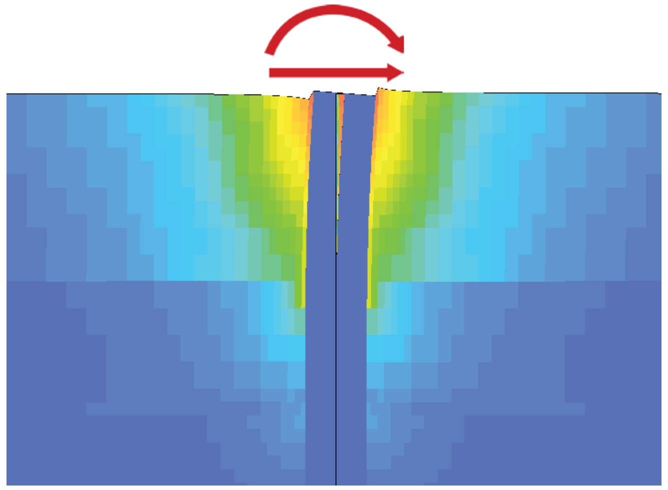

Figure 4. Rotation of monopile foundation with nonlinear soil behavior

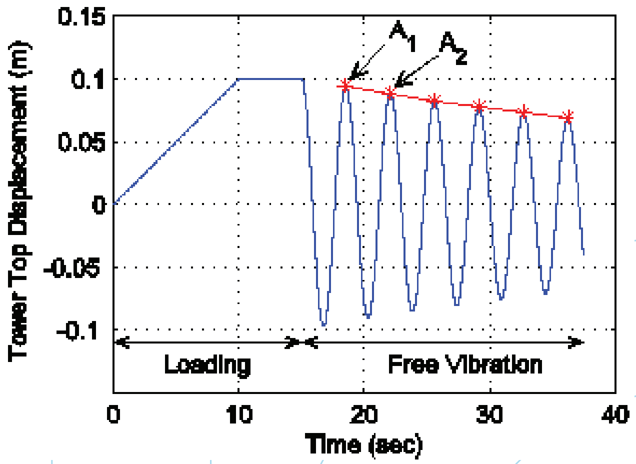

Figure 5. Offshore wind turbine tower free vibration numerical simulation.

A new method for deriving soil damping from the laboratory

A new method for quantifying soil damping from laboratory tests has been developed. Analyses of laboratory data have shown that the interpreted hysteretic soil damping has historically been overestimated for large accumulated strains. This is visualized in Figure 2, where damping as a function of cyclic strain level are compared for the new and old interpretation methods. The overestimation occurs when the stress strain loops are open due to strain accumulation, as illustrated for the clay sample. Figure 2 further demonstrates the damping behaviour for different soil types e.g. sand and clay. Whereas damping increases with the maximum cyclic strain for both clay and sand up to a certain strain level, an opposite trend is found at larger strains for sand. The shape of the stress-strain loop largely determines this behaviour.

Effect of the foundation nonlinearity on monopile Offshore Wind Turbines

OWTs are lightly damped structures, often with fatigue governing the design. Therefore, a thorough understanding of different damping sources, such as aerodynamic, hydrodynamic, structural, and foundation is essential for a cost effective design. Foundation damping is recently attaining more interest from the OWT industry. Foundation stiffness and damping depends not only on the soil properties but also foundation geometry, load intensity and frequency. As the damping is load dependent, the problem becomes non-linear and must be evaluated using realistic soil models. Examples of simulated cyclic motion of a monopile foundation, incorporating damping, are shown in Figures 3 and 4. The global damping of the entire OWT structure calculated from the simulations for a rotor stop scenario (see figure 5) is found to be comparable to those obtained from field measurements. Foundation damping gives an important contribution to the global system damping in addition to e.g. tower oscillation dampers. Radial spreading of stress waves in the soil does not contribute much to the global dynamic response of the first mode of OWTs. However, intrinsic soil damping as well as the effect of added mass do affect the overall response, which may be utlized in OWT design.

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UDCAM and PDCAM:

Soil models accounting for cyclic degradation

Offshore structures are subjected to combined static and cyclic loading due to the weight of the structure, wind, current and waves. The effect of cyclic degradation in the soil during these load conditions may be significant and therefore needs to be properly taken in to consideration.

How do we account for cyclic degradation?

