REPORT

BSEE Offshore Wind Recommendations

GUIDELINES FOR STRUCTURAL HEALTH MONITORING FOR OFFSHORE WIND TURBINE TOWERS & FOUNDATIONS

DOC.NO. 20160190 16-1036
REV.NO. 3 / 2017-06-15

NGI Inc.
WWW.NGI.NO/HOUSTON

Project

Project title:	20160190 BSEE Offshore Wind Recommendations
Document title:	Guidelines for Structural Health Monitoring for Offshore Wind Turbine Towers & Foundations
Document no.:	16-1036
Date:	2017-06-09
Revision no. /rev. date:	3 / 2017-06-15

Client

Client:	BSEE Environmental Enforcement Division
Client contact person:	Altan Aydin
Contract reference:	Contract No. E16PC00006, Requisition 0040246879

for NGI

Project manager:	Per Magnus Sparrevik
Prepared by:	Per Magnus Sparrevik
Reviewed by:	Amir Rahim

Abstract

The value in a Structural Health Monitoring (SHM) program is determined by the use and the benefits that can be obtained by the data. The monitoring system is only a tool and an investment to gather the data. The instrumentation plan should be based on the SHM data that is required for verification and investigation of uncertainties in design, as well as provide input for possible future design optimization. Other monitoring objectives may be early warning of progressing degradation that allows for condition based maintenance and status evaluation for possible life time extension or changed operational conditions (for example turbine modifications).

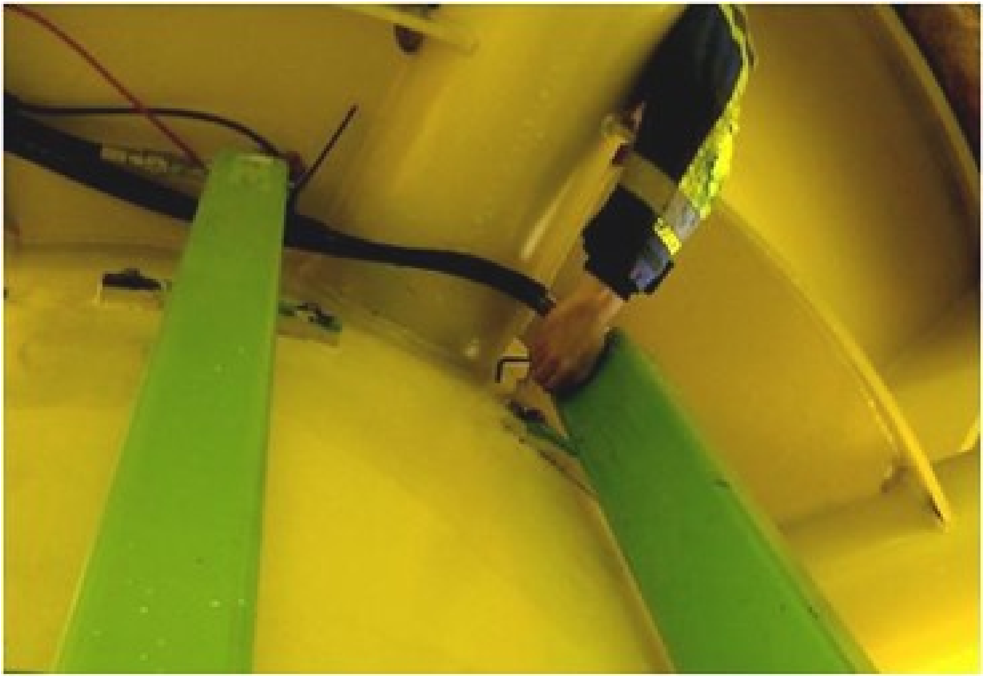
Reduced total costs and added value to the data can be achieved by applying an integrated SHM system approach instead of installing independent and specialized monitoring systems (geotechnical, structural, corrosion, met ocean, etc.). It is important that the set-up of instruments is configured such that all linked/correlated parameters are recorded.

The stakeholders must define WHY instrumentation is needed and HOW the collected data can be used. These aspects are discussed in the report which describes the purpose of integrated monitoring and specific monitoring aspects for different types of Offshore Wind Turbine (OWT) foundations. The following foundation alternatives are included in the study: mono piles, mono buckets, gravity base, jacket/tripod with piles or buckets and moored floaters.

Offshore SHM monitoring can be challenging both with respect to rough offshore conditions and costs. Experience is important when selecting the appropriate monitoring solutions and hardware. Recommendations and examples of monitoring set up for the defined parameters of interest to monitor are thoroughly described in the report. Finally, practical advices for execution of an offshore SHM project are given in terms of planning and design as well as practical installation work and how to make the instrumentation surviving as long as possible in a rough offshore environment.

Rough environmental conditions can be expected at many wind farm locations

Planning and configuration of the instrumentation set-up should be done at an early stage and incorporated into the structural design for simplified and cost effective installation during fabrication of the structure. Offshore retrofit is difficult and costly. If mobile instrumentation is relevant, preparations should be done at the yard in order to simplify offshore work.



Accessibility for installation of instrument is usually better at the yard than in the field

Contents

Review and reference page

1 Introduction

Long term Structural Health Monitoring (SHM) is an important tool for reducing risks and costs in development and management of offshore wind farms. An Offshore Wind Turbine (OWT) may not be a gigantic structure. However, systematic flaws or problems can be very expensive as a wind farm normally contains a large amount of OWT's, see Figure 1-1. Consequently, potential savings can be big if the design can be improved and optimized.

Figure 1-1 Presently the London Array wind farm located in the North Sea outside Kent is the largest in Europe with 175 OWT's producing 630 MW of power

Three main objectives are relevant for SHM:

- Design improvement (verification of novel design or optimization of existing designs)
- Early warning of degradation and condition based maintenance
- Possible extension of operational life span or changed design conditions

A well implemented an integrated monitoring approach can continuously track the "state of health" of a foundation and identify in a very early stage the onset of potential structural problems. This allows for early, less costly repairs and optimal preparation of the offshore operations, as well as follow-up of the repair measures themselves (rectification effect). As such, a significant risk reduction can be achieved over 20 to 25 operational years, the foreseen life span of a wind farm.

1.1 Definitions

An Offshore Wind Turbine (OWT) includes the complete structure with Rotor and Nacelle Assembly (RNA), Tower, Substructure and seabed foundation, see Figure 1-2. The "Foundation" includes the sub-structure below the base of the tower (Transition Piece, Jacket/Tripod or Gravity base) and the seabed foundation (piles, buckets or raft foundation).

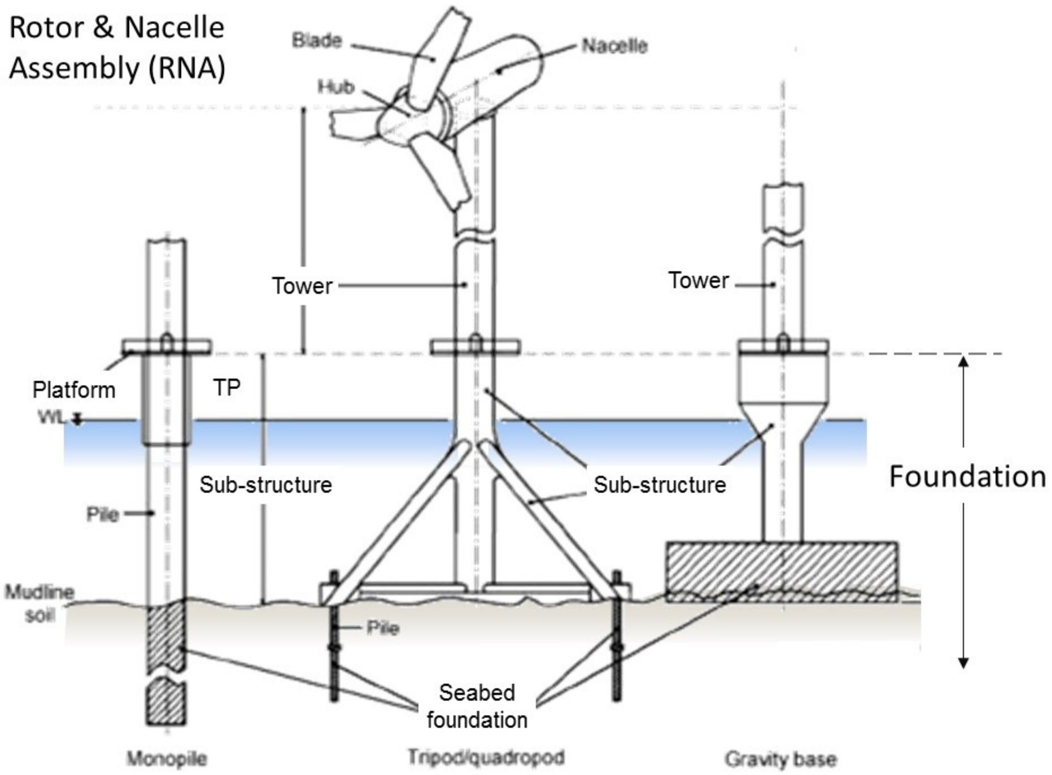


Figure 1-2 Parts of an Offshore Wind Turbine (OWT)

2 Overview of areas relevant to monitor

A proper remote monitoring scheme begins with identifying those components and/or phenomena that needs to be monitored for a certain structure at certain conditions. Other criterions for decision making about investment in an SHM system are the risks related to potential issues with structural components, the amount of information that can be acquired by instrumentation and the benefits from understanding the monitored structural response, for example in conjunction with design verification.

2.1 Types of OWT foundations

Presently the main alternatives for offshore wind turbine foundations can be divided into four categories:

1. Mono piles (or monopods if suction bucket is used) which normally used down to water depths of 30-40m
2. Gravity base structures with skirts, normally used from 25-60m
3. Jackets or tripods, piled, pre-piled or with suction buckets, normally used from 25-60m
4. Floating foundations, normally relevant from 50m and deeper

These four foundation categories are illustrated in Figure 2-1.

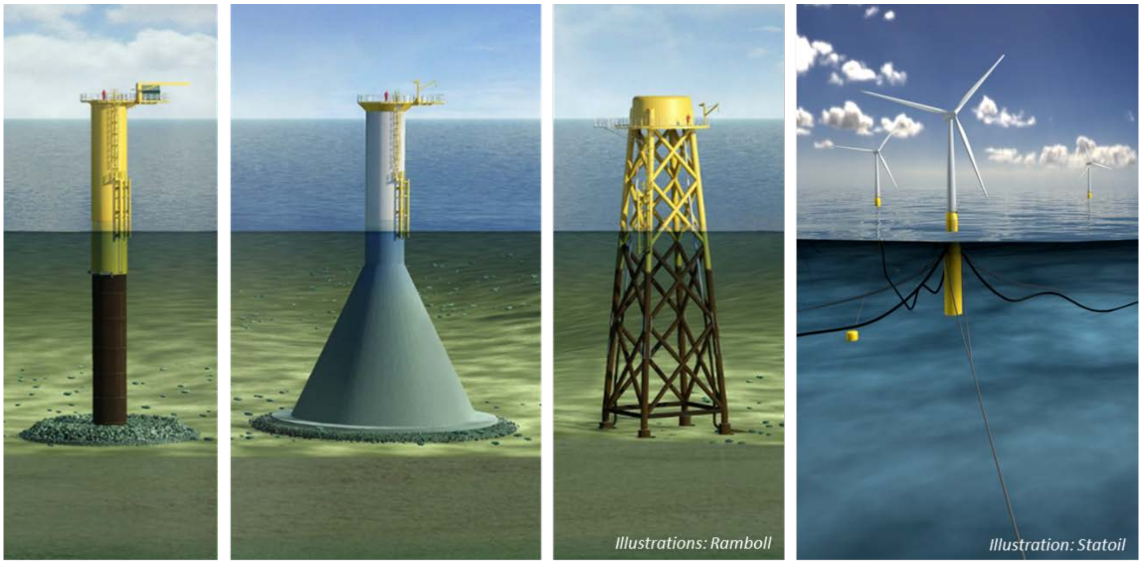


Figure 2-1 Main alternatives for Offshore Wind Turbine (OWT) foundations

Specific soil or environmental conditions, certain design issues and critical structural aspects may apply for the different types of foundations. Follow up of specific parameters by long term monitoring in the field can be beneficial (or even required). Thus, the optimal monitoring configuration will vary from site to site. The tower is more or less similar for all types of foundation. However, the response of the combined tower and foundation system may be different. The following areas and issues relevant to monitor must be considered as general recommendations with the specific relevance evaluated from case to case.

2.2 Corrosion

Corrosion is a major issue with respect to the operation life of an OWT foundation. The following phenomena are of interest, both for immediate follow-up and with regard to their evolution in time. These apply for more or less all steel structures, but especially mono piles (see also section 4.2.5):

- Degradation of organic coatings at the exterior part of the foundation, such as splash zone and higher parts, as this represents the onset of corrosion damage and the associated material loss.
- The degree of protection offered by the Cathodic Protection (CP) system in place at the foundation, as overprotection may result in hydrogen embrittlement, thus structural issues, while insufficient protection may lead to unforeseen corrosion activity.
- The occurrence of specific, mainly localized forms of corrosion such as pitting, water-level corrosion, microbiological corrosion (MIC), etc., as they give rise to stress concentrations or other structural problems. Better solutions to monitor mudline MIC on piles are in demand as inspection is difficult.
- Composition of isolated bodies from water as this has a significant influence on the type of corrosion damage that can occur and also on how to deal with it.

2.3 Structural integrity and response

Structural integrity is important for most foundations, the following parameters may be of key interest to monitor:

- Natural resonant frequencies of the structure, mainly regarding their relation to the frequencies of ambient excitations such as wind, waves, etc.
- Damping characteristics in the different vibrational modes of the structure, to verify with design assumptions. Especially important for mono piles
- Mode shapes and frequencies of the tower + foundation system
- The strain levels at those locations experiencing the highest stress concentrations (onset of permanent deformation). Design dependent.
- Strain (static as well as dynamic) in bolts in new foundation types or flanges subjected to potential damage during installation.
- RMS amplitude of vibrations, also connected to the vibrational modes
- Fatigue cycles on vulnerable locations, mainly welds.
- Stress field in the foundation and/ or transition pieces, including the resulting deformations and the evolution thereof.
- All parameters above are linked with directions of the loads (wind and waves) which should be monitored as well and location of secondary steel structures.
- For floating structures monitoring of the mooring loads and dynamic motion of the floater are important in order to understand the response to waves and wind.

Further structural issues deserving special attention:

- The integrity of the grout in grouted connections, transition piece connection for mono pile foundations and pile connection for pre-piled jacket foundations.
- Relative displacement in these connections
- Inclination of the tower.

2.4 Geotechnical and Soil-Structure Interaction (SSI)

- Scour around the foundation and the evolution thereof.
- Seabed stiffness, especially for large mono piles in deeper waters
- For bucket or gravity based foundations the pore pressure response to loading is important as well as the effective stresses

2.5 Correlated parameters

For a correct, unambiguous interpretation of the obtained data it is also essential to record metocean data such as wave height, tide, current, wind speed and direction as well as turbine data such as, RPM, pitch and yaw angle. For corrosion monitoring the environmental parameters inside and outside the foundation are also important to monitor (oxygen levels: gas phase and dissolved in entrapped water, pH, electric potentials, temperature, water levels. etc.). For monitoring of dynamic response and tracking of Eigen frequencies, scour monitoring may be relevant (or vice versa) as scour will affect the stiffness of mono pile foundations. All linked parameters must be thoroughly considered when setting up a monitoring program.

2.6 Installation Baseline

Finally, but not the least, monitored data during installation of the foundation in the field provides a very important baseline for interpretation of subsequently recorded SHM data. Installation data may be essential for calibration/offsetting of permanent SHM sensors and better understanding of the long term behavior of the structure recorded by the SHM system. The SHM recordings in the field should start as soon as possible. If possible, the SHM system or parts of it should be in operation also during installation of the structure. The initial structural response recordings under multiple conditions are very important for datum readings and comparison with future measurements in order to ascertain the possibility or nature (progress) of damage and/or potential life extension.

3 Integrated Monitoring

For each of the phenomena described, a dedicated monitoring setup containing a specific set of sensors can be designed and installed. However, an intelligent combination of sensors can result in an integrated follow-up of almost all these phenomena at once. Moreover, isolated monitoring setups next to each other cause loss of value in many other domains.

Examples include:

- The reduced ability for an efficient remote follow-up of the monitoring units themselves. Timing synchronization issues making it difficult to correlate the data recorded by different systems with each other.
- Overlap in recorded data, resulting in an enhanced consumption of bandwidth on the fiber optic link and storage space.
- Multiple contracts and points of contacts, resulting in an administrative overload.
- Difficulties with scaling, e.g. when expanding an existing setup using additional sensors.
- Inefficient management of backup power and backup storage due to the overlap of remote ‘logic units’.

Turbine and meteorological data is normally included as standard output included in the Supervisory Control and Data Acquisition (SCADA) system as part of the turbine supply. The other parameters should be monitored by an integrated SHM system. Thus, monitoring the foundation and the turbine are normally performed with two different systems, however with the ability to share data. Data integration can be done offshore using a common data link to shore or transmitted separately if sufficient transmission capacity is available (for example with fiber optic communication cables)

3.1 General considerations for an integrated SHM system

In order to obtain real and advanced information on the state of the offshore structures, the acquired data needs to be of sufficiently high quality (reliable, representative, precision, resolution, sampling rate, noise levels etc.). To obtain high quality data to the end user, multiple aspects (described in sections 3.1.1 to 3.1.8) must be taken into account in the specification and supply of an integrated SHM system.

3.1.1 Instrumentation plan

The instrumentation plan includes selecting the required sensors and where to locate them. This needs to be done in close collaboration with the designer and/or developer as decisions taken in the design process influence the decision on where to monitor and how frequently.

Next to the sensor selection, the instrumentation plan is governing for the architecture of the monitoring units themselves: what kind of data transfer to use, local backup power and backup storage, backup communication, remote management, timing of acquisition, etc.

3.1.2 Sensors

Next step is to select the exact sensors to use. Next to their functionality, the choice is guided by sampling interval, accuracy required, environmental conditions the sensors need to operate in, susceptibility for EM noise, expected operational life, ease of replacement, ease of maintenance, stability, etc.

3.1.3 Sensor interface

The choice of the logic unit is guided by many of the choices made during the Design and Sensor phase. The type of sensors (digital, analog 0-10V or 4-20mA), the number of sensors, their location, the accuracy required, all guide the blueprint of the logic unit. Moreover, this needs to be in line with the requirements put forward regarding data management, backup power and storage as well as remote management.

3.1.4 Data logging

This covers logging of all data acquired offshore. Elements of relevance are backup storage in case communication lines are disturbed, as well as initial treatments such as filtering, down sampling and matching with predefined alarm levels.

3.1.5 Data transfer

All data is prepared for transfer to the onshore data storage (the next 2 elements in the chain). The main data transfer is depending on the communication lines available. Usually fiber optic cable links are available with less restrictions on the available bandwidth.

3.1.6 Data storage

The data storage is the place where data obtained at multiple foundations in the wind farm will be stored for the long term. As a back-up, limited local data storage is recommended to be available on board the OWT foundation. Long term storage is essential as some phenomena will only occur after long (multiple years) periods of time. With respect to storage, emphasis lies on preventing data loss, as well as on availability. This is coupled with the next phase

3.1.7 Reporting

In reporting, the acquired data is used to generate reports for use by the operator and appointed parties. Reports can be monthly overviews of the situation, as well as more profound analysis of cross-correlations. They cover both the evolution of one specific structure and comparison between different structures. Long-term trends are reported, but also relations with regards to predefined threshold values. If issues are detected, advanced analysis based on long datasets can be required. This will involve sourcing long datasets from the data storage. Another type of report is relevant if lifetime extension becomes relevant, based on experience from the O&G industry long term SHM records has proven to be important documentation for continued operation beyond the life span initially anticipated in design.

An important part of the reporting is the evaluation of the data quality, this assessment should preferable be done by the instrumentation specialist and before more advanced structural analyses are done by other disciplines.

3.1.8 Alarms and Follow up

The alarms are the last link in the chain, and are to be generated in two physical locations: one is on the structure itself, when threshold values are exceeded. The other location is the onshore data storage, arising from a more profound analysis of acquired data. These structure-based issues are however not the only use of alarms. Issues regarding data acquisition, transfer and storage need to be brought to the attention as early as possible. This should however not be the concern of the operator, so these alarms are directed towards the provider/maintainer of the monitoring system such that the normal situation can be restored as fast as possible.

This follow-up of the monitoring process itself thus becomes an inherent part of the Observation and Measurement (O&M) process of the farm. In case of advanced monitoring, the resulting knowledge will be used to guide the O&M activities (planning and contents), and servicing the monitoring setups will be part of the O&M process itself. The amount of additional transfers needs to be limited however by implementing advanced remote management features and using almost maintenance-free sensors and monitoring hardware.

The approach proposed here is universal: foundation types, turbines and installation methods may become more and more uniform, but these are not the only factors contributing to the state-of-health of a foundation structure. Wind regimes (thus loads), temperatures, water movement, soil type and soil movements are more difficult to control, as they are inherently governed by nature. Also, variations in material properties, quality of construction and components play a relevant role. All factors result in an inherent variability that only can be determined by implementing an integrated, intelligent continuous monitoring system.

3.2 The value of integrated monitoring

Proper installation and commissioning of the sensors and monitoring setups are essential parts for obtaining the desired information from an advanced monitoring package. Therefore, dedicated training of the operator staff and a follow-up by continuous remote (onshore) assistance is vital.

Depending on foundation type, location and experience of the operator, the layout of the monitoring setup may differ. However, this should not result in additional costs as the same concept applies and our setups all are based on interchangeable building blocks. A final result of the approach offered is in maintaining state-of-the-art setups. The remote management schemes implemented to the setups have made it possible to continuously upgrade the setup from the shore. As such every setup located offshore can, at minimal cost, be made more intelligent during the 20 or 25 years of operational life, based on the knowledge gained during the long-term follow-up of the farm, as well as from advanced analysis performed on the data as well as experience in other farms.