We analyse the behavior of the soil under cyclic loading based on non-linear stress-strain relationships from cyclic contour diagrams. These contour diagrams are established from laboratory tests, and they contain information about the reduced strength, the increased cyclic strain amplitudes and increased permanent strains as function of number of cycles at different cyclic and average shear stress levels. Figure 1 shows an example of a cyclic contour diagram.

In order to calculate the cyclic degradation of the soil, the real cyclic load history is transformed into an idealised loading composition, where the design storm is divided into parcels of constant cyclic load amplitudes. An equivalent number of cycles, N_{eq}, is used as a memory of the cyclic effect. A high N_{eq} implies a high cyclic degradation of the soil, while $N_{eq} = 1$ means no cyclic degradation. Figure 4 shows the calculated distribution of the equivalent number of cycles, N_{eq}, at the end of an applied cyclic load history.

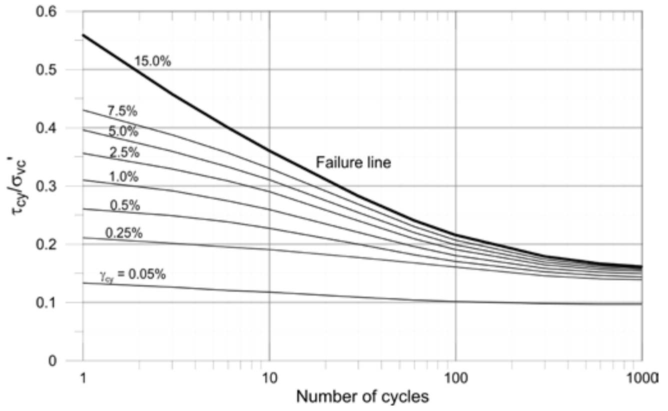

Figure 1. Example of a cyclic contour diagram. The strength, defined by the failure line, decreases significantly with the number of cycles.

This procedure has been implemented into the finite element code PLAXIS as the UnDrained Cyclic Accumulation Model (UDCAM) and the Partially Drained Accumulation Model (PDCAM). These models allow us to apply the advantages of the FEM in combination with our well-proven calculation procedures. We can then calculate the cyclic degradation of the soil in any point of the soil and model the capacity and displacements of any foundation subjected to cyclic loading.

What is cyclic degradation?

Cyclic degradation is the reduction in strength and stiffness of the soil due to the generation of pore pressures under undrained and partly drained conditions and destructuration during cyclic loading. The generation of pore pressure results in reduced effective stresses in the soil and the development of permanent strains.

Figure 2 shows load-displacement curves of a model test with monotonic and cyclic loading on a gravity platform. The figure shows the reduced capacity during cyclic loading compared to monotonic loading, and the increase of the cyclic displacement amplitudes (or reduction in stiffness) and increased permanent displacement of the foundation with the number of applied load cycles.

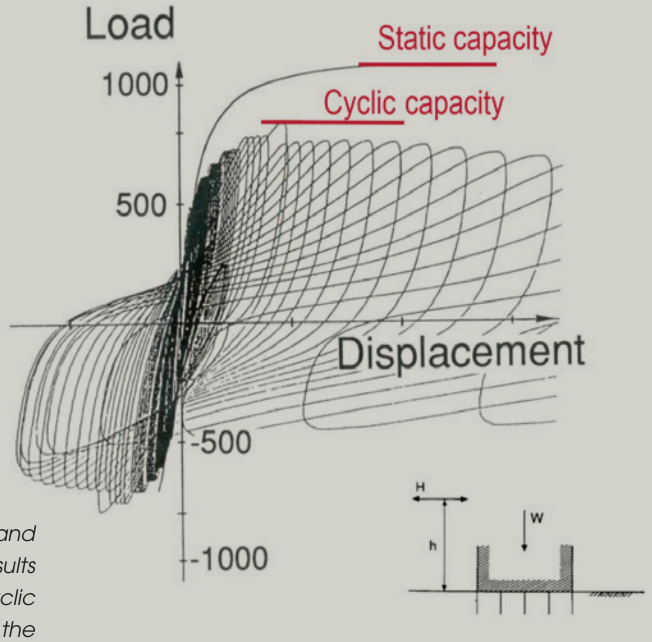

Figure 2. Results of a model test with monotonic and cyclic loading on a gravity platform on clay. The results show that the stiffness and strength are lower for cyclic loading and that the displacements increase with the number of cycles.

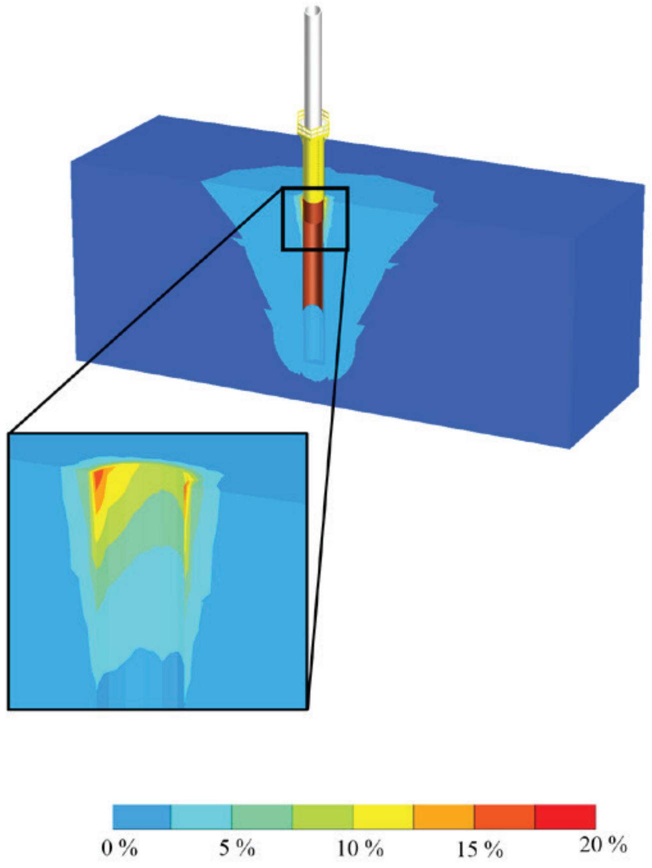

Figure 3. Contour plot of total cyclic shear strains at the end of the applied load history for a monopile foundation

Applications

UDCAM and PDCAM are applicable for general boundary value problems and have been proved especially suitable in the design of:

- Monopiles, where the cyclic degradation of the soil varies along the pile. This is important for wind turbines structures, since the permanent rotation of the structure can govern the design (figure 3).
- For jack-up structures on bucket foundations: it is important to assign the correct rotational soil stiffness to these structures, since the moment fixity at the bottom of the legs can govern structural utilisations in the legs (figure 4).

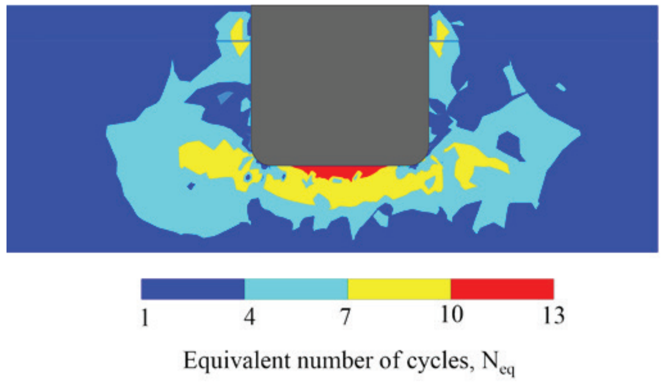

Figure 4. Distribution of the equivalent number of cycles, N_{eq}, at the end of an applied cyclic load history for a bucket foundation. Higher values of Neq imply higher cyclic degradation of the soil.

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Instrumentation and Monitoring Strategy

Background

Offshore Wind Turbine Structures are tall and slender, thus relatively sensitive installations in regards to structural loading and structural response. In particular when water depths and turbines are getting bigger the dynamic motions, settlements and possible tilting are particularly onerous for the generator and rotors. In addition, confirmation of foundation and structural performance are essential to verify design assumptions for large scale field developments. Finally, the instrumentation and monitoring data from current installations provides insight and a technical basis for optimizing future foundation and structural solutions.