An example of a customized monitoring set-up is given in Figure 3-1. In this case the primary objectives for the SHM system was to evaluate the in-place behavior of the novel bucket foundations and to monitor the strain and dynamic response of the tripod jacket structure in order to allow for further structural design optimization.

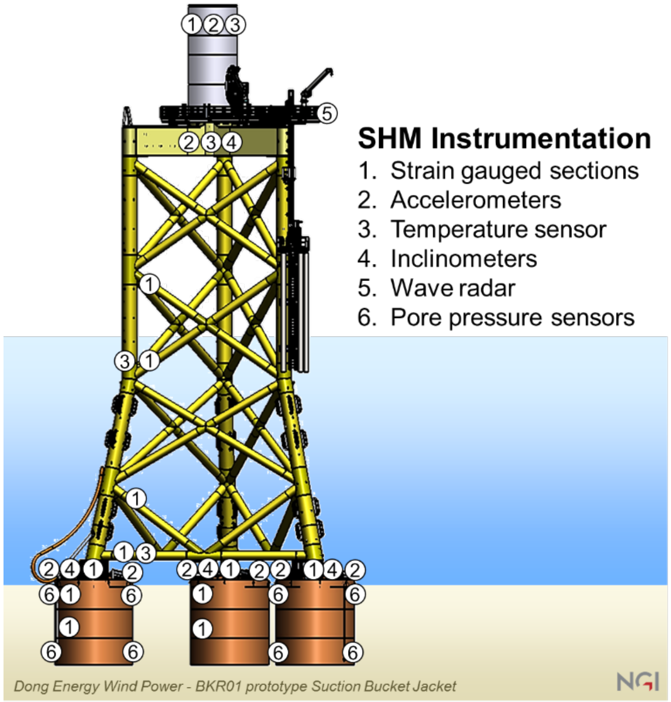


Figure 3-1
Example of integrated SHM system with 141 sensors implemented on Dong Energy Wind Power's prototype Suction Bucket Jacket BKR01 installed in 2014. (SHM system provider: NGI)

The integrated monitoring approach can allow for cost reductions in multiple ways as follows:

- As the sensors are monitored remotely, the amount of offshore inspection trips can be reduced. As inspections provide only data in discrete time points, the information content obtained is also limited, resulting in the need for additional trips for further interpretation. Continuous monitoring results in continuous data sets. Interpretation is much more straightforward and more trips offshore can be avoided
- In reality, a limited number of inspections will still be needed to complement the data obtained. Using the monitored data and knowledge of the setup, inspection trips will however be more targeted and better prepared and can be guided from the monitoring center to obtain the highest value possible.
- Due to integrated monitoring and trend analysis, deviations of the behavior from the predicted behavior will be detected in a very early stage. As multiple parameters are monitored an accurate image of origin and result can be assembled. This allows early, minor, thus relatively cheap interventions to be set up and stabilize the issue. The same monitoring setup will be used in the follow-up stage to assess the long-term performance and efficiency of the repair.
- An advanced monitoring setup will allow making the transition from planned maintenance to condition based maintenance. This will reduce the total cost of maintenance operations, although condition based maintenance is more relevant for the turbine compared to the foundation structure.
- As deviations from the normal or expected behavior are captured in a very early stage, chances are high that the situation can be restored to normal within a very short time frame. This results in a significant reduction of the risk associated to the foundation structures.
- The same risk reduction is also a benefit in the financing phase. More and more external, risk-averse sources of financing are sought in the offshore wind sector. As proper monitoring significantly lowers the uncertainty regarding the long-term structural integrity, this will be reflected in the premiums asked by external parties to invest in the farms.
- At a certain stage in the life of an offshore wind farm, the permitted period to operate the park will come to an end. At that point, the operator may choose to apply for an extension of the permit or for a new one, coupled with a repowering project. This process will be based on an extensive report on the state of the foundation. Imagine how much more straightforward this process can be based on 20 years of continuous data and the associated knowledge, compared to having to set up a dedicated inspection campaign offshore.
- Last but not least: savings related to future constructions. As the advanced monitoring leads to a profound knowledge of the in-operando behavior of the foundations, the origin of unexpected phenomena can be fully analyzed and subsequently remedied in future designs.

By mean of continuous monitoring, the risk related to the management of offshore foundation structures can be kept at a minimum for the foreseen life of 20 years and beyond. In the design stage, all measures are taken to ensure this lifetime is reached, but in practice the real state of health of the structures still comes with a degree of uncertainty. New concepts, assumptions regarding soil conditions and loads as well as unforeseen events all have an influence on how the structure or some of its key components degrade. This in turn influences the real state of health of the foundations. The only way of having a continuous records on the foundation's state of health together with its evolution in time is by equipping it with an appropriate multi-sensor monitoring solution that continuously collects essential data, but also translates these data into indicators quantifying the various aspects of the state of health of the structure.

The structural integrity monitoring serves as a tool to guide O&M operations. Additionally, the long-term monitored structural and operational data can aid in providing a lifetime extension or repowering (a part) of the farm.

3.3 Limitations and failures in a monitoring program

A lot of arguments for integrated monitoring have been listed, but there are also limitations and challenges to be considered. There are numerous examples of less successful SHM projects where, in spite of the ambitions, the observational method could not be used. Some of the reasons may be:

- Faults (quality) and poor workmanship
- **Ambiguous data is recorded**. Many times the reason for dubious data cannot be linked to direct faults (sensors, cables, calibration etc.). It is unfortunately quite common that the sensor/recording system works perfect but does not measure the parameter of interest or is influenced by external conditions affecting the recorded signal.
- **Unrealistic expectations**. In-place monitoring cannot be compared with controlled load/model testing. The loads are determined by Mother Nature and would rarely get close to ULS (Ultimate Limit State) conditions and certainly not failure. The recorded structural response will be significantly less compared to the design load response and scaling up this information to ULS conditions may not be correct. Some parameters such as soil stiffness are not linear and signal to noise ratio may be poor for small strain signals. Noise and other errors will also be up scaled. For small signals, it may be uncertain what phenomena are actuality measured. For example is it displacement of the foundation or only local flexing of the steel?
- **Missing links**. Recordings of all linked parameters are not included in the monitoring scheme, for example monitoring strain without any information about the loads does not make sense. **Integrated monitoring** thoughts and concept should be implemented.

How to avoid some of these shortcomings and failures are discussed in this document. Figure 3-2 shows examples of rare ULS conditions which most likely never will occur,

Figure 3-2 Do not expect ULS events to be captured in the SHM data

3.4 Reasonable extent of SHM monitoring

The reasonable extent obviously depends on specific aspects such as challenging environmental or geotechnical conditions, introduction of new technology or foundation concepts, optimized design etc.

It is costly and not realistic to instrument every foundation in a wind farm with integrated multi sensor SHM systems. Only spot checks and a few percent of the foundations can be fully instrumented. For limited types of instrumentation mobile sensor systems allows for periodic monitoring of several foundations by rotating the instrumentation between the OWT's in the wind farm. If new concepts and design are introduced, a demonstrator OWT foundation may be installed ahead of full implementation in a wind farm. Implementation of an integrated SHM system on the demonstrator is important in order to maximize the information which can be derived from the demonstrator project.

3.5 An extreme event on tape

The following example is a recording obtained from an integrated SHM system installed on an offshore Oil & Gas platform. Statoil's "Draupner" platform was the first jacket in the world with bucket foundations when installed in 1994 at 70 m water depth in the North Sea. As Draupner was a prototype, an extensive monitoring campaign was executed in order to verify the novel foundation design. At New Year's Day, half a year after installation, an extreme event was recorded by the instruments on the unmanned platform.

The weather was rough but not severe by North Sea standards when suddenly the down looking wave radar registered one single wave with a peak of almost 20m above mean sea level. The reading would probably have been dismissed as a noise spike in the readings if it was not for the fact that the event was traced by almost all SHM sensors on the platform, see Figure 3-3.

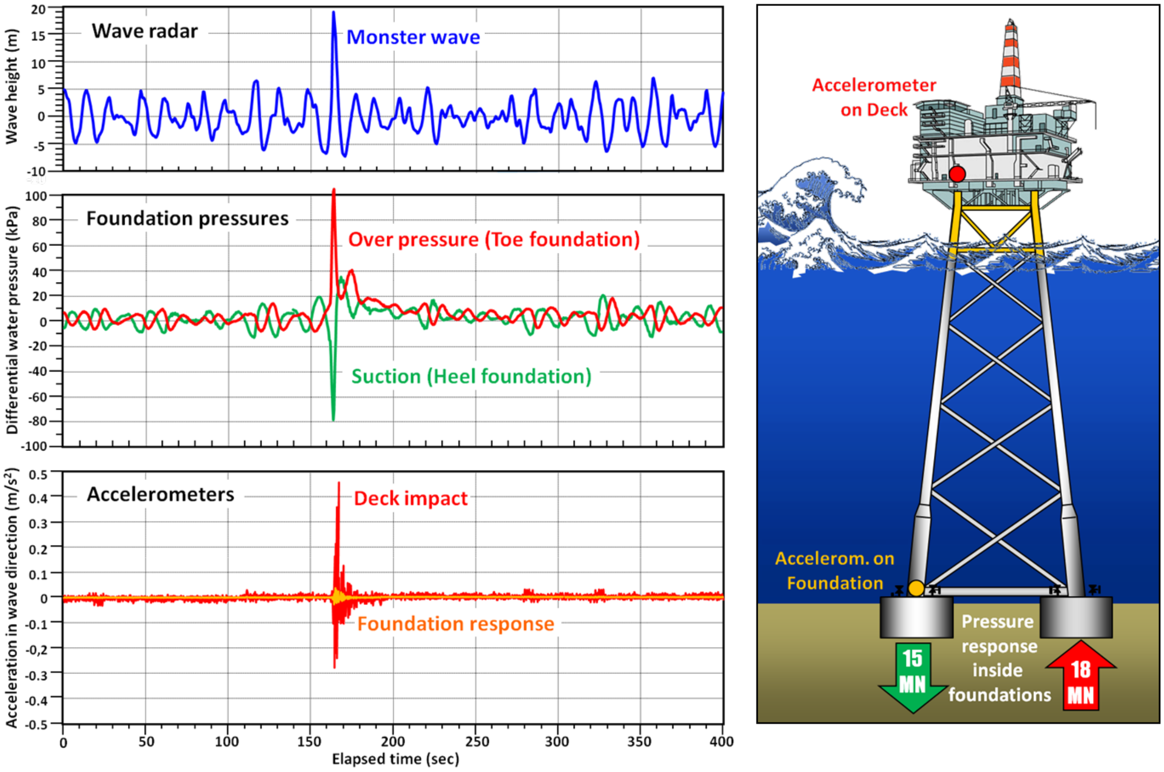


Figure 3-3 Some of the sensors readings during impact of the Monster wave to Statoil's Draupner platform (data and illustrations: NGI)

All readings of significance had a logical correlation to the impact of the monster wave with respect to structural response, the wave hit the top of the platform like a sledgehammer. The overturning moment caused by the wave generated an over pressure response in the toe foundation and suction pressure in the heel foundation. By comparing with the forces distributed through the legs (recorded by strain gauges) it was concluded that most of the "punch" by the wave was taken by the hydraulic reaction forces in the buckets.

Topside accelerometers and those on the buckets (seabed level) indicated severe vibrations in the deck while the bucket foundations hardly moved. No permanent deformations (tilt) was recorded by the inclinometers on deck after the incident. Those few seconds of recorded data immediately proved the new concept, and also demonstrated that the capacity for transient loads of the bucket foundation was much higher than the design codes would allow at that stage (the seabed consisted of dense sand).

The story is an excellent example demonstrating the value of an integrated SHM system. However, recording such events can only be expected "once in a life time", in fact the loads were higher than ULS conditions and would statistically be defined as a once in 10 000 year event. These readings are also the only case were a rogue wave has been directly measured and consequently proved the theory behind (quantum physics), rogue waves could no longer be dismissed as fairy tales, see Figure 3-4.

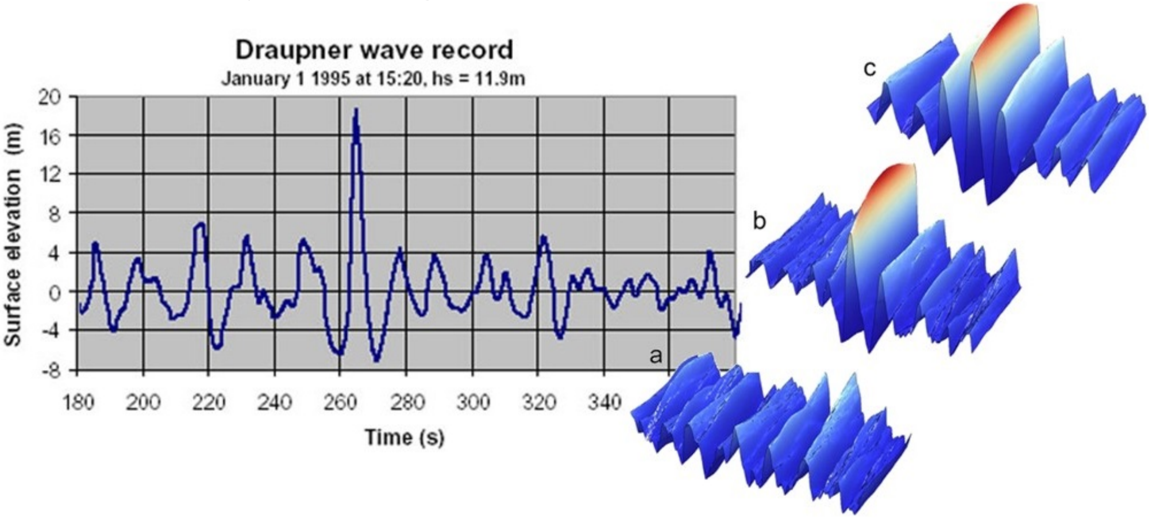


Figure 3-4 The Draupner wave recorded by the on-board SHM system compared with quantum physical modelling demonstrating how and that rouge waves suddenly can occur

4 Specific SHM objectives for OWT foundations

The described objectives for structural health monitoring and instrumentation systems apply for mono piles, jacket and gravity base foundations. Moored floating systems are also discussed. Both piles and suction buckets are considered as relevant seabed foundation alternatives. Presently piled foundations are the dominating alternative for OWT's in Europe. The suction bucket concept is not yet fully implemented in the Offshore Wind Industry but frequently used by the offshore Oil and Gas industry. Monitoring aspects and solutions for buckets (shallow foundations) also to a large extent apply for Gravity Base Structures with skirts.

4.1 Objectives for Foundation Response Monitoring in the field

Although the scope in this report does not include structural or geotechnical analyses, general design aspects which are expected to also apply for OWT foundations in US waters are discussed as relevant for monitoring in the field. The main objectives for monitoring foundation response is design verification and possible future optimization in addition to early warning of possible development of weaknesses.

For **mono piles**, horizontal loads and moment are directly transferred to horizontal soil reactions, as shown in the left-hand side of the Figure 4-1. As the pile is not fixed at the top, it is free to rotate and translate. This horizontal load transfer usually dictates the pile length, the pile must be driven long enough to mobilize enough soil over its length to transfer all loads and prevent "toe-kick" displacement of the tip of the pile. It is however the lateral stiffness of the pile and not bearing capacity which is governing for the design.

For **multi-pile foundations** (jackets and tripods), the overturning moment is mainly transferred as axial loads (compression and tension) to opposing foundation piles as shown in Figure 4-1. For this type of foundation, either the vertical bearing or pull-out capacity of the piles is governing for the length of the piles. Similar distribution of loads the seabed foundations applies for mono or multi-bucket OWT structures.

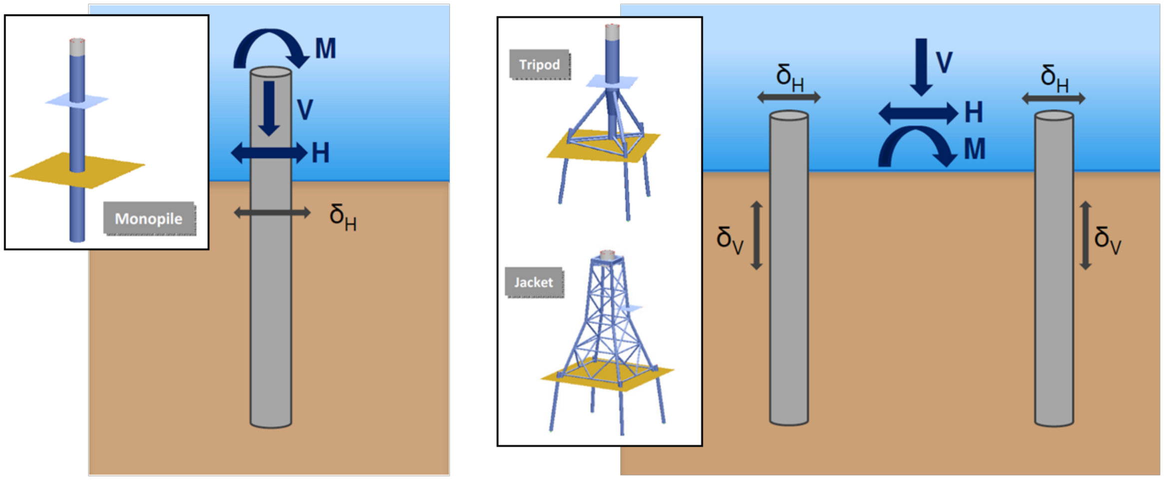


Figure 4-1 Load transfer to the soil for a mono pile (left) and tripod/jacket (right) foundations

Similar overturning loads are also transferred to the soil for **gravity base foundations**, however the soil reactions are different. Usually tension loads are not present beneath the gravity base foundation, the dominating loads are compression and horizontal shear.

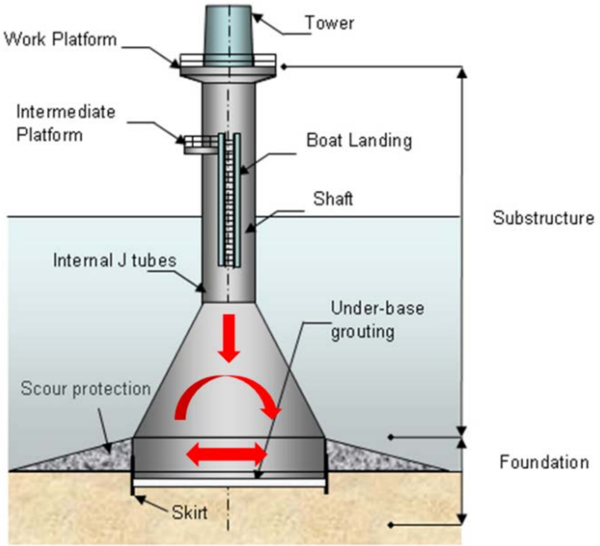


Figure 4-2 Load transfer to the seabed for a gravity base foundation

Bucket foundations are also shallow foundations, however compared to a gravity base structure, the bucket foundation have significant tensile capacity obtained by the suction response inside the close bucket, especially for dynamic (short term) loads.

A **floating wind turbine** supports a large payload (wind turbine and tower) with large aerodynamic loads high above the water surface and challenges basic naval architecture principles due to the raised center of gravity and large overturning moment. The static and dynamic stability criteria can be challenging to achieve as the hull weight must be limited for a cost competitive foundation concept. The motion of the floating wind turbine is a function of the restoring forces from the mooring and the environmental forces, see Figure 4-3. The dampening effect by the mooring lines has significant impact on the dynamic response of the wind turbine, the stiffness of the anchors is negligible in this context.

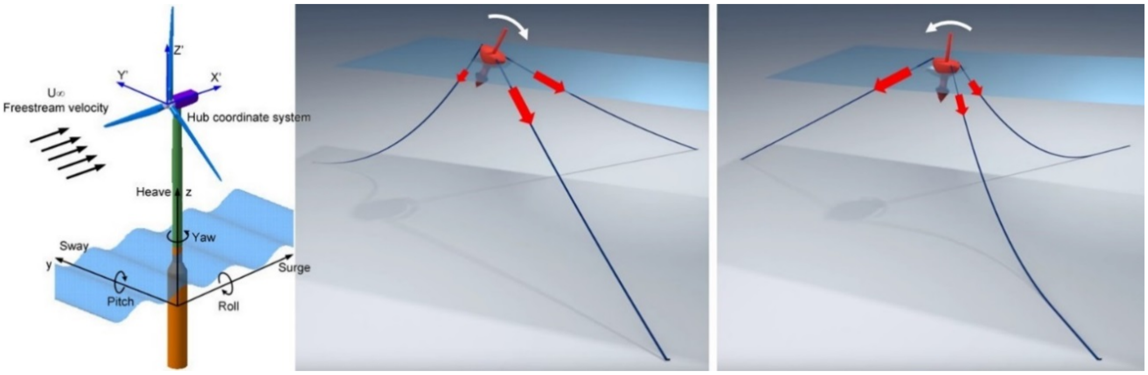


Figure 4-3 Catenary mooring loads and dynamic response of a floating OWT foundation

Independent of foundation type, an offshore wind turbine is a tall, slender with a heavy top structure. Possible accumulated cyclic deformations or bending of the foundation will result in a tilt of the tower which may become critical for operation of the wind turbine. Measuring tilt (inclination) at the base of the tower is therefore recommended as a standard parameter to be included in a monitoring scheme. In addition, the turbine will shut down if the dynamic motions exceed the operational limits, the motions in the nacelle are monitored as part of the SCADA system. For floaters, the static (mean) tilt is relevant for possible trimming by ballasting/de-ballasting and/or mooring tensioning. The towers with nacelles are based on similar structural arrangement as for land based wind turbines, although they are usually much taller and bigger in offshore windfarms, see Figure 4-4.

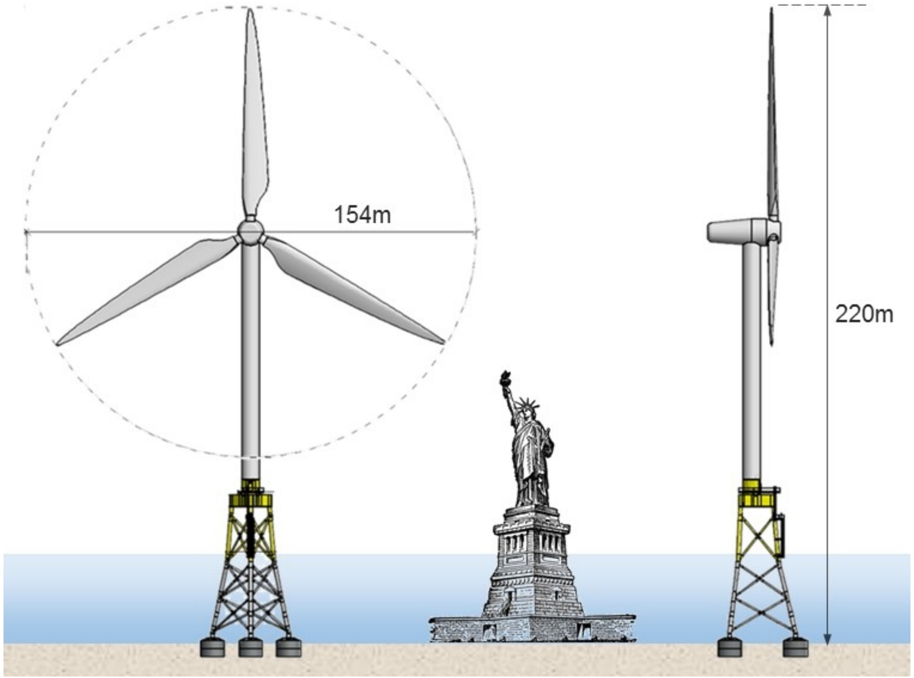


Figure 4-4 Dimensions of Dong Energy's 7MW Offshore Wind Turbines considered for installation at the Hornsea wind farm (UK)

A main difference for offshore foundations compared to onshore wind turbines is the dynamic loading and response of the foundation. Both tower and foundation must be included in the modal analysis, see Figure 4-5. It is difficult to properly model the response of the seabed in such analysis, field monitoring of the dynamic response is therefore relevant.

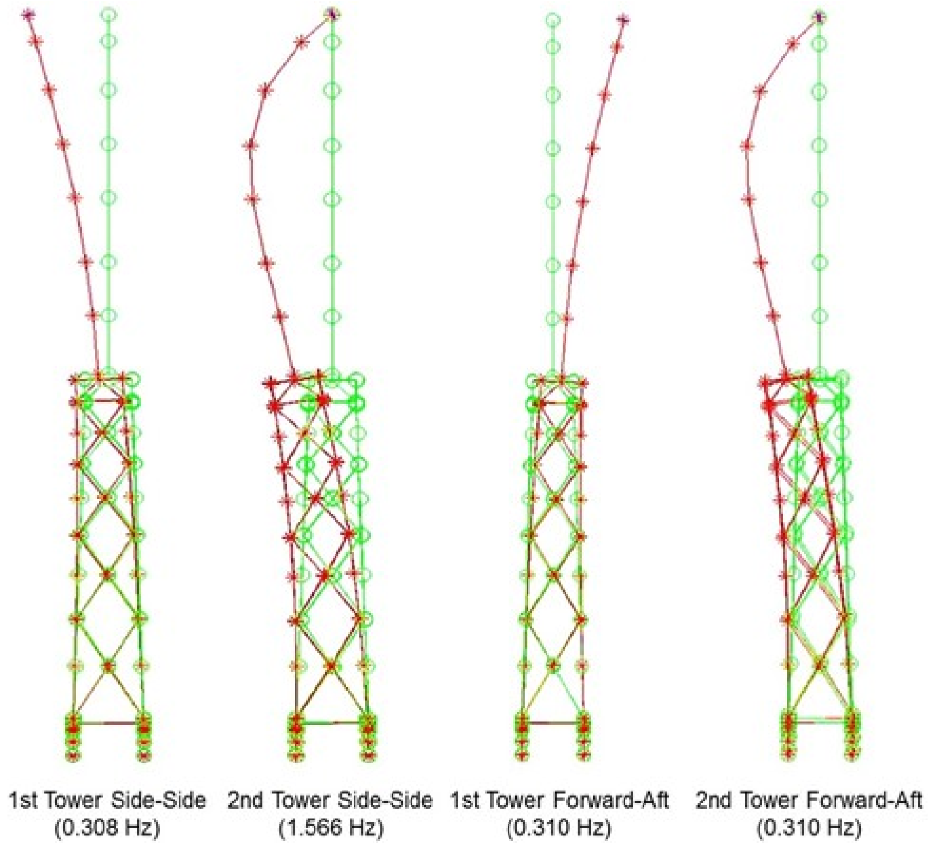


Figure 4-5 Dynamic modelling of mode shapes for a jacket foundation with tower

Monitoring the environmental load conditions is relevant for all foundation types:

- Wind and temperature (usually integrated as part of the turbine control system)
- Wave height

Note that the extreme loads may not occur during extreme weather and for winds exceeding the cut-out speed (typical 25m/sec), but may for example occur if big waves hit the foundation just before cut-out wind speeds occur and/or in conjunction with an emergency stop of the turbine. Figure 4-6 shows simulated wave action against a typical mono pile.

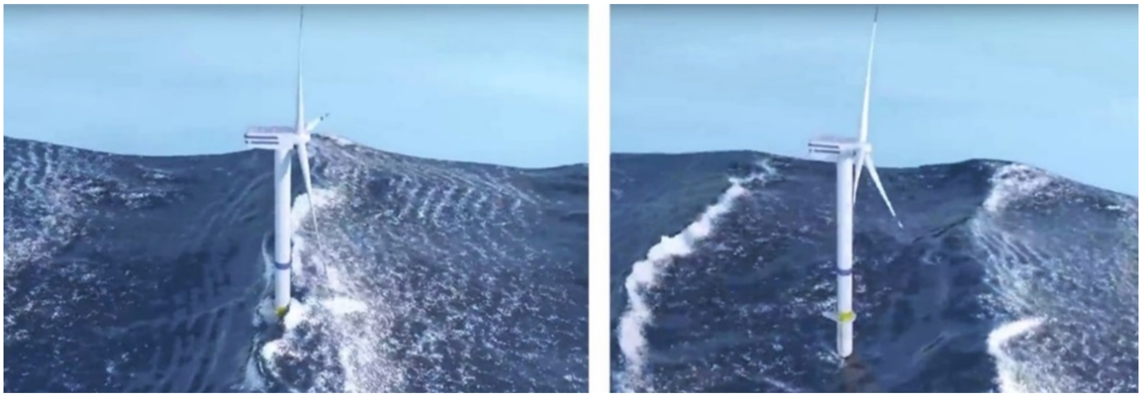
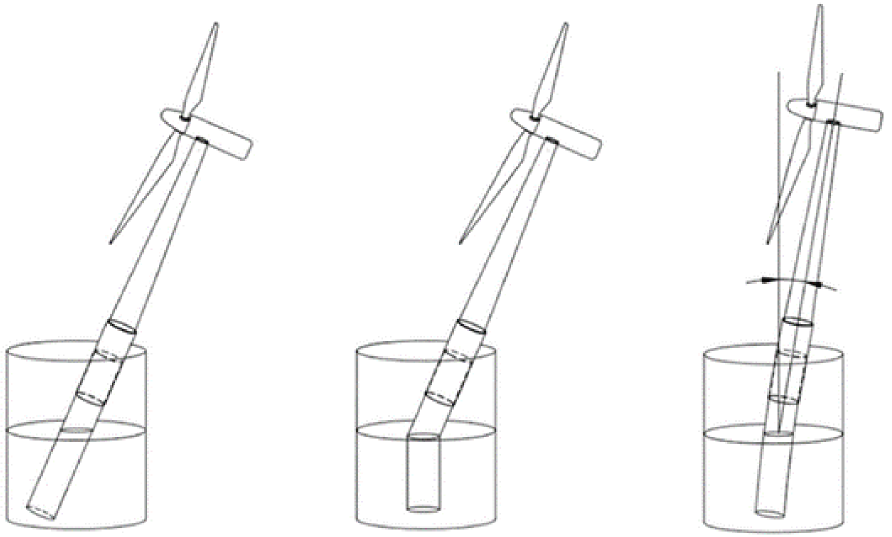


Figure 4-6 Simulated wave action against an offshore wind turbine mono pile foundation (animation by Kostack Studio)

4.2 Specific monitoring aspects for Mono piles

The failure modes for a mono pile foundation are illustrated in Figure 4-7. The ULS and SLS failure conditions are usually not critical for design and therefore of less importance to monitor. The exemption is Tilt of the tower which always is of critical concern. The dynamic response and stiffness are the main design drivers and of paramount interest to monitor. In addition, local and site related effects such as scour, corrosion and connection of the Transition Piece can be relevant to monitor.



ULS: Failure through exceeding the foundation's ultimate lateral capacity (soil failure)

ULS: Failure through plastic hinge of the pile (pile yield failure)

SLS: Tilt angle exceeds allowable value (serviceability failure)

Figure 4-7 Failure modes for Mono piles (from L Aranya et al)

4.2.1 Dynamic response

The dominating and critical loading condition for a mono pile foundation is the alternating lateral loads at mudline, consequently the cyclic stiffness and damping of the foundation are very important design parameters governing for the natural frequency of the OWT, see Figure 4-8.

A natural frequency close to the rotor frequency may result in excessive vibrations that will cause shut down of the turbine. The natural frequency of a mono pile is decreasing with larger water depth and size of turbine, approaching the rotor revolution frequency. Thus, it is of paramount interest to monitor the in-situ modal response of the complete foundation and tower when challenging the allowable frequency limits. Even if the critical parameter is the magnitude of vibrations shutting down the turbine, it is important to understand the dynamic response of the complete structural system in order to optimize future design. This includes monitoring the dynamic behavior (stress and motion) of the tower with turbine, transition piece connection to the pile and the pile-soil stiffness (P-Y response).

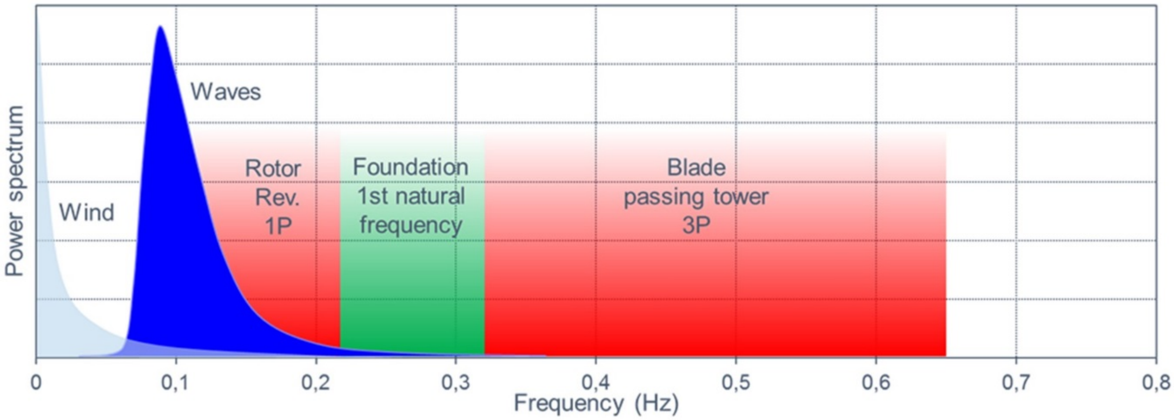


Figure 4-8 Load frequencies for a typical mono pile OWT and simulation of dynamic radial dampening in the soil

For mono pile wind turbines, the aerodynamic damping D_{aero} is the main damping contributor in the Fore-Aft (FA) direction due to the rotor blades. D_{aero} plays only a very little role in sideways (SS) motion were the soil damping plays an important role, see Figures 4-9 and 4-10.

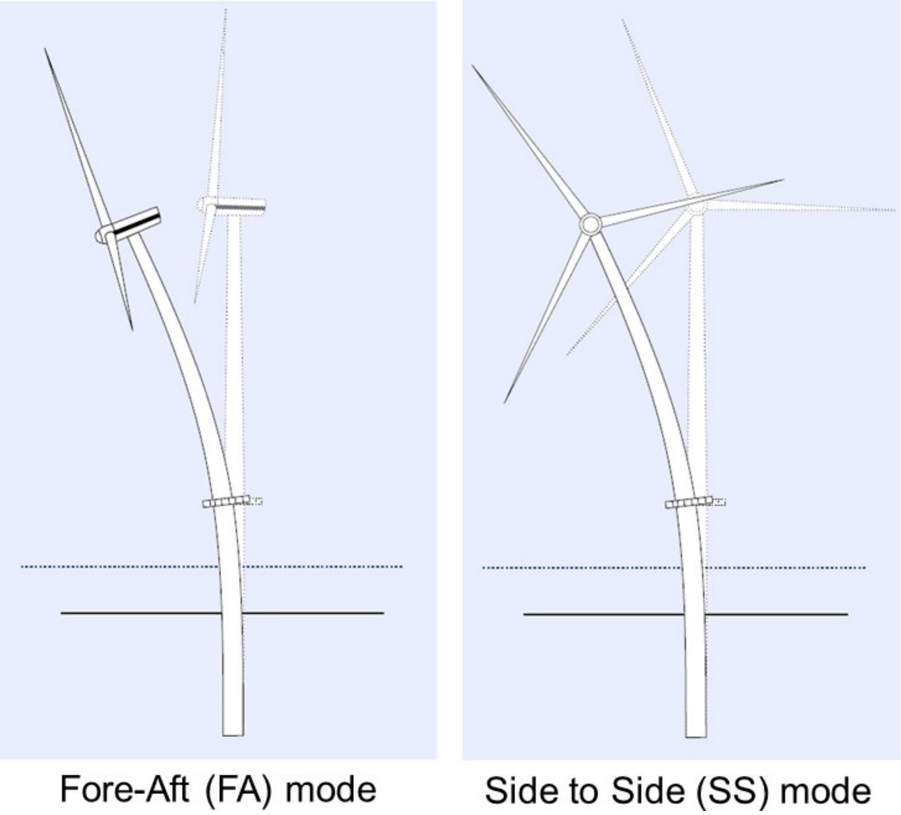


Figure 4-9 Principal tower vibration modes for an OWT with mono pile foundation

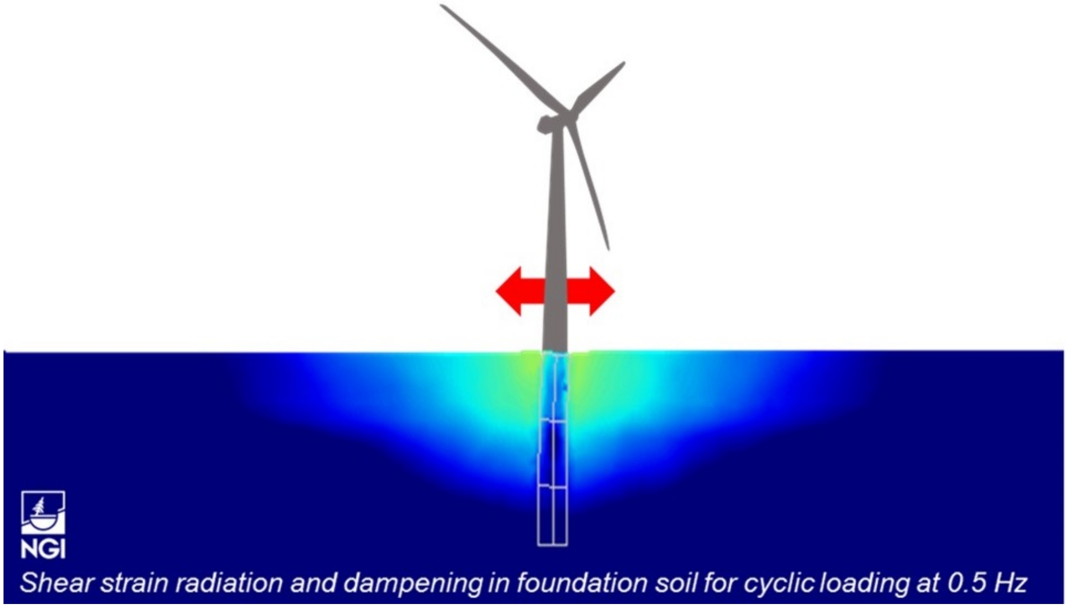


Figure 4-10 Simulation of dynamic radial dampening in the soil (SS mode)

The soil stiffness for a mono pile is traditionally derived based on API's P-Y approach, see Figure 4-11. There are many indications (from various monitoring programs and lateral load tests) that this approach is conservative, i.e. the foundation is stiffer than predicted according to API guidelines. This is especially important for the large diameter mono piles. A stiffer foundation will increase the fatigue life of the pile and (more important) keep the resonant frequency above the rotor frequency (1P) when the water depth and turbine size are increased.

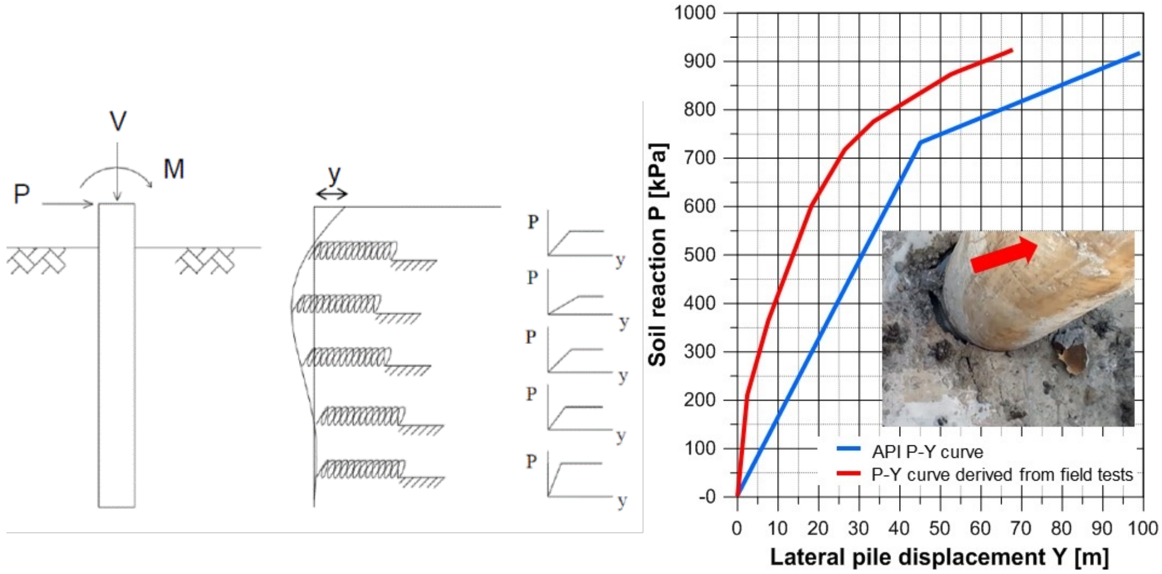


Figure 4-11 P-Y stiffness approach from API (left) and a comparison of API predicted response with measured (and stiffer) response measured during lateral pile load tests in stiff clay (source NGI)

The moment distribution used to determine the soil stiffness is monitored by strain gauges along the embedded part of the pile, see Figure 4-12. The moment is derived from diametric opposite strain gauges (compression and tension), normally along X-Y sections of the pile such that the distribution of maximum bending moments can be computed for loading in any direction.