Understanding monitoring needs

Presently the alternatives for offshore wind turbine foundations can be divided into three broad categories:

1. Monopiles /monopods (single pile/single suction anchor)
2. Jackets or tripods, with piles or suction caissons
3. Gravity base structures with skirts

Objectives

The main objectives of this research component were as follows:

- Evaluate monitoring needs specific for the wind energy industry, related to type of installation. Understanding the monitoring needs is the basis for the monitoring strategy
- Review specific technologies and instruments relevant for the monitoring needs to identify suitable system solutions to implement the strategy
- Consolidate experience from a related industry (subsea oil and gas installations) to develop guidelines for the practical design, procurement and installation of appropriate monitoring systems.

These foundation solutions have many similar monitoring/instrumentation needs, as well as specific monitoring needs for piled foundations and caisson foundations:

For all types of foundations:

- Wind
- Wave height
- Tilt of tower
- Scour and currents (if the seabed is prone for sediment transport)
- Cyclic pore pressure along foundation elements (pile or caisson)
- Strain/fatigue in critical structural members
- Dynamic motion of the structure / tower at various levels

Driven pile foundations
(monopiles or jackets with three or more piles):

- Axial strain along the pile (P-Y behaviour)
- Lateral earth pressure along the pile (difficult)
- Internal corrosion transition piece-pile top
- Deformations/strain/integrity of grouted connections and transition pieces

Caisson foundations
(monopods or tripod/quadropod jackets):

- Strain in connections between tower/ jacket structural elements and the caisson
- Dynamic motion (rotation/linear) of the foundation
- Load distribution, vertical earth pressure along the base of the caisson (if not grouted)
- Settlement (shake down)

Technology application example: pore pressure measurement in caissons

Piezometers suitable for submerged installation generally consist of heavy duty filters at depth, communicating via piping to a measurement point positioned above the caisson (often on top of it). For skirted foundations it is usually the pore pressure at either sides of the skirt tip (0.5-1m from the tip) and the caisson pressure at the base which are of primary interest for monitoring (both direct response to transient overturning loads and possible cyclic pore pressure accumulation).