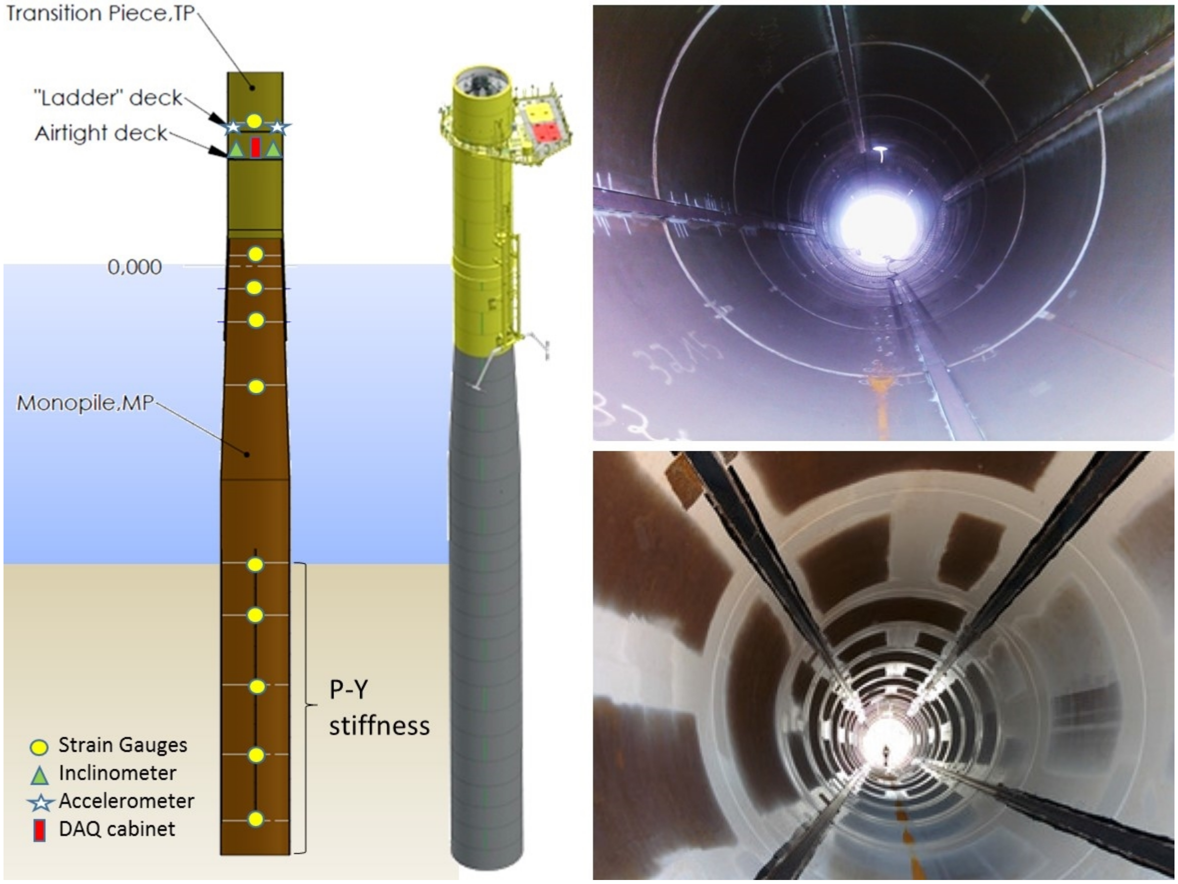


Figure 4-12 Example of mono pile instrumentation with strain gauges along the X-Y sections in the embedded part, the tensile and compressive strain generated by the moment is measured along the diametric opposite sections. Top right photo shows resistance wire gauges and lower right photo is from a mono pile instrumented with FBG strain sensors. In both cases the embedded sensor sections must be protected by channels with cover plates and driving shoes

The moment distribution derived from the strain gauge measurements (mean values) recorded in the field can be plotted against a parameter representative for the applied load, for example average wind speed. Based on the measured moment at each instrumented level of the pile, the moment distribution with depth is plotted for different applied loads (moments) and compared with predicted values. The moments in the pile diminish faster with depth if the soil response is stiffer than predicted, see Figure 4-13.

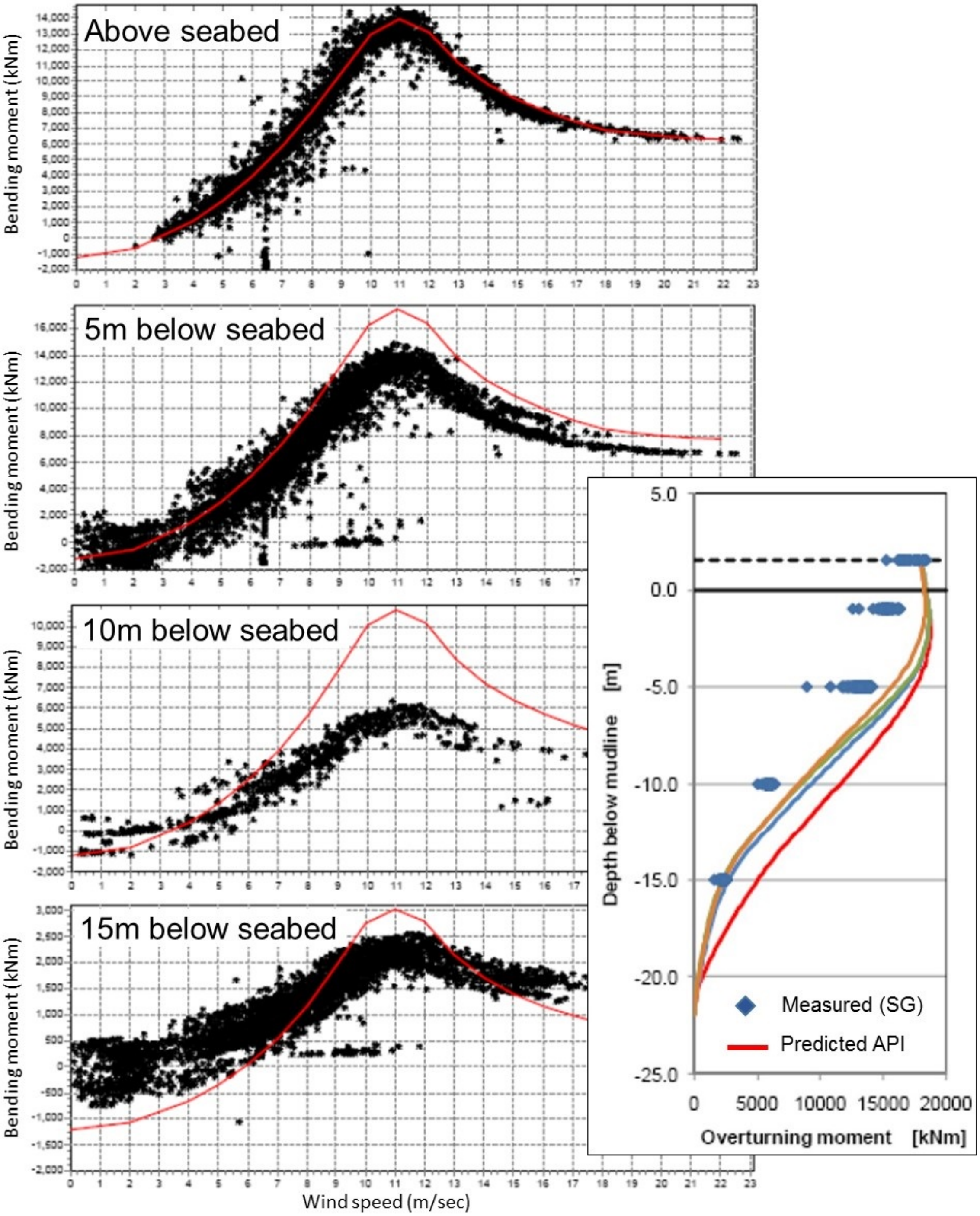


Figure 4-13 Moment measured at different depths of a mono pile and plotted against wind speed. Note that the range of the Y (Moment) scales are decreased with depth. The inserted plot shows measured (blue dots) and predicted moment distribution with depth for 10.5-11-5 m/s wind speed where maximum moments are recorded. Data from Horns Rev, Dong Energy.

As large dynamic motion of the turbine is the main problem during operation it is equally important to monitor and understand the dynamic response and modal shapes of the tower itself using accelerometers at different levels in in order to track the FA and SS modes, see Figure 4-14.

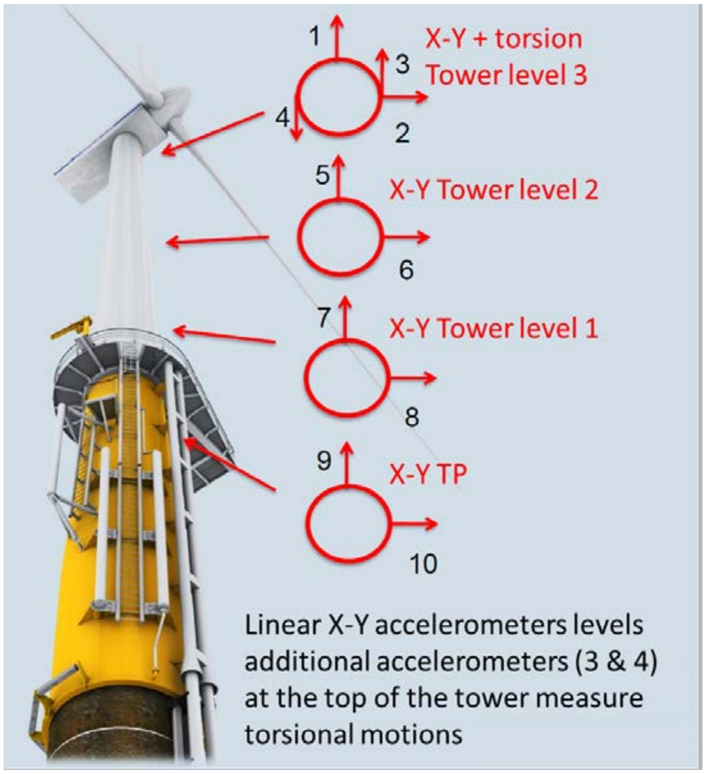


Figure 4-14
Configuration of accelerometers along the mono pile tower (proposed by OWI-lab)

Resonance frequencies can be tracked during operation in the field, see Figure 4-15 and damping can be derived from transient loading for example over speed stop of turbine, see Figure 4-16.

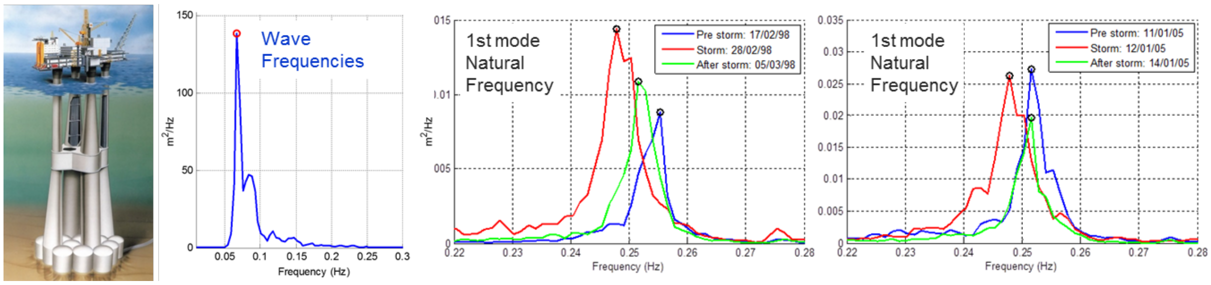


Figure 4-15 Tracking resonant frequencies of a large GBS foundation (Statoil's Troll C platform through a storm. Data was compared to storm readings 7 year later in order to verify that the stiffness of the foundation remained unchanged

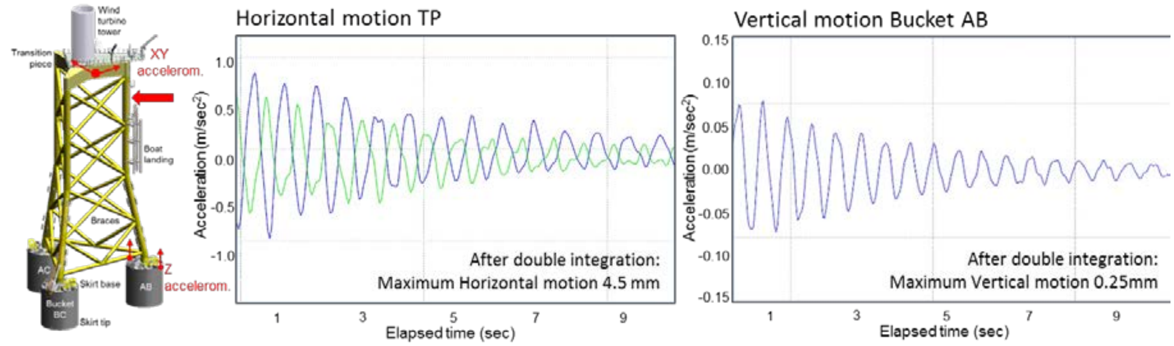


Figure 4-16 Damping of dynamic motions of Suction Bucket jacket after transient excitation (example from NGI/Dong Energy)

Aerodynamic, hydrodynamic, structural damping and, if used, tuned mass damping can be calculated based on known material properties and dimensions. The soil stiffness and dampening properties are as described uncertain and more field data is needed in order to improve empirical methods and correlations to different soil conditions.

As monitoring on the pile itself (under water and below the mudline) is difficult and costly, some researchers claims that these measurement can be omitted by means of a combination of modelling and measurements on the tower (i.e. extrapolating data to the mono pile), see Figure 4-17. The "virtual sensing" concept is based on a range of assumptions and empirical relations which in many cases probably are representative. The uncertainty can however be discussed for example if degradation occurs in the grouted TP connection. It is also impossible to evaluate difference stiffness of the soil in different layers without strain measurements along the pile.

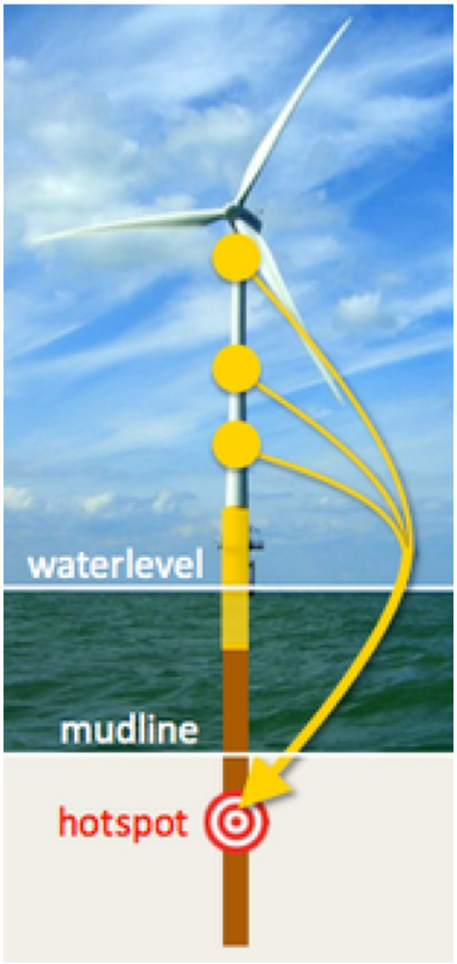


Figure 4-17 Virtual sensing concept as presented by OWI Lab, extrapolating data from the tower to hotspots below the mudline

Evaluation of the lateral loading stiffness and dampening of the pile, after installation and with time, is a paramount objective for monitoring. The instrumentation may include:

- Dynamic motion (accelerometers) along the structure (above seabed)
- Stress (strain measurements) in the pile at the TP connection and from mud-line and downwards
- If relevant in certain soil conditions, cyclic pore pressure build up (affecting the soil stiffness) with piezometers along the pile

4.2.2 Scour

Scour is another feature which will affect the stiffness (and resonant frequency) of the mono pile foundation, see Figure 4-18. Usually, lowering of the natural frequency due to scour is more critical for operation of the wind turbine than the reduced bearing capacity. Thus, unless scour protection is applied (or before possible scour protection is installed) in-situ monitoring of possible scour development is relevant if the current and seabed conditions are susceptible for scour. For shallow foundations (buckets) scour may also introduce a bearing capacity or undermining problem, see Figure 4-19. Scour monitoring should be complemented with current recordings in order understand the scouring process and add value to the observations.

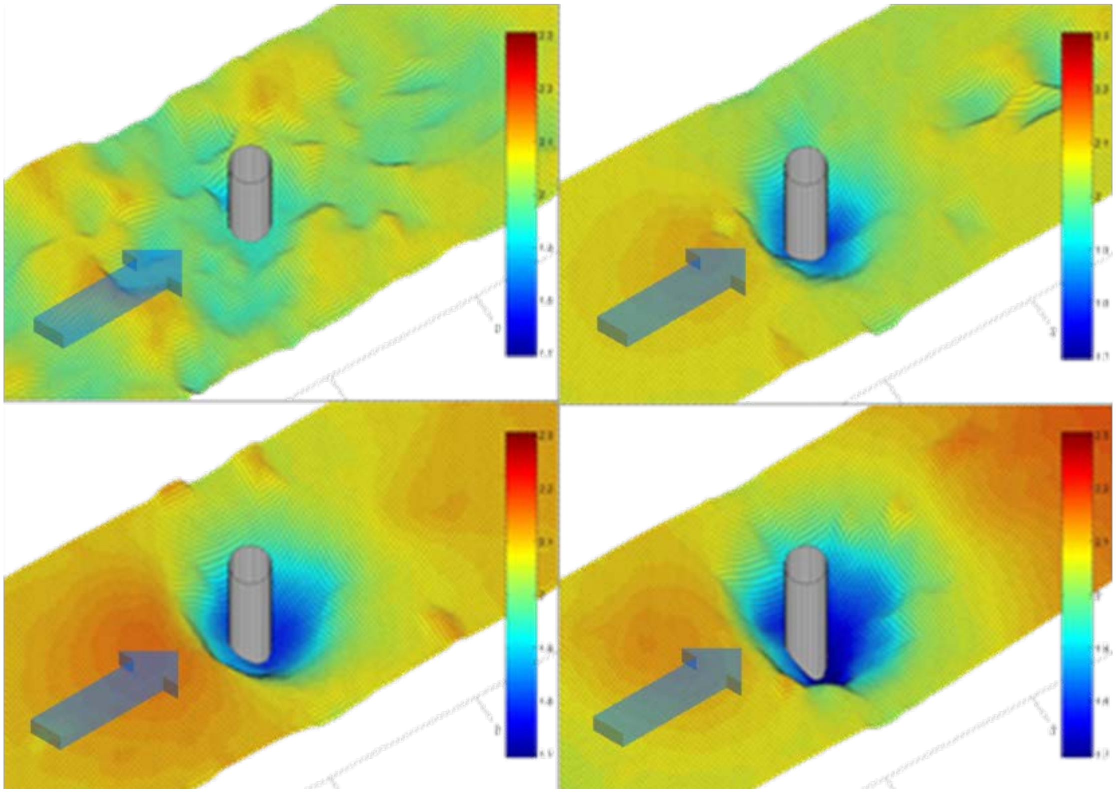


Figure 4-18 Measured scour development around a mono pile during large scale model testing (from www.fzk.uni-hannover.de)

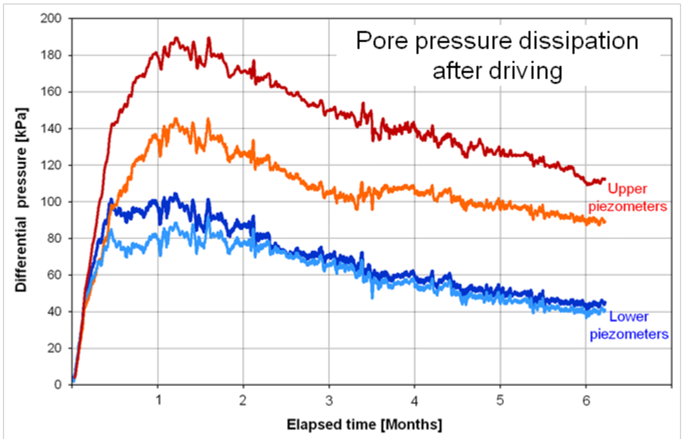
Figure 4-19 Scour pattern after basin testing of a mono bucket foundation (HR Wallingford)

Scour may occur immediately after installation of the foundation in the seabed. It is therefore important that the monitoring system is operational as soon as possible after completed installation. Note that scouring is many times a cyclic process dependent on the current direction. If the foundation is subjected to reversing tidal currents, scour may be followed by re-sedimentation. Therefore continuous monitoring is recommended.

4.2.3 Bearing capacity

The ultimate bearing capacity of a mono pile is normally not a critical issue for design, it is the lateral stiffness which usually is the design driver.

However, cyclic degradation and pore pressure build may be an issue for impermeable soil conditions. The pore pressure build-up during pile driving (or vibro piling) and the subsequent dissipation (pile setup) time may also be an issue for design and operation.



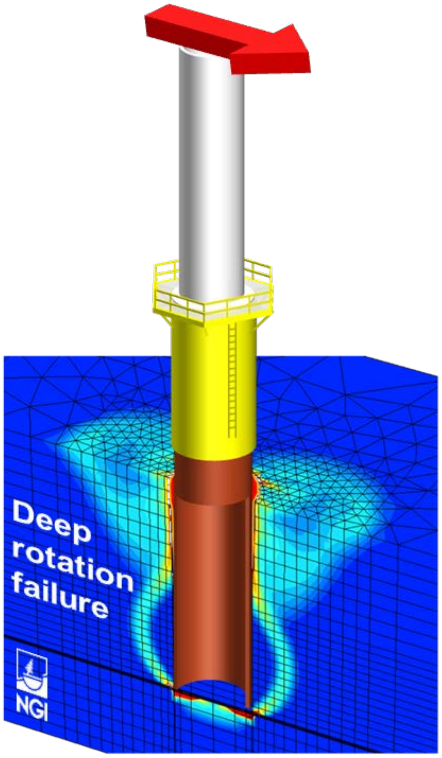


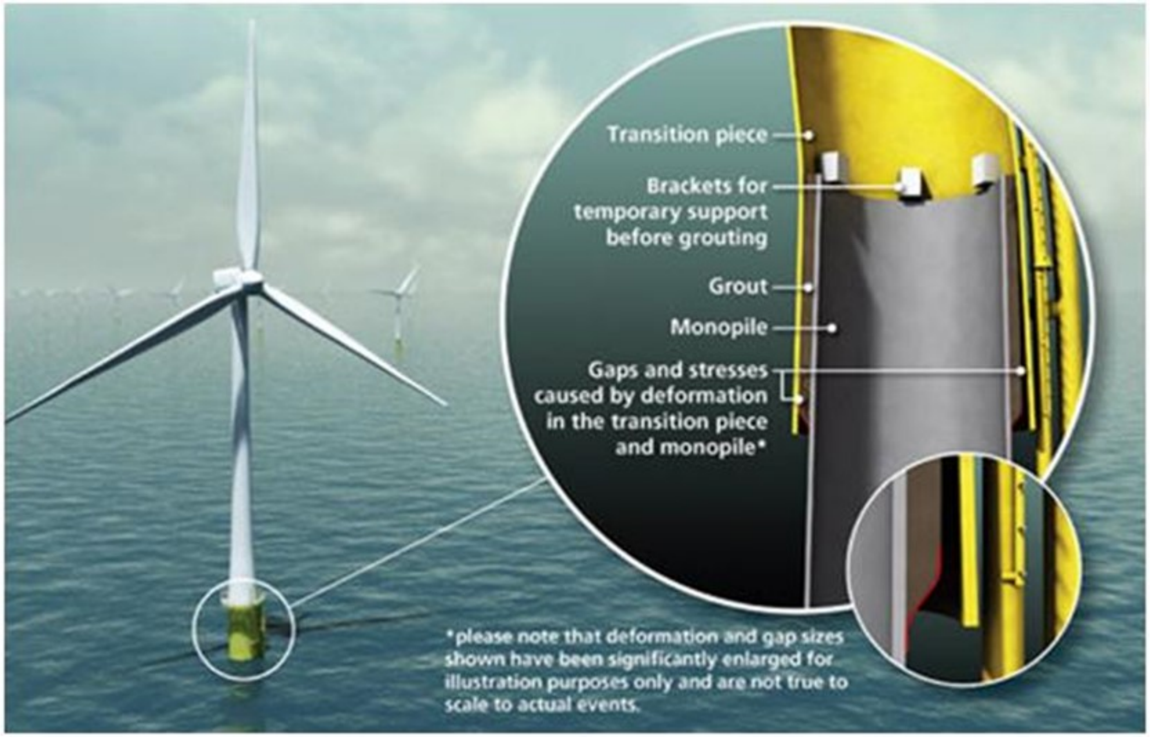
Figure 4-20 Excess pore pressures generated during driving and dissipation 6 months after installation of a steel pile in seabed consisting of clay in conjunction with the Femern Large Scale field tests (left). Deep rotation failure for a mono pile in clay modelled by NGI (right)

The radial effective stresses (earth pressures) may for some soil conditions be an important parameter to monitor both with respect to set-up effects and lateral stiffness. It is however difficult to obtain reliable lateral earth pressure readings for a driven steel pile. Total pressure cells are used for these measurements and the data must be compensated (subtracted) by the pore pressure measured at the same position such that effective stresses can be determined. In order to obtain representative readings, it is absolutely essential that the membrane of the total pressure cell is integrated with the pile wall with a curvature corresponding to the pile diameter, which implies a customized design.

4.2.4 Grouted connections of the transition piece

The grouted connection is used to fix the Transition Piece (TP) to the mono pile as shown in Figure 4-21. The transition piece is placed on top of the monopole and initially rests on temporary supports. During installation, the temporary supports on the TP are jacked up to correct the verticality of the transition piece before the grouting is carried out.

After curing of the grout, the jacks are removed, leaving a gap between the temporary supports and the top of the pile.



*please note that deformation and gap sizes shown have been significantly enlarged for illustration purposes only and are not true to scale to actual events.

Figure 4-21 Old transition piece connection with temporary supports and straight grouted section (illustration DNV-GL)

The large bending forces occurring at the grouted connection may eventually degrade the grout (cracking and crushing), see Figure 4-22. If the TP settles (slip) down to the temporary supports, a different force distribution than that intended at the design stage occurs between the structural elements. Eventual force transfer through the temporary supports (not designed for permanent loading) can be critical with respect to fatigue cracking in the transition piece structure. This fundamental shortcoming in design was discovered in April 2010 when it was observed that the transition piece for some mono pile foundations had slipped down by up to 25mm.

An extensive monitoring program was initiated in order to alert wind farm operators if the strain in temporary support brackets exceeded acceptable limits. A Joint Industry Project was executed by DNV in order to analyze the slippage problem and to improve on the design practice. Reference is made to "*The summary report from the JIP on the Capacity of grouted connections in Offshore wind turbine structures DNV Report No: 2010-1053, rev. 05*" which can be downloaded from the internet.

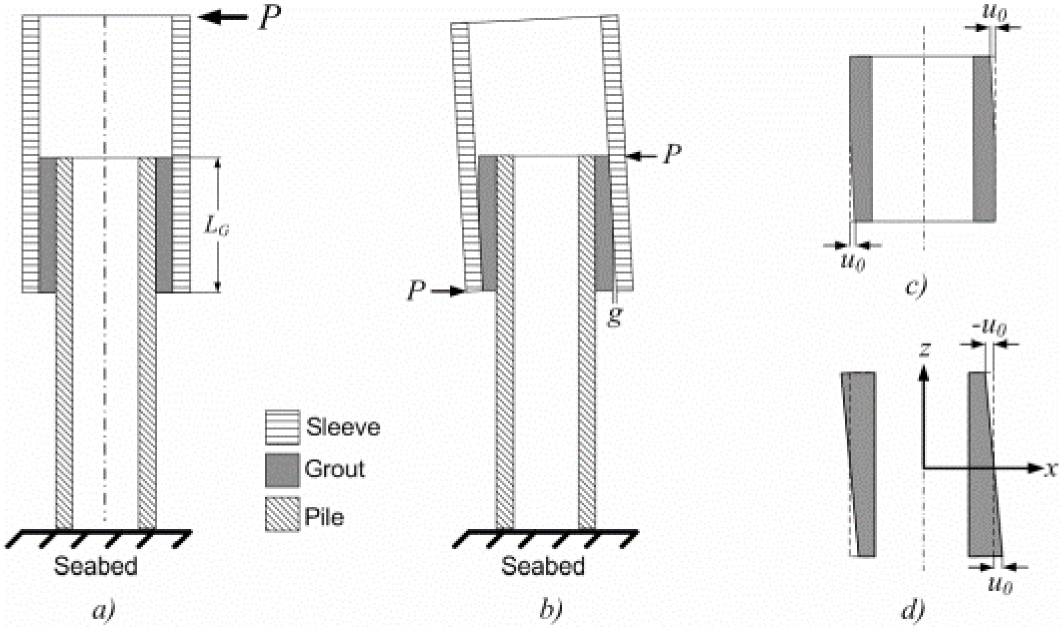


Figure 4-22 Structural behavior of the grout due to horizontal load transfer from the transition piece to the pile (temporary supports not shown)

Accounting for the large dynamic bending moments on mono piles, a more robust design has been developed using conical shaped connections. According to this concept, the pile top and transition piece are fabricated with a small cone angle in the grouted section with the narrower side pointing upwards. The coned connection will expose the grout to compression loads, rather than shear forces as on traditional designs. Also, relative deformations between the pile and transition piece will be reduced in case of grout failure and prevent load transfer directly to the temporary supports.

The report: *DNVGL-ST-0126 Support Structures for Wind Turbines* includes the new recommendation for the fixture of the transition piece using conical shaped connections, see Figure 4-23. There are also other new solution for the TP-Pile connection in the market. As this is an important structural part with a problematic history, new solutions are relevant to monitor (until fully field proven).

Deformations between the pile and TP in the grouted connection can be monitored using crack/joint meters (miniature extensometers) or long base strain gauges. The sensors can be fixed between the top of the mono pile and the inner wall of the transition piece or across the vertical gap between the temporary supports and the pile top, see Figure 4-24. The stress in the grout may also be monitored by embedded load cells. Strain gauges in the transition section of the pile and TP can also be used to monitor the load transfer.

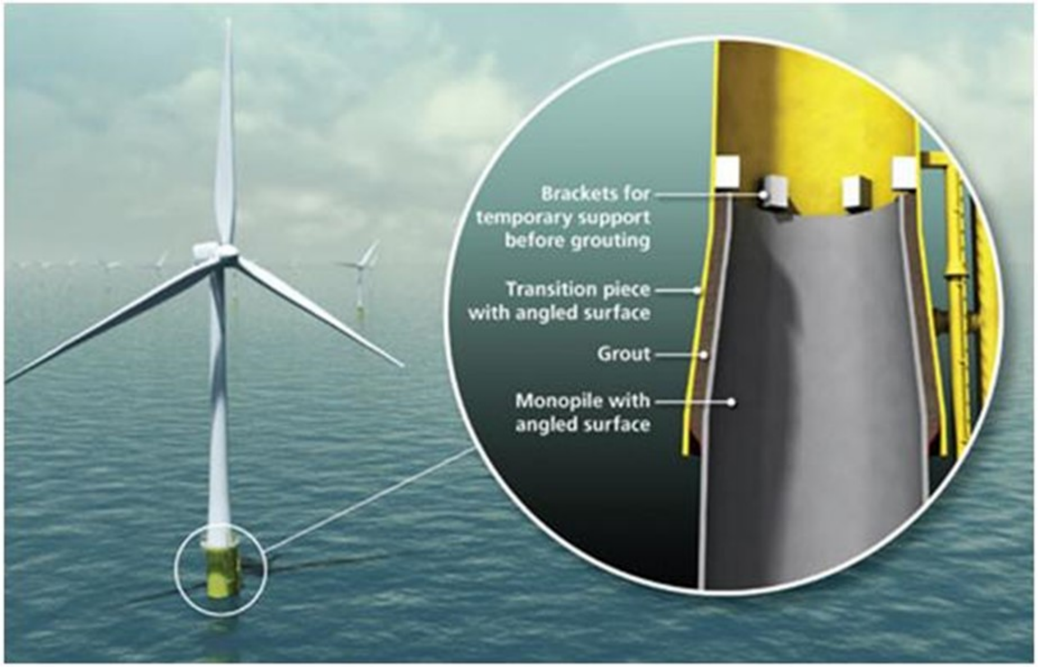


Figure 4-23 Recommended transition piece connection with conical grouted section. Based on DNVGL-ST-0126

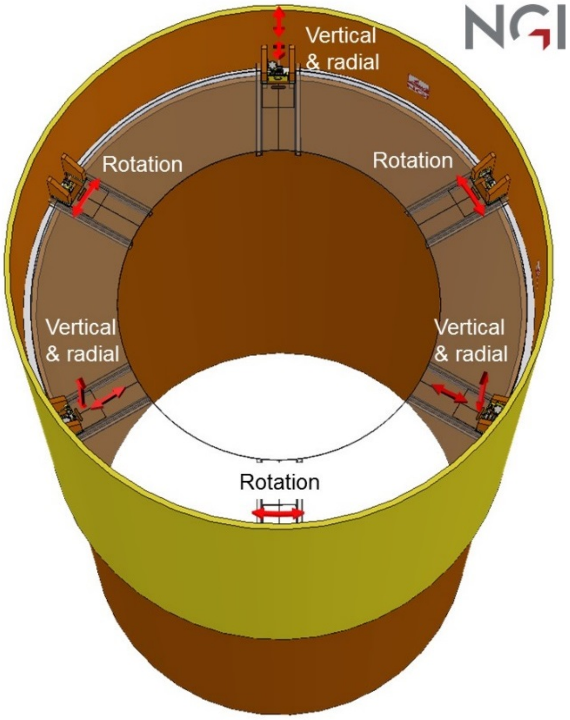


Figure 4-24 Example of extensometer configuration for monitoring relative deformations in 3D between TP temporary supports and the pile (illustration NGI)

4.2.5 Corrosion

Figure 4-25 External corrosion on a transition piece at Scroby Sands wind farm (UK)

Corrosion is a major factor limiting the operation life of offshore wind structures. Refurbishment and repair can be very expensive if the corrosion is progressing without control. For a mono pile the internal corrosion at sea level (transition piece) is the most important aspect. Low uniform corrosion rates in a closed compartment are normally anticipated in design. However, sea water ingress and supply of oxygen to the closed compartment below the airtight deck have been detected for several old mono pile foundations and caused accelerated rates of corrosion, see Figure 4-26.

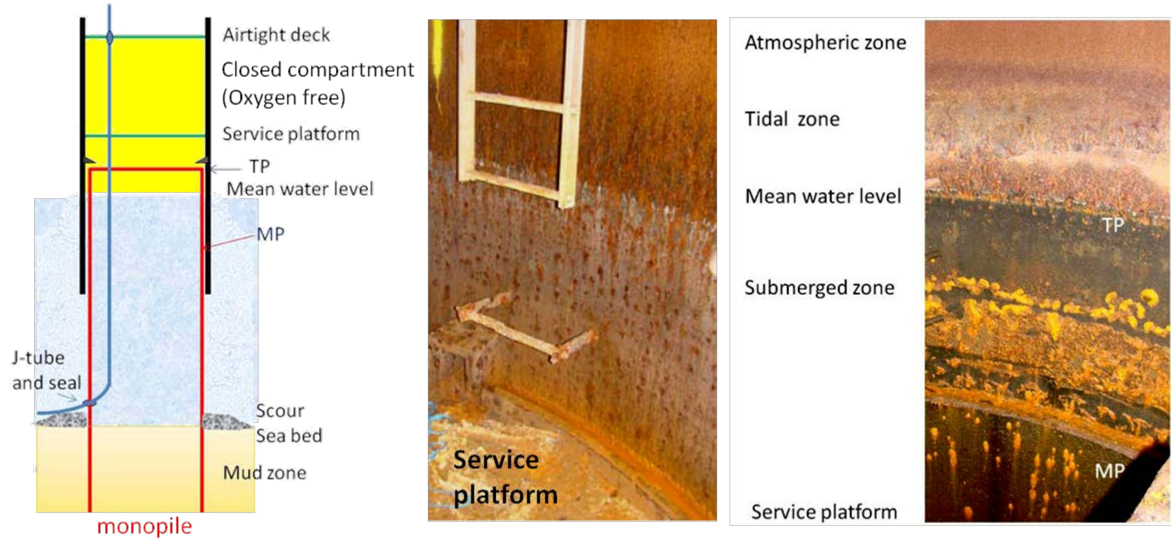


Figure 4-26 Closed compartment at Mono pile (MP) and Transition Piece (TP) joint (left) Observed internal corrosion on Transition Piece and top of Mono Pile (right). Source: Force Technology

Corrosion mechanisms and problems relevant for mono piles are summarized as follows:

- Degradation of organic coatings at the exterior part of the foundation, such as splash zone and higher parts, as this represents the onset of corrosion damage and the associated material loss.
- The degree of protection offered by the Cathodic Protection (CP) system in place at the foundation, as overprotection may result in hydrogen embrittlement, thus structural issues, while insufficient protection may lead to unforeseen corrosion activity.
- The occurrence of specific, mainly localized forms of corrosion such as pitting, water-level corrosion, microbiological corrosion (MIC), etc., as they give rise to stress concentrations or other structural problems. Better solutions to monitor mudline MIC on piles are in demand as inspection is difficult.
- Composition of isolated bodies from water as this has a significant influence on the type of corrosion damage that can occur and also on how to deal with it.

Inspections are necessary to evaluate the current corrosion state, prevailing mechanisms, cause of changed conditions, and whether areas with risk of stress concentration, e.g. at welds, are susceptible to corrosion fatigue. Monitoring campaigns increase the understanding of the conditions under which wind turbine foundations must function in the years to come and document effect of a given change. The gained knowledge should be integrated in future designs, thus simple corrosion monitoring arrangement should be installed at the time of construction and in operation directly after the foundation is installed at the field.

4.3 Specific monitoring aspects for Mono bucket foundations

The stiffness is also important for mono buckets foundations (monopods). However, for this type of shallow monopod foundation it is the rotational stiffness (not lateral) in the soil which is critical for the motions of the turbine, see Figure 4-27.

The general objectives for monitoring are similar as for a mono pile with the following exceptions:

- Strain in the bucket walls is not important for soil stiffness evaluation as lateral bending of a shallow foundation is not an issue. From a structural point of view the fixture between the bucket and the tower itself is subjected to large stresses that may be relevant to monitor.
- In combination with cyclic moment loads, a monopod bucket may be subjected to cyclic settlements in conjunction with a progressing rotational failure. Thus, in addition to monitoring the dynamic **rotational** motion of the foundation, accumulated settlements are relevant to monitor.
- Load distribution to the base (top lid) of the bucket foundation may be important for some soil conditions in order to obtain the required overturning capacity and rotational stiffness. Therefore under base grouting is normally used. If other solutions are implemented to increase load transfer along the base to the seabed, monitoring total stress to the seabed becomes relevant.
- Pore pressures along the skirt walls are relevant to monitor in some soil conditions, especially if the response to loading (drained, partially drained or undrained) is uncertain. The pore pressure response close to skirt tip level is of primary interest.

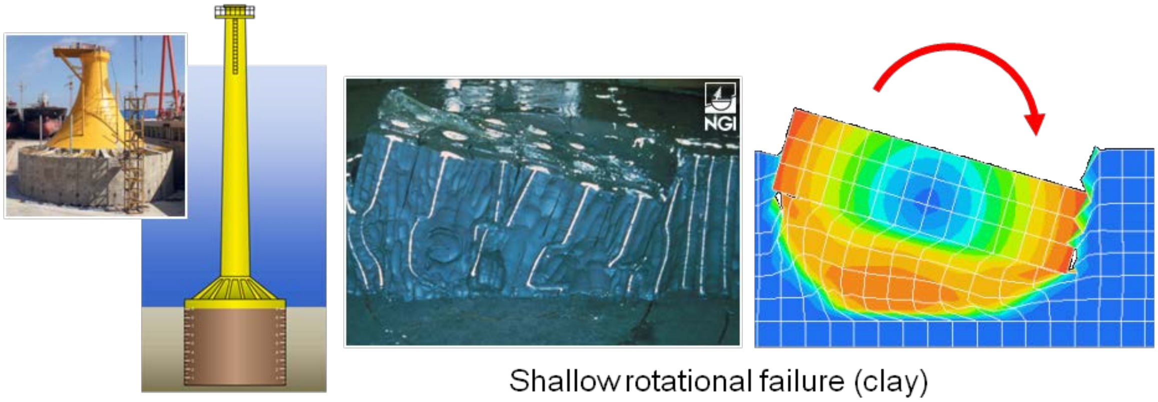


Figure 4-27 Mono bucket OWT foundation and critical rotational failure mechanism in clay

4.4 Specific monitoring aspects for Gravity base foundations

A gravity base foundation mainly relay on the weight to obtain sufficient over turning stability. Usually the base of the foundation have shallow skirts.

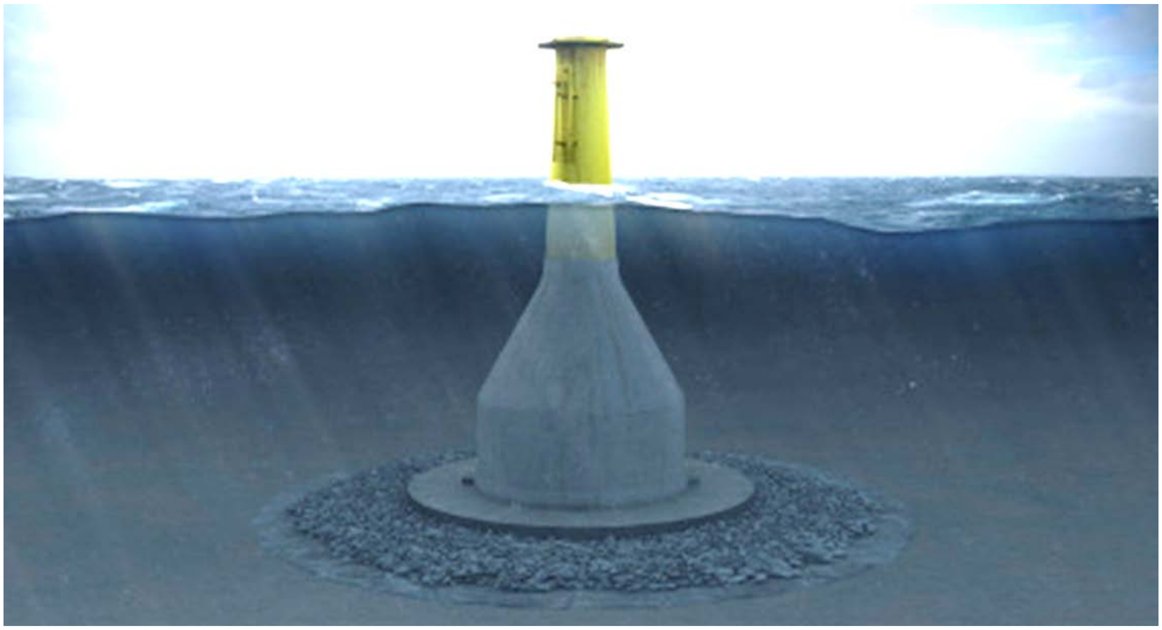


Figure 4-28 Gravity base foundation from Seatower consisting of a steel transition piece with a concrete gravity base

The monitoring aspects for a gravity base foundation (Figure 4-28) are in many perspectives similar as for a mono bucket foundations. Soil contact stresses and pore pressures under the base may even be more important to monitor as the bearing capacity of this type of foundation to a large extent depends on the conditions at the base-seabed interface. Due to the weight, consolidation settlements may also be relevant to monitor for certain soil conditions (clay). In addition, the long term condition of the concrete structure (strain, cracks etc.) is relevant to monitor, especially the joint between a steel transition piece and the concrete base may be a "hot spot".

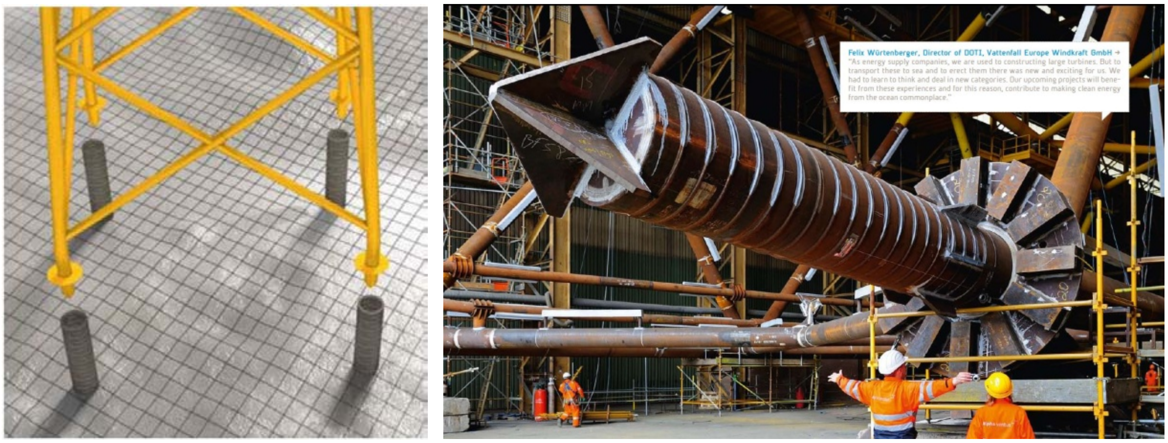
4.5 Specific monitoring aspects for Piled jackets or tripods

As described earlier the overturning moment for a multi legged structure is transferred as axial loads to opposing foundation piles. The axial capacity (compression and tension) of driven piles is well documented in several design methods and the axial soil/pile stiffness is usually not a critical design issue. As these structures are normally placed in deeper water (from 30m) the structural stiffness may be more important to monitor.