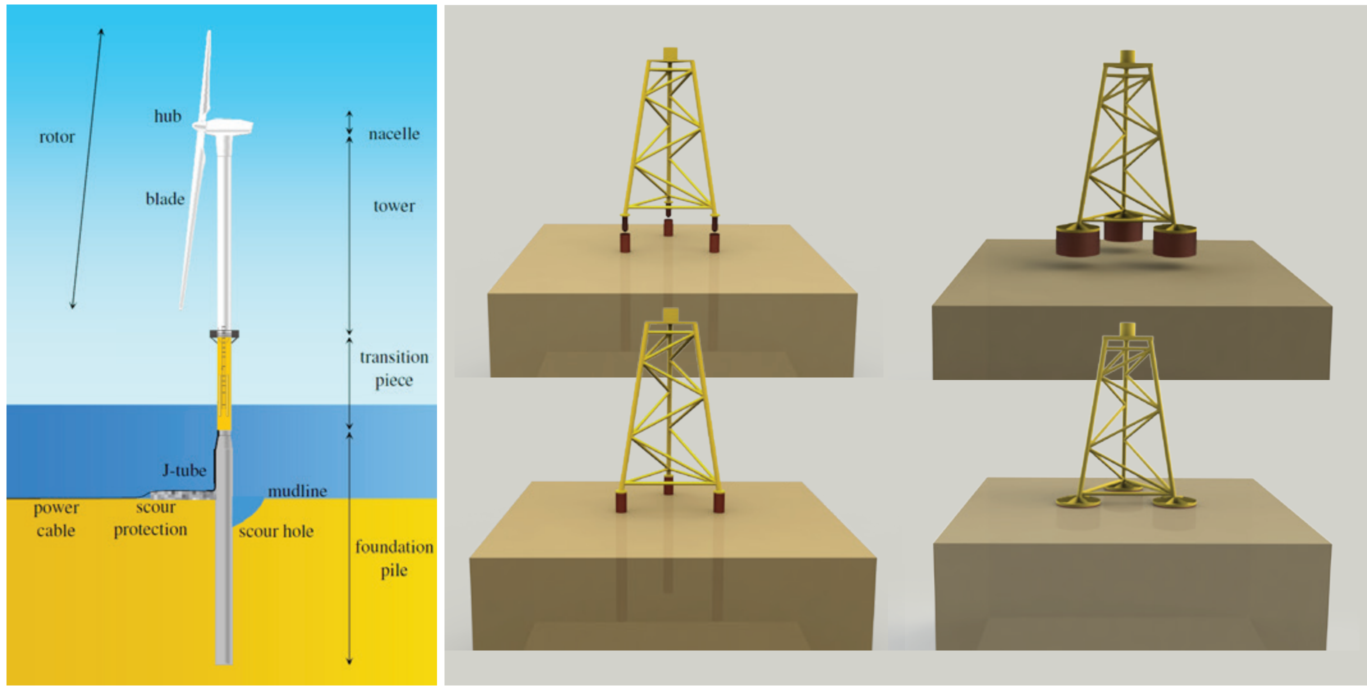

Figure 1. Monopile foundation (left) and tripod jackets with pre-driven piles or suction caissons (right)

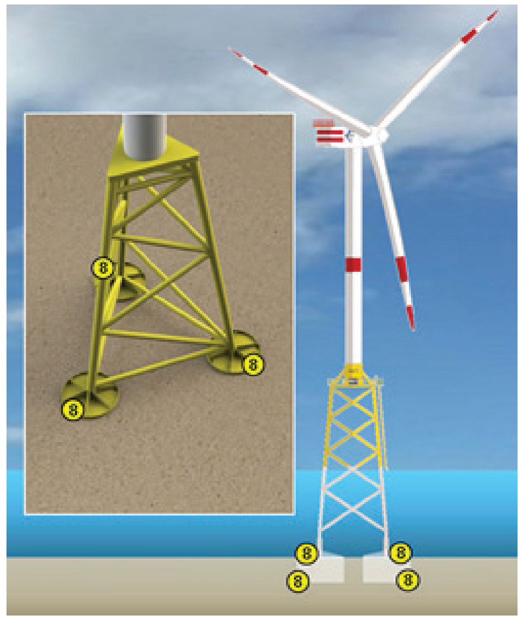

Figure 2. Caisson piezometers (8) on a tripod jacket with caisson foundations

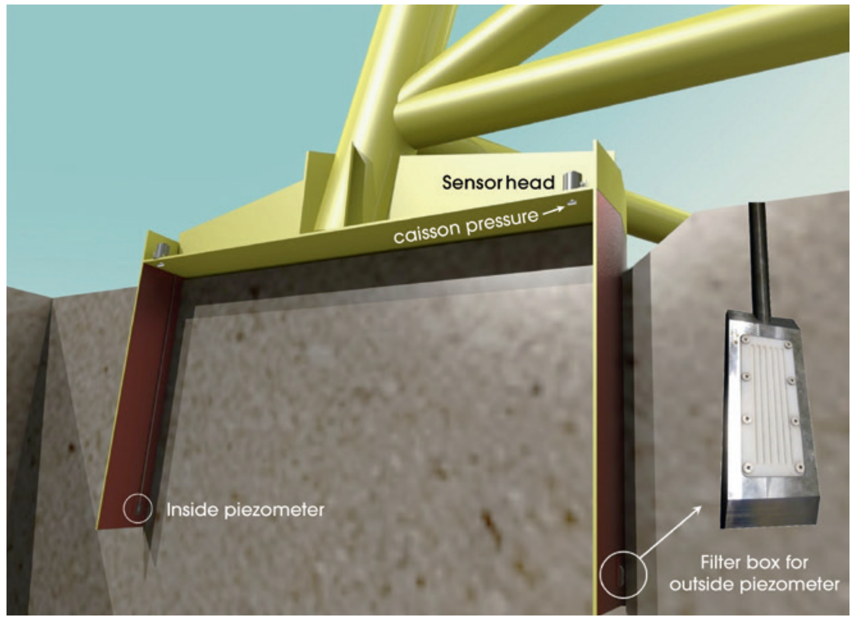

Figure 3. Position of piezometer filters on the caisson and routing of hydraulic lines to the sensor heads

The hydraulic piping from the piezometer filters are routed to a sensor head containing differential pressure sensors and other electronics. The sensor head can be hooked up in advance or after driving (piles). The termination can be equipped with a solenoid operated bypass valve (opens the piezometer line to sea) allowing for de-airing of the line and zero point check of the differential pressure sensor. By means of using differential pressure sensors and hydraulic lines saturated with seawater, the pore pressure is directly recorded and compensated for tidal and atmospheric pressure variations. Multiple piezometers and other sensors such as accelerometers can be integrated in the sensor head optimizing the configuration of the monitoring system.