Pore pressure build up in certain layers along the piles during cyclic loading may be an issue that can be relevant for monitoring (dependent on soil conditions). Thus, in addition to corrosion and tilt of the tower, the specific monitoring parameters may include pore pressure along the piles and structural health/fatigue life monitoring such as dynamic motion and strain in critical members/connections of the jacket/tripod.

For pre-piled foundations, the grouted stab connections between the piles and the structure may be a weak link and depends on the quality of the grouting operations as well as long term degradation (*see also Section 2.2.1 Grouted connection of the transition piece*).

Grouted stab connections have been used widely in the offshore industry. The legs of the structure are either outfitted with a male stabs inserted into the piles or with sleeves around the piles sticking up from the seabed. The piles and stabs/sleeves are equipped with shear keys (weld beads) for improved bonding of the grout, see Figure 4-29.



Felix Würtenberger, Director of DOTI, Vattenfall Europe Windkraft GmbH →
"As energy supply companies, we are used to constructing large turbines. But to transport these to sea and to erect them there was new and exciting for us. We had to learn to think and deal in new categories. Our upcoming projects will benefit from these experiences and for this reason, contribute to making clean energy from the ocean commonplace."

Figure 4-29 Example of grouted male stab connections to pre-driven piles (OWEC tower)

The grouted connections can be monitored using subsea extensometers which must be retrofitted by diver or ROV, see Figure 4-30. It may also be possible to use inductive contacts sensors which would detect any spacing developing between the pile top and the flange of the stab. Provided that the structure is designed with adequate coating and cathodic protection system there is no special concern and requirements for corrosion monitoring.

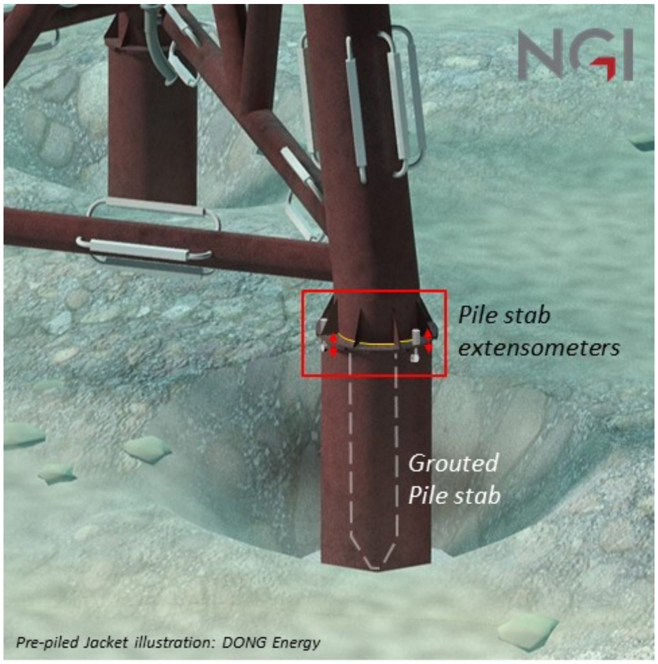


Figure 4-30 NGI Pile stab extensometers for detection of relative vertical movement between pile and jacket stab if degradation of the grouted connection is suspected

Post piled jackets/tripod have mud mats with pile sleeves which also are fixed to the piles by grouting. Such arrangement has been used within the Oil & Gas industry for more than 50 years and the long term performance is well exploited. Normally these connections have longer sleeves and grout bonding sections with larger margins against degradation failure. The same applies for piles driven through the jacket/tripod legs. Nevertheless, all grouted connections may be subjected to long term degradation with a potential need for monitoring. If serious degradation has occurred and relative pile/sleeve motions may occur, retrofitted extensometers with high resolution can be used for monitoring, see Figure 4-31.

Figure 4-31 Example of a retrofitted extensometer for measuring relative vertical deformations in a traditional sleeve-pile grouted connection for a jacket foundation

For the load distribution and fatigue life of a four-legged foundation it is important that the pile top elevations are accurately measured after installation and the stab flanges are shimmed to compensate for possible deviations. The required accuracy in these measurements are normally better than +/-10mm.

Scour is less important to monitor as increased pile stick-up from the seabed will have limited effect on the Eigen frequencies of the structure and little impact on the axial bearing capacity of the piles (which normally are designed with ample margins against scour in the top soil).

In order to optimize steel design and decrease the cost for jacket structures, stress measurements (strain gauges) at critical locations may be relevant.

For special jacket design such as Louisiana based Keystone's twisted jacket, see Figure 4-32, special monitoring aspects may apply for design verification. In this case, monitoring strain in critical members is probably relevant and in addition to lateral response (dynamic motion), torsional stiffness of the foundation may also be of interest to monitor in the field.

Figure 4-32 The twisted jacket from Keystone Engineering Inc.

4.6 Specific monitoring aspects for tripods/jackets with bucket foundations

Similar monitoring objectives as for the mono bucket tower apply for the seabed foundations. However, the load transfer to the buckets is mainly in axial compression and tension (rotation is prevented by the stiff connection to the legs), see Figure 4-33. In terms of structural health, the leg connections to the buckets are subjected to large stresses and may be relevant for strain monitoring. For sandy soils the drainage conditions during cyclic loading is important, especially for the ULS pull-out capacity. Thus, monitoring pore pressure at different depths along the skirt walls may be relevant.

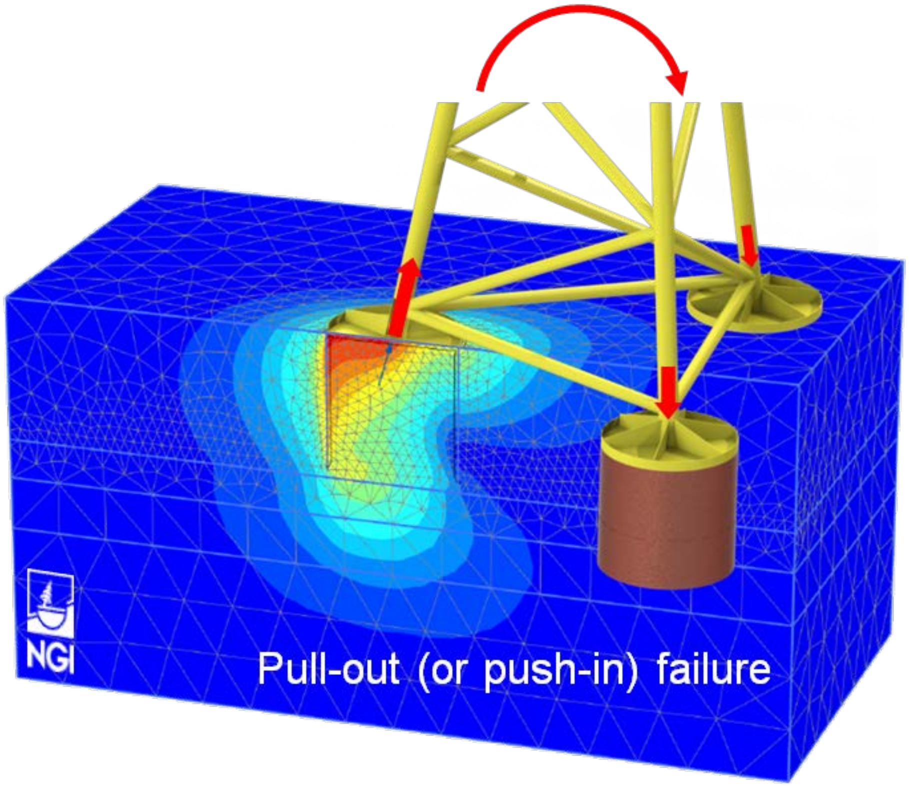


Figure 4-33 Tripod bucket foundation and critical failure mechanism in clay (model: NGI)

In order to obtain a statically determinant system, three legged (tripod) foundations are preferred. For a four-legged foundation, it is important that all four buckets are penetrated with the same rate or that the corners are kept in a straight plane. For large buckets the driving forces generated during suction penetration can be significant. Potential distortion or bending of the jacket during penetration would induce large stresses in the structural members. Thus, the elevation of each bucket must be monitored during installation as the tower may remain vertical even if the base is distorted, see Figure 4-34.

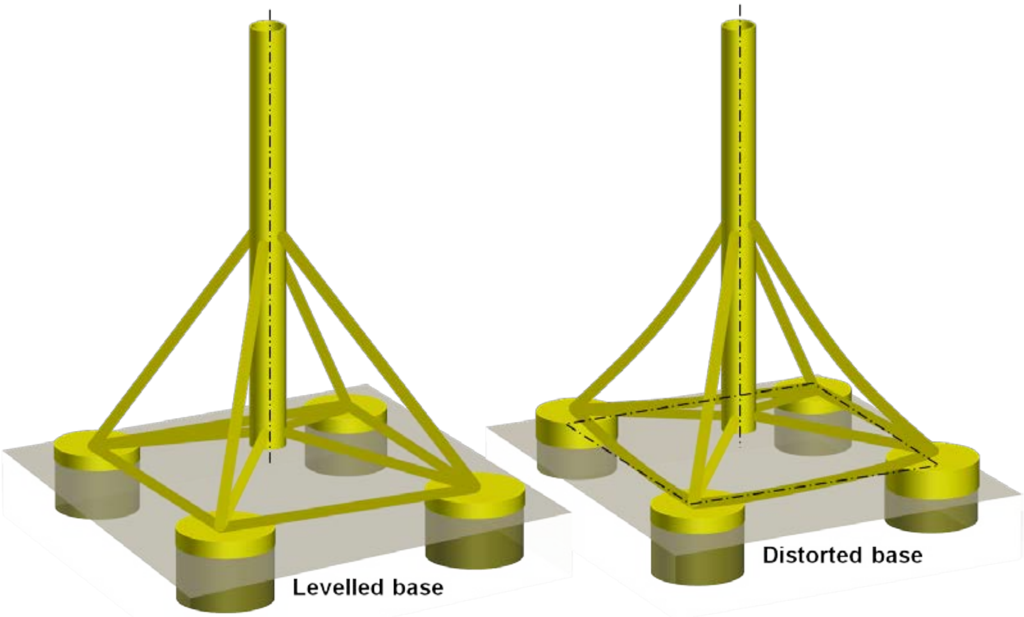


Figure 4-34 Vertical four-legged bucket foundation with levelled or distorted base

With respect to the jacket/tripod structure itself, the monitoring aspects are similar to a piled jacket/tripod, however without grouted connections.

4.7 Specific monitoring aspects for floating OWT foundations

Floating OWT foundations can be an alternative solution for wind farms located in deeper waters (>50m water depth). The different concepts include Spar type or semi-submersible floaters with catenary moorings or Tension Leg Platforms with taut moorings, see illustrated examples in Figure 4-35. The catenary moored floaters are stabilized by ballast and buoyancy, while the TLP is stabilized by the tension leg moorings.

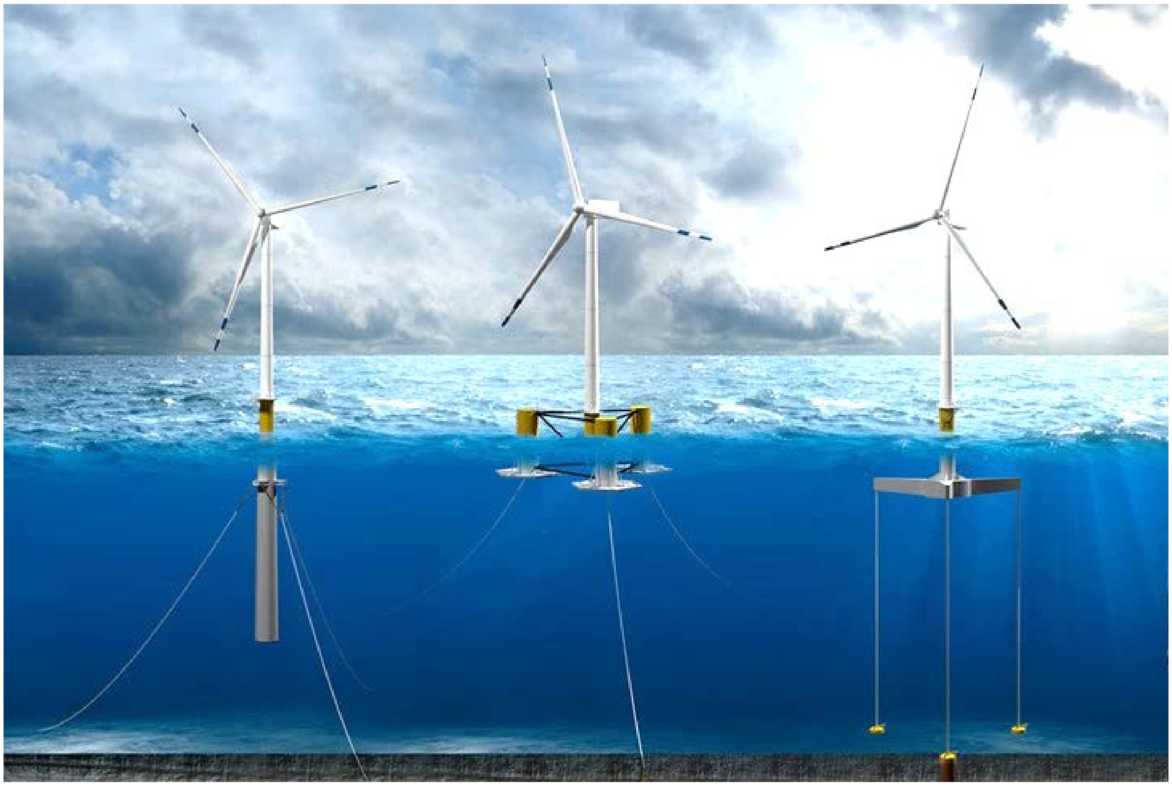


Figure 4-35 Different types of OWT floaters (Illustration: DNV-GL)

The mooring response and the turbine motions are the primary design issues for a floating OWT and relevant for monitoring. Dependent on the type of floater the critical motions to monitor may be different and more complex compared to fixed foundations. Free-floating bodies have six (6) degrees of freedom. The three (3) translational movements like heave, surge, sway and the three (3) rotational motions in pitch, roll and yaw, see Figure 4-37. To reduce extreme loads acting on the turbine especially heave, roll and pitch motions should be avoided or reduced. The TLP structures achieve the best performance and have low motion response, especially with respect to heave, pitch and roll. These motions are more or less eliminated through the taut tension leg mooring system. For deep draft floaters with catenary moorings like the spar or the semi-submersibles, heave pitch and roll motions are minimized but not eliminated. Surge, sway and yaw motions applies for both types of moorings.

Other stabilizing systems for the floaters may be hull trim systems allowing ballast water to be pumped to different compartments to compensate for vertical misalignment of the OWT caused by the wind force (thrust). The three columns on the WindFloat foundation are outfitted with water entrapment plates acting like brakes with significant dampening of the dynamic heave motions. The correlation between the vertical motions and the hydrodynamic loads taken by the water entrapment plates is of interest to monitor during field operation.

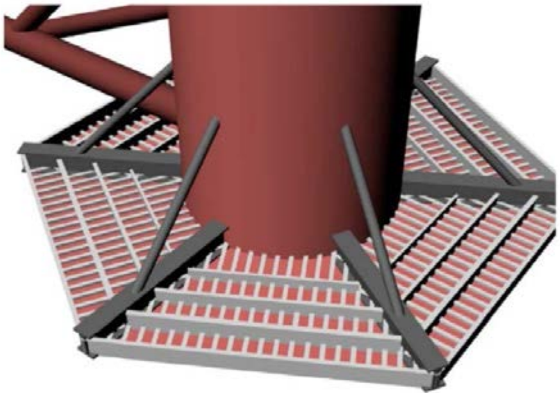


Figure 4-36 Water-entrapment plate on WindFloat (Source: Principle Power Inc.)

The seabed anchors for catenary moorings (normally driven piles, drag or suction anchors) are proven technology from the O&G industry and may be less relevant for monitoring as they seldom experience loads with detectable response of the anchor (also challenging with cabling to the surface). TLP anchors are however always subjected to tension load and even if most of the average tension usually is balanced by the dead weight of the anchors, they are more actively loaded compared to catenary mooring anchors and therefore vital for the stability of the TLP. Thus, in place monitoring is relevant for TLP anchors and can provide useful data for later design optimization, see section 5.11.

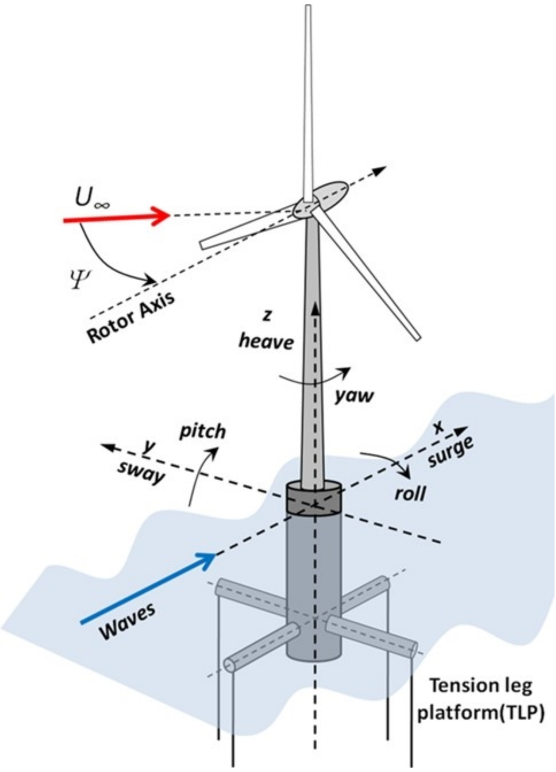


Figure 4-37 Definition of possible floater motions. Note for a tension leg foundation (as illustrated) the heave, pitch and roll motions will be restricted

Figure 4-38 Suction anchors for catenary mooring to a large floater installed 1997 in the North Sea

Gridline connections extend from the floater to the seabed and their operational behavior can be compared to flexible risers in the O&G industry, see Figure 4-39. Motion tracking of the riser cable provides important input for fatigue design of the cable assembly with bend restrictors and seabed anchoring points. Vortex induced vibration due to sea current drag forces acting on free cable spans is also a critical phenomenon that can affect the service life of exposed grid sections.

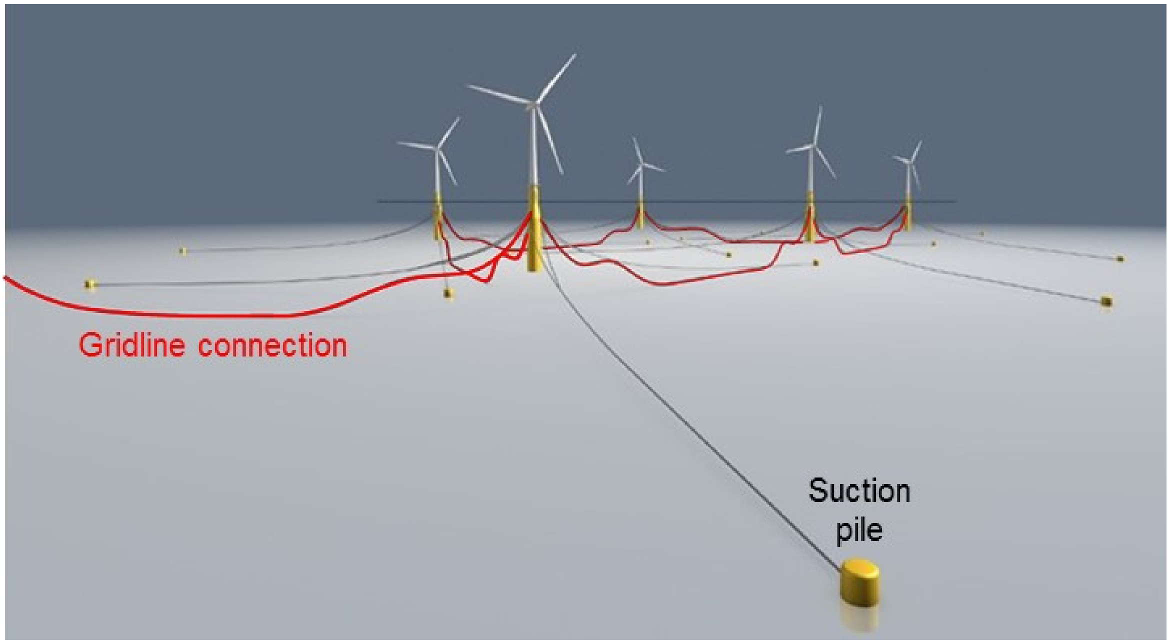


Figure 4-39 Hywind mooring system and gridline connection (illustration Statoil)

Combined and novel mooring systems as outlined in Figure 4-40 involve complicated modelling design verification by in-field monitoring would most likely be required.

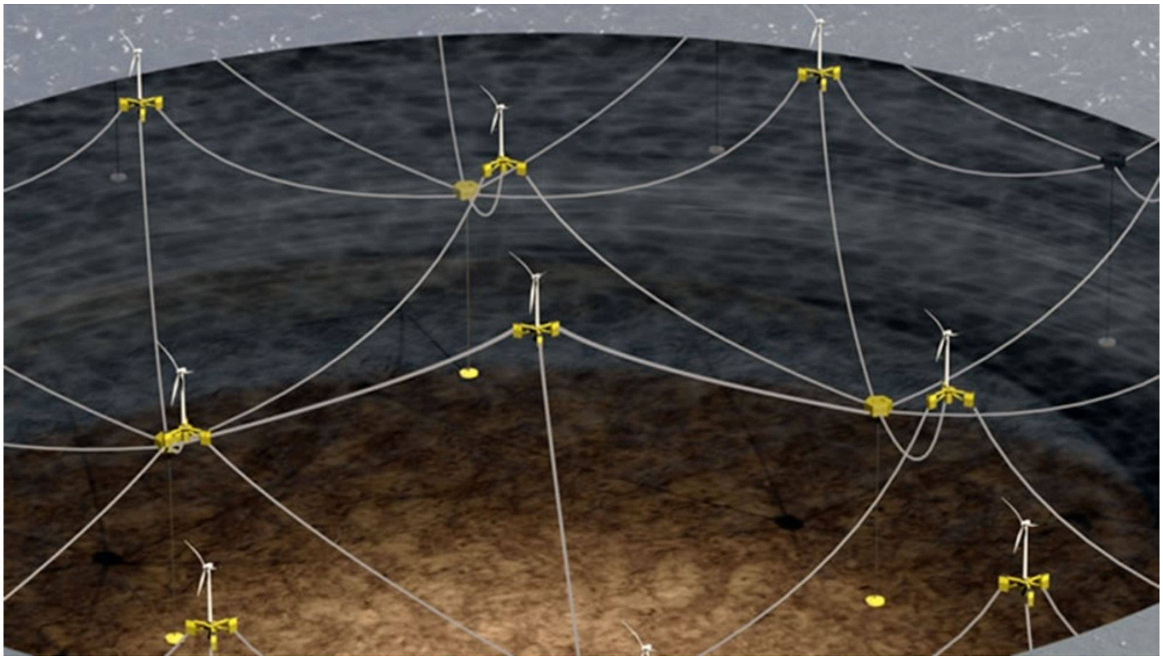


Figure 4-40 Concept with combined mooring system for multiple OWT's (Illustration DNV-GL)

The design of Statoil's Hywind Demo spar floater (Figure 4-41) was verified by means of a comprehensive monitoring program including more than 200 sensors, the following data was recorded in the field:

- Waves wind and current (magnitude and direction)
- Motion and position of floater
- Mooring line tension
- Strain gauges at tower and hull (4 levels – bending moments and axial force)
- Rotor speed, blade pitch and generator power
- Flap- and edgeways rotor bending moments
- Motion (tower pitch) /blade pitch controllers

Figure 4-41 Statoil's Hywind Demo spar OWT floater

4.8 Summary of recommended monitoring parameters

The following parameters may be relevant for long term monitoring of the different types of foundations:

All types of foundations (Metocean and Turbine data)

- Wind and Wave height
- Current
- Rotor speed, blade pitch and generator power
- Turbine vibrations/motions

Driven Mono pile foundations:

- Tilt of tower
- Lateral dynamic motion (FA and SS response) of the structure at different levels
- Corrosion TP and pile top
- Scour and currents (if the seabed is prone for sediment transport)
- Axial strain along the pile (P-Y behavior/soil stiffness) and grouted connection (load transfer)
- Deformations in grouted connection transition piece (if critical)
- Cyclic pore pressure along the pile (dependent on soil conditions)
- Lateral earth pressure along the pile (difficult)

Mono bucket foundation:

- Tilt of tower
- Lateral dynamic motion (FA and SS response) of the tower at different levels and dynamic rotation of the foundation bucket
- Scour and currents (if the seabed is prone for sediment transport)
- Strain in TP connection to bucket lid
- Corrosion in exposed members and CP protection

- Cyclic pore pressure along the skirts and inside bucket
- Load distribution, vertical earth pressure along the base of the bucket (if not grouted)
- Settlement (shake down)

Gravity base foundation:

- Tilt of tower
- Dynamic motion (rotation of the gravity base)
- Scour and currents (if the seabed is prone for sediment transport and without scour protection)
- Cyclic pore pressure beneath the base
- Contact stresses beneath the base
- Settlement (differential)
- Stress in reinforcement and cracks in concrete, if relevant connections to steel TP.

Piled jackets/tripods:

- Tilt of tower
- Strain in critical members and joints (fatigue)
- Cyclic pore pressures along the piles (for particular soil conditions and pile design)
- Integrity/deformation in grouted connections (pre-piling)
- Corrosion in exposed members and CP protection

Jackets/tripods with bucket foundations:

- Tilt of tower
- Dynamic motion of structure (lateral on TP and vertical on buckets)
- Scour and currents (if the seabed is prone for sediment transport)
- Strain in connection legs to buckets and critical members/joints
- Corrosion in exposed members and CP protection
- Cyclic pore pressure along the skirts of the buckets
- Load distribution, vertical earth pressure along the base of the bucket (if not grouted)
- Settlement (shake down)

Floating OWT foundations:

- Tilt of tower
- Dynamic motion of floater and turbine
- Position (offset) of floater
- Mooring loads
- TLP anchor response
- Strain in critical structural members
- Corrosion in exposed members and CP protection

5 SHM instrumentation solutions for OWT structures

An offshore wind farm comprises numerous foundation structures, for monitoring campaigns normally only a few selected OWT's can be instrumented with integrated SHM systems, see also section 3.4. In order to gain useful experience for the complete wind farm development, instrumented structures should preferable be installed in advance. Metmasts are installed some years ahead of full development and these structures are sometimes also outfitted with SHM systems in addition to the meteorological instruments. It should however be noted that the loads on a Metmast are significantly different compared to full scale wind turbine.

In order to add value to the instrumentation, the design should if possible allow for retrofit and re-use (of parts) on other structures in order to maximize the utilization and expand the data base obtained from the monitoring system. Some subsea instruments may be possible to install with a hoisting (guide wire) system allowing for deployment and recovery without under water intervention. Topside, battery operated wireless sensors may be used in some applications. Such sensors are not dependent on infrastructure such as cabling etc. and therefore mobile. It should be noted that the EM noise and strong magnetic fields around the turbine may affect radio transmission and must be checked out, wireless data transmission between outside and inside of the steel structure may also be limited.

For dynamic monitoring synchronization between different wireless units (for example accelerometers) may require special broadcast synchronization protocols. If possible, mobile or replaceable sensors should be considered. For example, in some cases permanent strain gauges can be replaced by long-gauge sensors (like an extensometer with very high precision). These are installed between brackets or studs on the structure, with mountings that allow for replacement, see Figure 5-1.

Figure 5-1 Example of long-gauge deformation sensors, fiber optic strain sensor by Smartech (left) and fiber optic extensometer by Opsens (right)

In many cases, the required integration of the sensor in the structure and restricted accessibility in the field, limit the mobility. Therefore the base case is normally to pre-install the instrumentation at the foundation construction yard. For "permanent" instrumentation it is important to consider the operational life, especially for sensors exposed to the environment and subsea. Materials and packaging are usually the limiting factors, following the general rule of thumb: higher cost-better quality-longer life. A realistic expectation may be 5 years of operation in such conditions without special maintenance or replacement.

Examples of instrumentation and sensor solutions for relevant SHM parameters are described in the following sections. The list of options is not complete and recommendations are mainly based on NGI's experience from more than 35 years with offshore structural and geotechnical instrumentation projects.

5.1 Wave height

A cost-efficient instrument to monitor wave height from a fixed position is to use a down-looking microwave radar measuring the air gap between the instrument and sea. It is also possible to range the water surface from below (instrument mounted below sea level) using acoustic Doppler's. The most commonly used down-looking wave radars are the *Maritime Microwave Altimeter* from MIROS or the *Rex Wave Radar* from Rosemount. The wave radars must be mounted with free sight to the sea surface and at sufficient distance out from wave breaking structures to monitor representative wave height, see Figures 5-3 and 5-4.

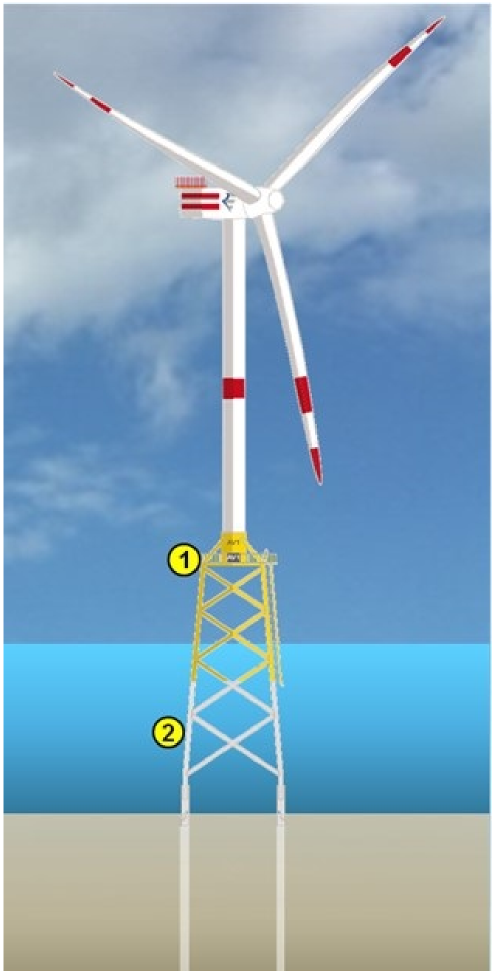


Figure 5-3 (Above) Rosemount wave radar on a mono pile OWT. The radar can be mounted directly on the TP guardrail with a hinged frame for easy maintenance from deck

Figure 5-2 Left) Positions of Down looking microwave radar (1) or Up looking acoustic Doppler (2)

Figure 5-4 Down looking micro wave radars from Miros (left) and Rosemount (right)

The up-looking Acoustic Doppler Current Profilers (ADCP's) usually provide multi-directional wave height measurements in addition to current profiling data. The most commonly used acoustic Doppler instruments are manufactured by TeledyneRDI or Nortek (AWAC)

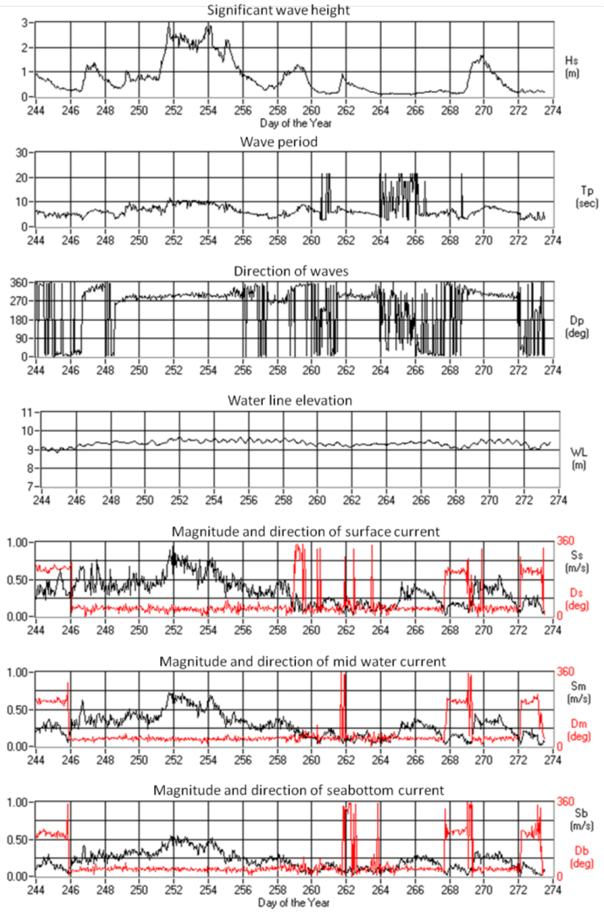
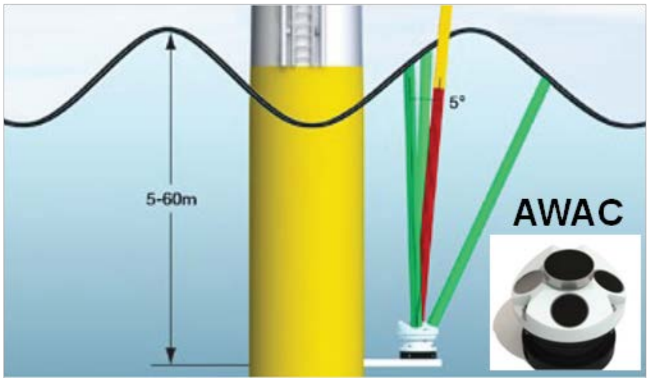


Figure 5-5 ADCP's from Teledyne-RDI (left) and typical wave and current data (right)



The disadvantage with a submerged instrument is limited accessibility and possible biofouling, the advantage is that wave and current measurements can be combined for one instrument.

Figure 5-6 AWAC from Nortek mounted on a mono pile foundation

5.2 Current

Dedicated current measuring instruments are divided into current meters and current profilers (ADCP). If ADCP's are used, the current profiling and wave height measurements can be combined in one instrument, see previous section.

Single point current meters can be based on mechanical (impeller) or electromagnetic sensing principles, see Figure 5-7.

Figure 5-7 Mechanical (impeller) and electromagnetic current meters from Valeport

For current monitoring in conjunction with scour assessment only the sea-bottom currents are of interest thus a 3D current meter can be used (placed close or at the seabed). A cost-efficient instrument is the Aquadopp current meter from Nortek which is delivered in Delrin housing for shallow water applications (down to 300m depth), see Figure 5-8.

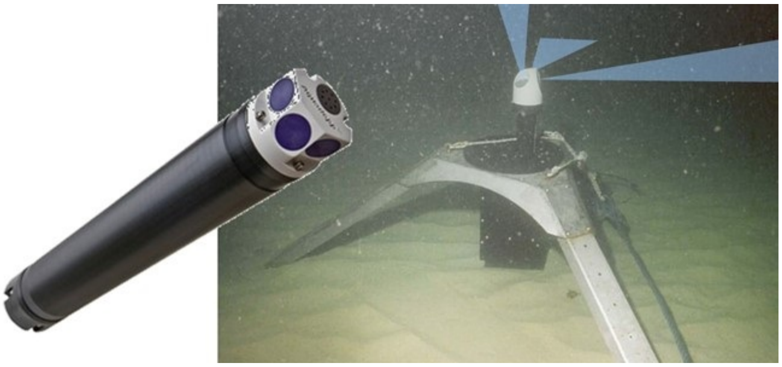


Figure 5-8 Norteks Aquadopp 3D current meter

5.3 Scour monitoring

Figure 5-9 (Left) Positions of scour monitoring sonars on a mono pile foundation

Scour development around an OWT foundation can be monitored by echo sounders or sonars scanning the seabed. The instruments (3) are fixed to the structure well below the water line and continuously measure the distance to the seabed around the foundation. Echo sounders or sonars are ranging the distance to the seabed reflector by measuring the travel time of submitted acoustic signals reflected from the seabed. The acoustic beams can vary in width and consequently in spatial resolution, the first arrival (shortest travel time) will usually be registered as the measured distance. The acoustic beam from the sonars must not be obstructed by structural elements as they will create an acoustic shadow or cause false reflections.

The acoustic frequency band suitable for this purpose is typical between 500-1000kHz, with a usable range up to 50-150m. With higher frequency a higher resolution is obtained but the range becomes shorter. The acoustic beam width is usual between 3-6°. Note that the acoustic sensors do not work in air and should therefore be mounted well below the splash zone. Entrapped air bubbles in front of the transducer head may interrupt the measurements.

Standard echo sounders or altimeters are single point instruments. Nortek has combined 4 acoustic beams for a cost-efficient solution in their scour monitoring sonar. The output from these instruments will be numeric ranging data, see Figure 5-10.

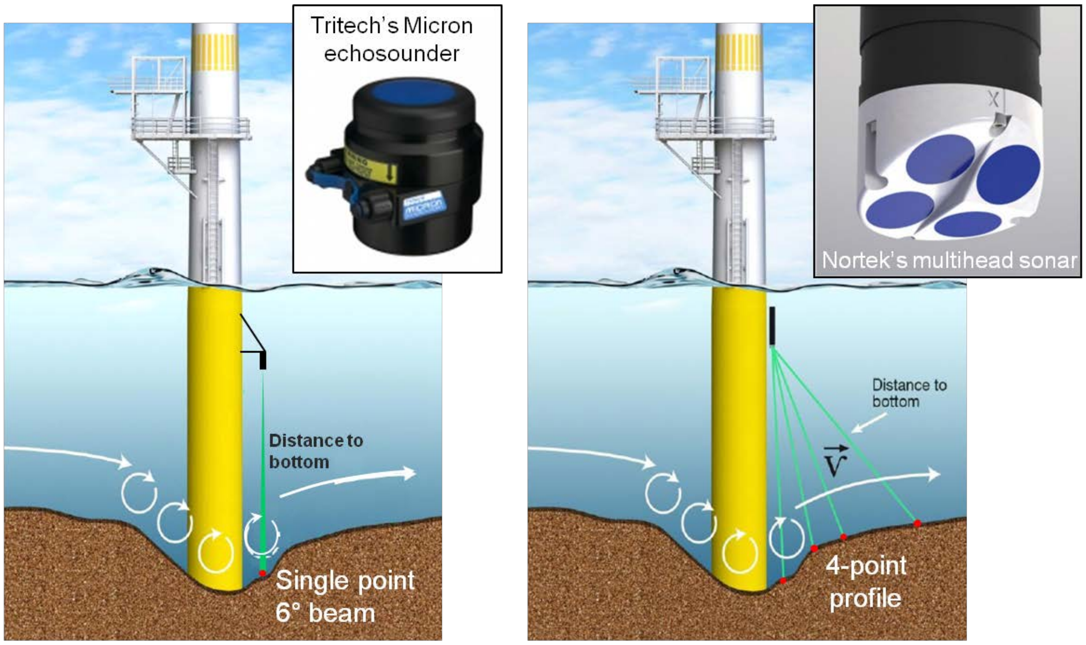


Figure 5-10 Single point echo sounder from Tritech and Norteks multi-head sonars for scour monitoring

For even more information about the seabed topography scanning (profiling) sonars can be used providing a continuous image of the seabed profile. The MS1000 scanning sonar system from Kongsberg-Mesotech represents the industry standard for this type of sonars and is frequently used for scour surveys, see Figures 5-11 and 5-12.

Note that seabed profiling with sonars is performed by scanning in vertical mode.

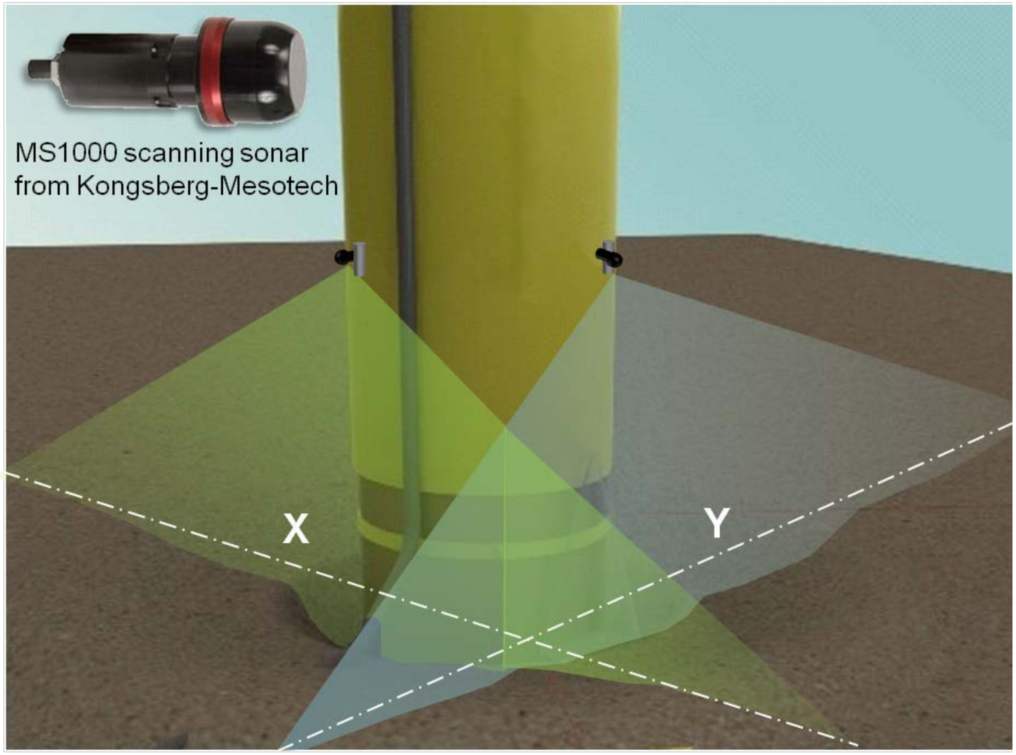


Figure 5-11 Two scanning sonars used for Mono pile scour imaging along two baselines

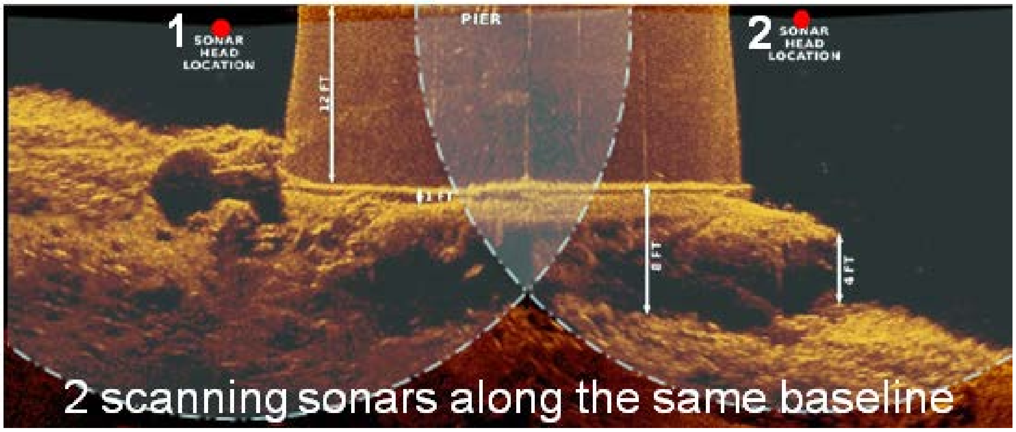


Figure 5-12 Sonar image of scour/seabed profile across a bridge pier using Kongsberg-Mesotechs MS1000 scanning sonars located at either side of the pier scanning in the vertical plane

For a full 3-D image of the scour development the scanning sonars can be mounted on rotators (obtaining dual axis rotation of the single beam), the scanned profiles can be merged in a 3D image during post processing using dedicated software, see Figure 5-13.