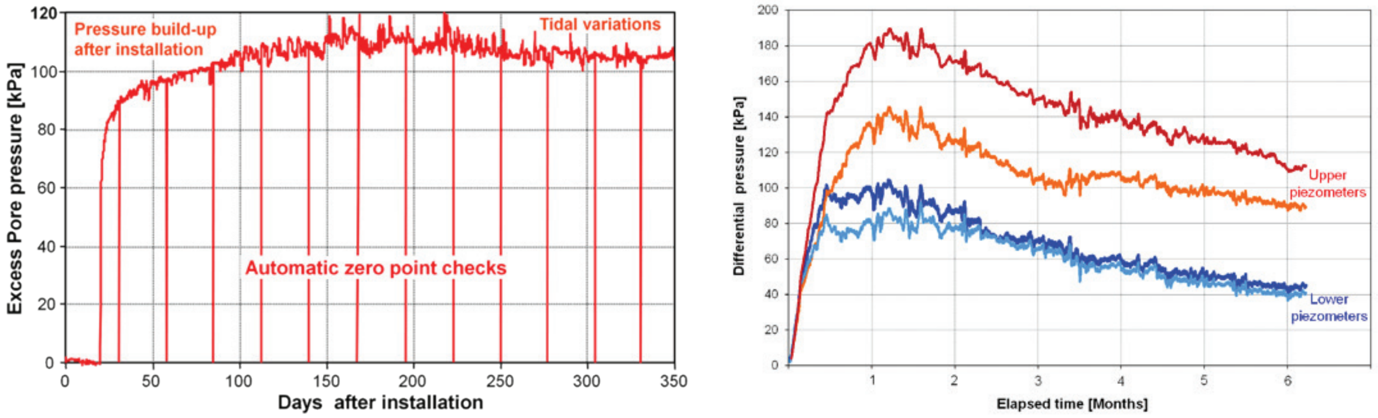

Figure 4. Left: Data record from Ormen Lange down hole piezometer slope stability assessment with the sensor head at the seabed. The differential pressure sensor was equipped with solenoid operated bypass valve for automatic zero point checks and de-airing. Right: Data example from Femern large scale tests pile piezometers showing pore pressure dissipation after driving.

Considerations for the selection of sensors

Some basic guidelines for sensor selection include:

- Parameter to be measured: Determine the best method to obtain the required parameter(s) including how to get the desired accuracy and resolution.
- Measuring range, precision and accuracy required. Cost is a function of the specifications - choose the specifications appropriate for the design and overall monitoring performance and not simply the very best sensor on the market (the sensor may not be the limiting factor).
- Priority: Which priority do you give to this particular measurement? This may govern the type of equipment you choose with respect to price and redundancy.
- Duration: For how long shall the measurement program last? Type of equipment, choice of materials, etc. will depend on this. Bear in mind, however, that a successful monitoring program which gives interesting data is often extended – be prepared for this.
- Environmental: The environmental conditions must be taken into account when choosing materials, ruggedness of enclosures, barrier philosophy, physical mounting points and similar mechanical design properties.
- Signal type: Which signal type (frequency, voltage, current, digital, optical etc.) is best suited for this particular application? Noise and cable lengths, will this system interface with other systems, and are there existing data architecture/interfaces which have to be complied with?
- Sensor materials: Requirements regarding corrosion, pressure, size, electrical effects etc.
- Sensor manufacturer: Previous experience with supplier.
- Modifications and special calibrations: Are the intended sensors / instruments to be used under conditions outside of normal specifications? Contact the manufacturer or implement a dedicated test/verification program to establish suitability of the technology.

Summary experience: The '10 commandments' of subsea instrumentation

1. **Provide for adequate planning and concept design development**
2. **Design for harsh conditions and rough handling**
3. **Plan for contingency, redundancy and back-up**
4. **Maintain barriers and control corrosion**
5. **Perform functional testing**
6. **Simplify the installation approach if possible**
7. **Work closely with the offshore contractor**
8. **Meet the delivery schedule**
9. **Make the data available**
10. **Mind the devil (he is in the details)**

Dissemination of results

The results of this study are introduced as part of the 'Best Practice' for instrumentation and monitoring system design at NGI.

Our work is also made available to commercial projects providing design advice and monitoring solutions for offshore wind energy development.

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