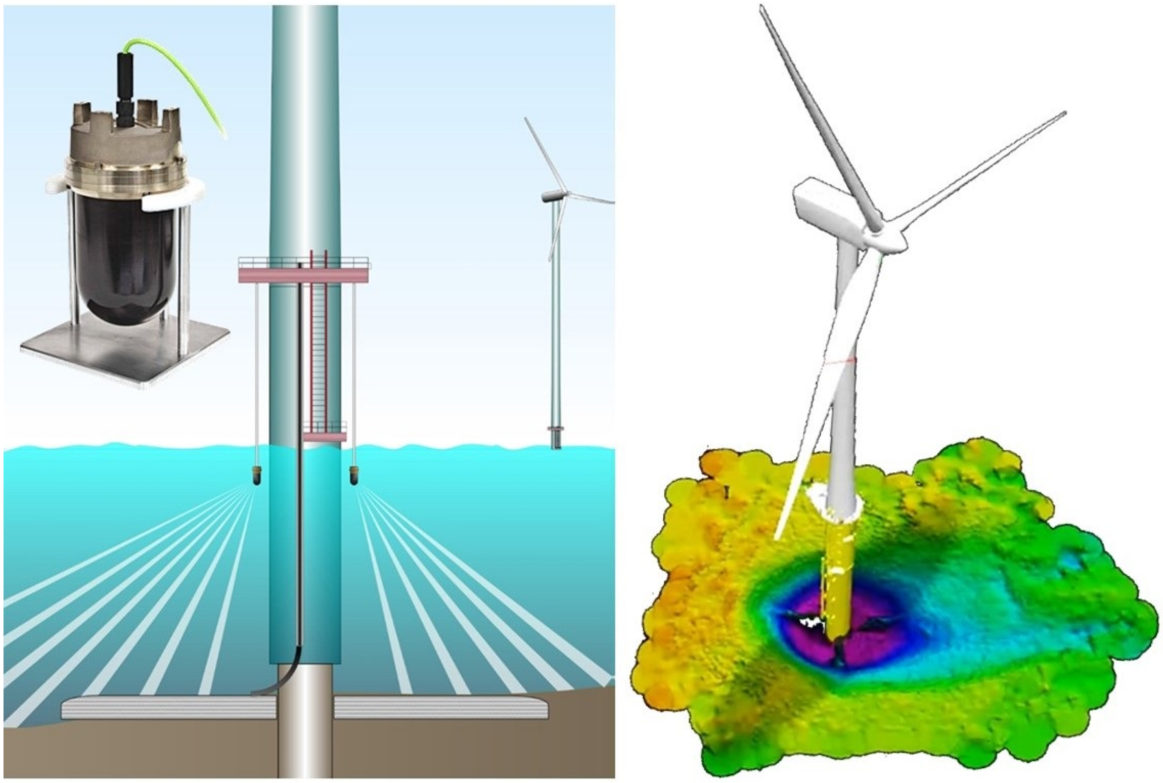


Figure 5-13 Kongsberg dual axis scanning sonar and post processed 3D image from rotated sonar profiles

5.4 Dynamic motion monitoring

Understanding the dynamic response of the structure and configuration of the accelerometers are perhaps the most important aspects when monitoring dynamic motion. The accelerometer data is used for modal analysis of the structure and tracking of Eigen frequencies. The data is used to verify stiffness and dampening of the foundation, changes in the dynamic response can also indicate structural degradation.

For an OWT foundation dynamic motion is usually monitored at 3-4 different levels (see Figure 5-14), namely Foundation, Tower base/midpoint and Turbine elevations. For tall towers, an accelerometer can also be located at the tower midpoint in order to monitor the 2nd mode of vibrations. For fixed foundations, mainly horizontal motions are of interest (X-Y), for jackets/tripods vertical accelerometers shall be used at the seabed level as the response to overturning moments mainly is in the vertical direction at the seabed. For mono piles, the main focus is on the horizontal dynamic motions.

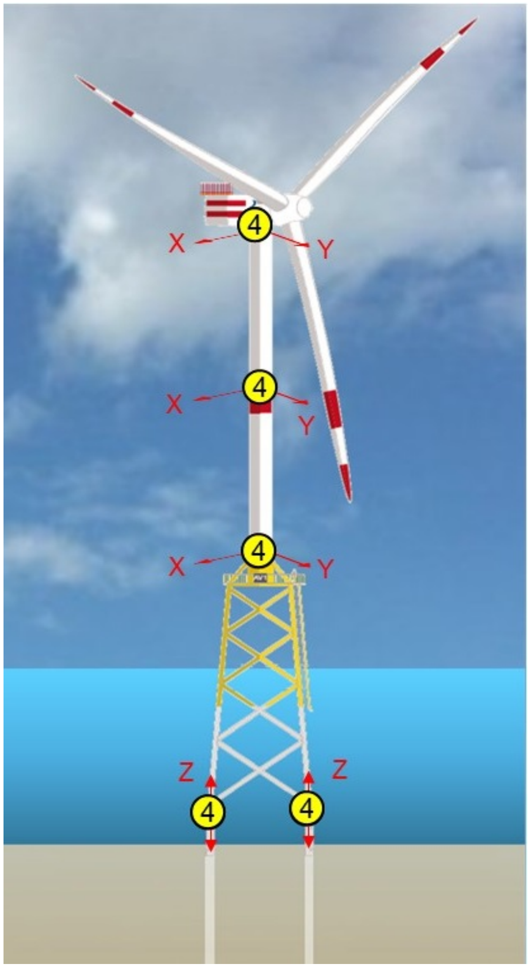


Figure 5-14 Key dynamic motion monitoring elevations for an OWT jacket structure

The sensitivity of the accelerometers must be tuned to the expected amplitudes of motion. Therefor very sensitive sensors must be used at the seabed foundation where the motions (if any) are expected to be small. Although the turbine usually is equipped with accelerometers integrated in the control system, a dedicated system should be used for monitoring the dynamic behavior of the complete structure (SHM). For later analysis, it is important that identical sensors are used at all locations and that the data from all sensors is synchronized.

In some cases, it is also of interest to monitor the yaw or twist of the foundation or tower. Angular rate gyros to monitor rotation are usually less sensitive and more expensive compared to linear accelerometers. Therefore, two linear accelerometers located at either side of a baseline are normally used to detect rotation. For dynamic SHM monitoring of typical OWT structures the frequency band of interest is typical from DC up to a few Hz. A range of suitable accelerometers is available in the market.

For SHM applications, high sensitivity and low noise accelerometers able to record slow accelerations down to DC must be used. Suitable types of accelerometers are force balanced (usually highest sensitivity), MEMs (Micro Electro Mechanical systems), Variable Capacitance (VC) or Piezo Resistive (PR) sensors. Note that the common piezoelectric type accelerometers are not DC.

In order to select a suitable accelerometer, the required sensitivity or resolution in motions must be specified (how small displacement must be traced) within the frequency band of interest. For practical reasons, reliable tracking of motions less than 0.25-1mm may be difficult even if the sensitivity of the accelerometer itself is good. In addition to the sensitivity, the sensor noise level must be considered as this will be the lower limit in the measuring range, see Figure 5-15.

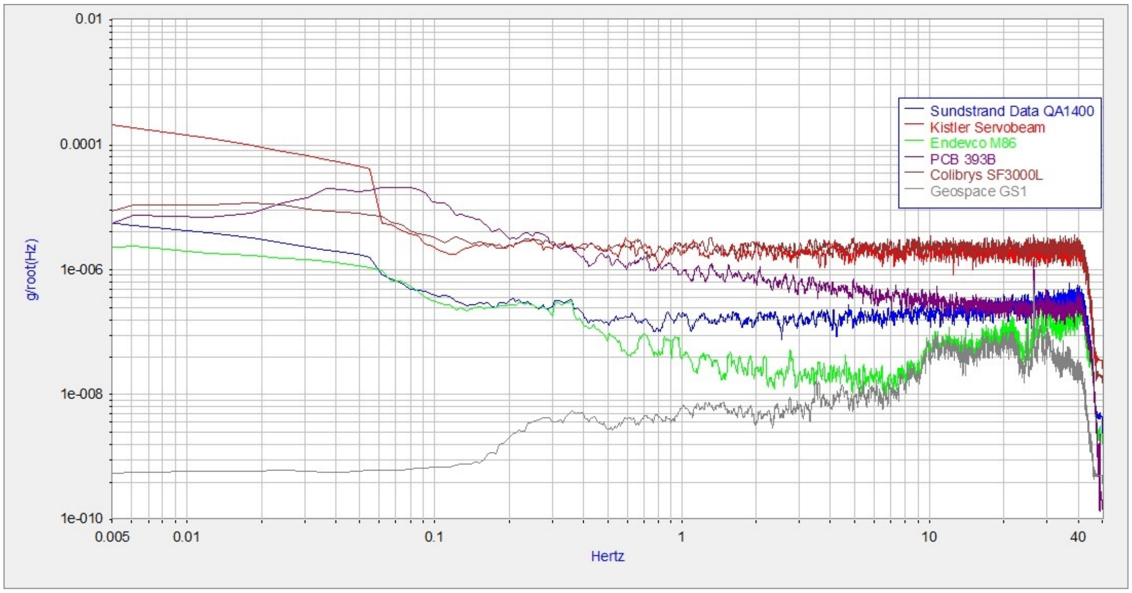


Figure 5-15 Comparison of noise density spectra's made by NGI for different accelerometers

In addition to the sensor noise, EM noise picked up by the cables must be considered. If longer cables are used, accelerometers with digital output are recommended. Instrument units with integrated accelerometers in the required directions allows for simplified installation and cabling. The initial accelerometers readings should be at high rate, band pass filtered and re-sampled at minimum 10 Hz rate (20 Hz is recommended).

Normally a measuring range of ± 1 to 2 g and frequency range of DC-200 Hz are sufficient for monitoring of the dynamic response of fixed foundations, examples of suitable sensors are given in Figure 5-16.

Figure 5-16 Examples of accelerometers suitable for SHM, from left to right: Force balanced accelerometers from Geosig with analogue output, Force balanced accelerometer from Jewel instruments with digital output and combined 3D mems accelerometer and dual axis mems inclinometer unit with Ethernet output from SENSR.

Mobile accelerometer units with simple hook-up (like the one from SENSR) can be moved between OWT foundations in order to check Eigen frequencies. The accelerometer units can be fixed with magnetic footings, although some suppliers claims that such fixtures not are sufficiently rigid. Welded/glued double plates or directly bolted fixtures are better.

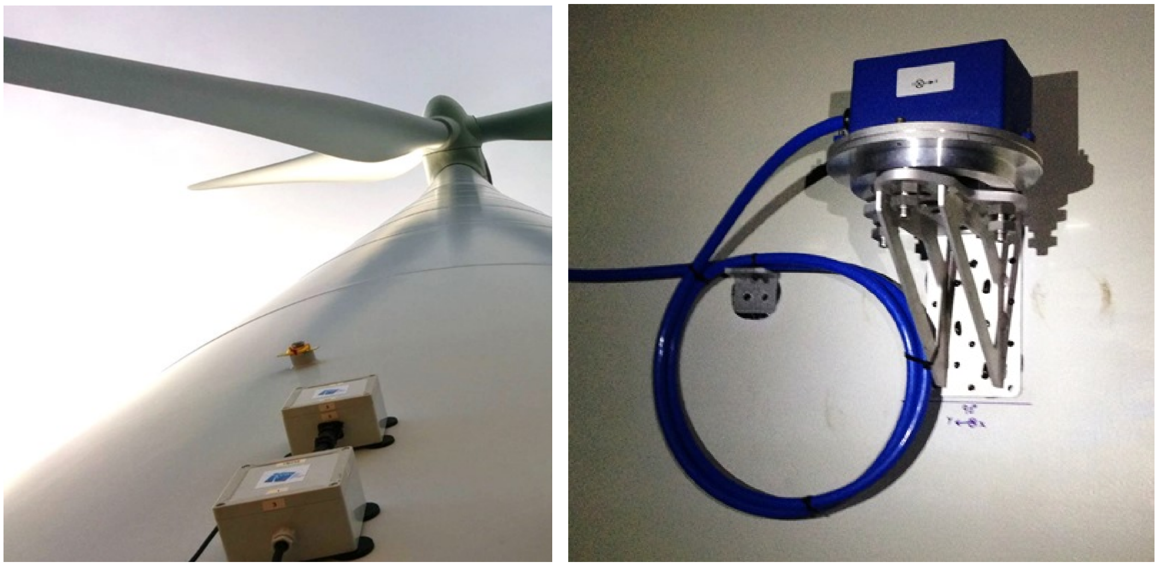


Figure 5-17 Left, accelerometers with magnetic footings (photo OWI-Lab) and mounting arrangement from NGI (combined accelerometer and inclinometer holder which can be turned)

The DC and gravity referred accelerometers can easily be checked by the tap and flip tests, checking the response when gently taping the enclosure and flipping the sensor (sensitive axis) vertical the oupt should be +1g pointing downwards and – 1g pointing upwards. Note that for vertical measurements the sensor range must be larger than +/-1 g as Earth's gravity will be included in the measurements, As described in section 4.7 floaters have more degrees of freedom compared to fixed foundations and accelerometer units (Motion Reference Units – MRU's) with 5-6 components may then be used, see Figure 5-18. It must however be checked if the MRU has sufficient sensitivity to monitor the motions of interest (the sensitivity usually not sufficient for fixed foundations).

Figure 5-18 Motion reference Units from Kongsberg- Seatex, normally used on larger DP vessels

In order to monitor motions of subsea power umbilical's for connection to the grid, small self-contained dynamic loggers may be used. These are equipped with accelerometers, data logger, memory and internal battery. The motions loggers are strapped/clamped directly to the umbilical by divers (or ROV), see Figure 5-19. The small standalone loggers are made for temporary monitoring have limited capacity with respect to battery and memory, but can be re-deployed after charging.

Figure 5-19 Subsea dynamic motion logger "IntegriPod" from Pulse deployed on unsupported sections of a subsea grid cable at the Gunfleet Sands wind farm (DONG Energy) in the UK sector of the Southern North Sea. The investigation was to determine the impact of tidal activity (Vortex induced vibrations) on the fatigue life of the cable

The following operational capacity applies for the IntegriPod dynamic motion logger from Pulse outfitted with three accelerometers and shown in Figure 5-19:

- Continuous logging @ 10Hz 12 days (limited by memory)
- Continuous logging @ 4 Hz 16 days (limited by memory)
- Continuous logging @ 2kHz 32 days (limited by memory)
- 20 minute logging every 2 hours @10Hz 76 days (limited by memory)
- 20 minute logging every 2 hours @ 4 kHz 96 days (limited by memory)

5.5 Tilt - Verticality of the tower

Tilt is measured by a biaxial inclinometer sensing the inclination along X and Y baselines. For **small** deviations from the horizontal, the maximum tilt can be derived from the vector sum of X and Y inclination. The heading of maximum tilt is derived based on the headings of the X and Y baselines and their magnitude of inclination.

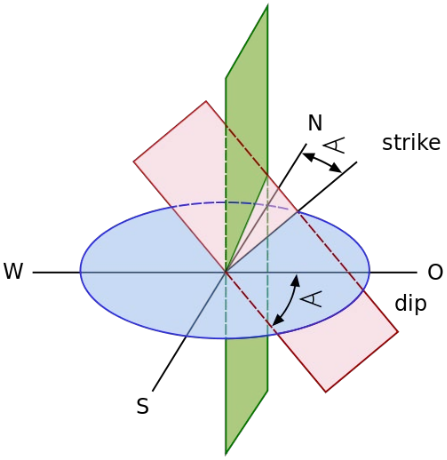


Figure 5-20 Above: Definitions Dip angle = Maximum tilt and Strike = Heading of maximum tilt

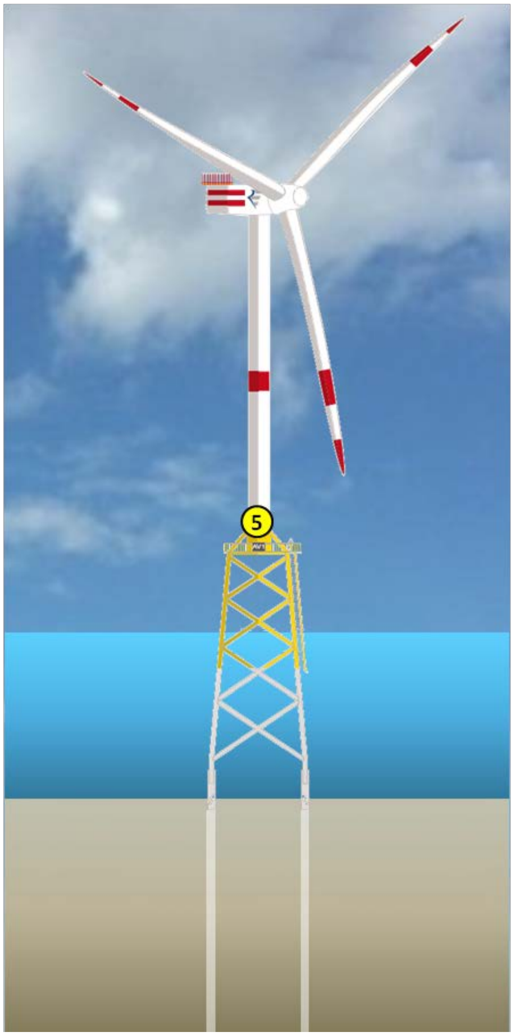


Figure 5-21 Left: The biaxial inclinometer is preferable located at the base of the tower (5)

Many high precision inclinometers are available in the market for this purpose. As for accelerometers the force balanced (servo) and gravity referred inclinometers have the best precision. However, today most of the precision MEMs based inclinometers have sufficient accuracy. Normally, an overall accuracy better than 0.01° and a range within ±3-5° is sufficient for fixed foundations. As tower inclination measurements relate to small deviations from the vertical axis, full scale accuracy and linearity is of less importance. Zero point drift and temperature sensitivity are the critical parameters for specification of suitable inclinometers for monitoring tower tilt. For in-situ calibration (zero point check) it is an advantage if the instrument can be turned 180^0 (as shown in Figure 5-17), the same reading with opposite sign should be obtained when the sensor is turned (unless the zero point has drifted).

The common error when measuring inclination is that the mounting offset (alignment to the structure) is not properly determined. Also the mounting location may not be representative for the tilt of the structure, local deformation due to temperature gradients (direct sunlight) or structural flexing may generate false readings. Solid mounting and screening from sunlight is important. These aspects are in most cases more important for the overall measuring accuracy than the sensor performance. For large structures, it can be challenging to determine the offset in mounting alignment compared to the baseline of the overall structure, thus a reference baseline must be used (for example the mounting flange to the tower).

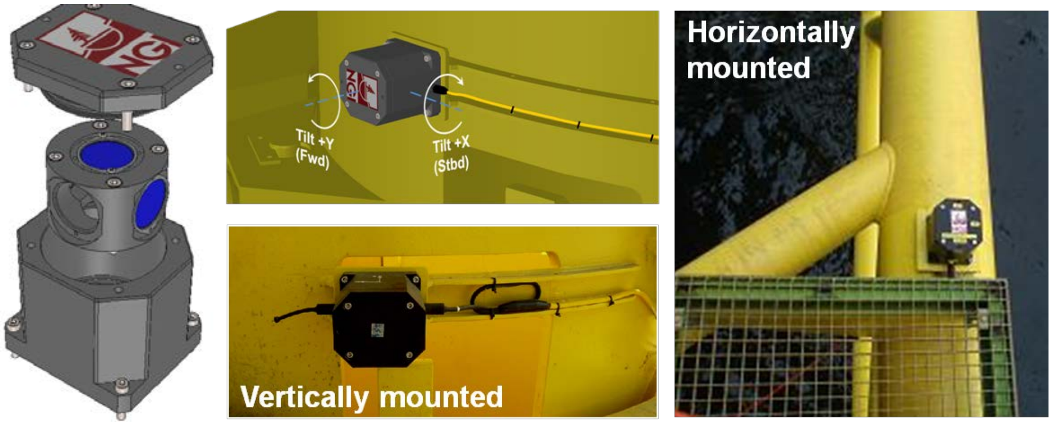


Figure 5-22 NGI biaxial inclinometer assembly with capacitive inclinometers (blue), the unit can be mounted horizontally or vertically by changing the internal position of the two inclinometers. These enclosures are intended for subsea use and without turning option (zero point check)

5.6 Structural strain, stress and fatigue

Structural strain is measured in order monitor derived stresses and to assess distribution of forces but also to assess structural health at critical locations (joints etc.), this includes stress magnitude with respect to yield and stress history with respect to fatigue.

The recorded strain is converted to stress using Hooke's law:

$$\sigma = E \cdot \varepsilon$$

where σ represents stress, ε represents strain and E represents Young's modulus of elasticity.

The dynamic stress response is important for SHM on offshore foundations, the strain gauge monitoring solution must allow for dynamic sampling rates. See Figure 5-23.

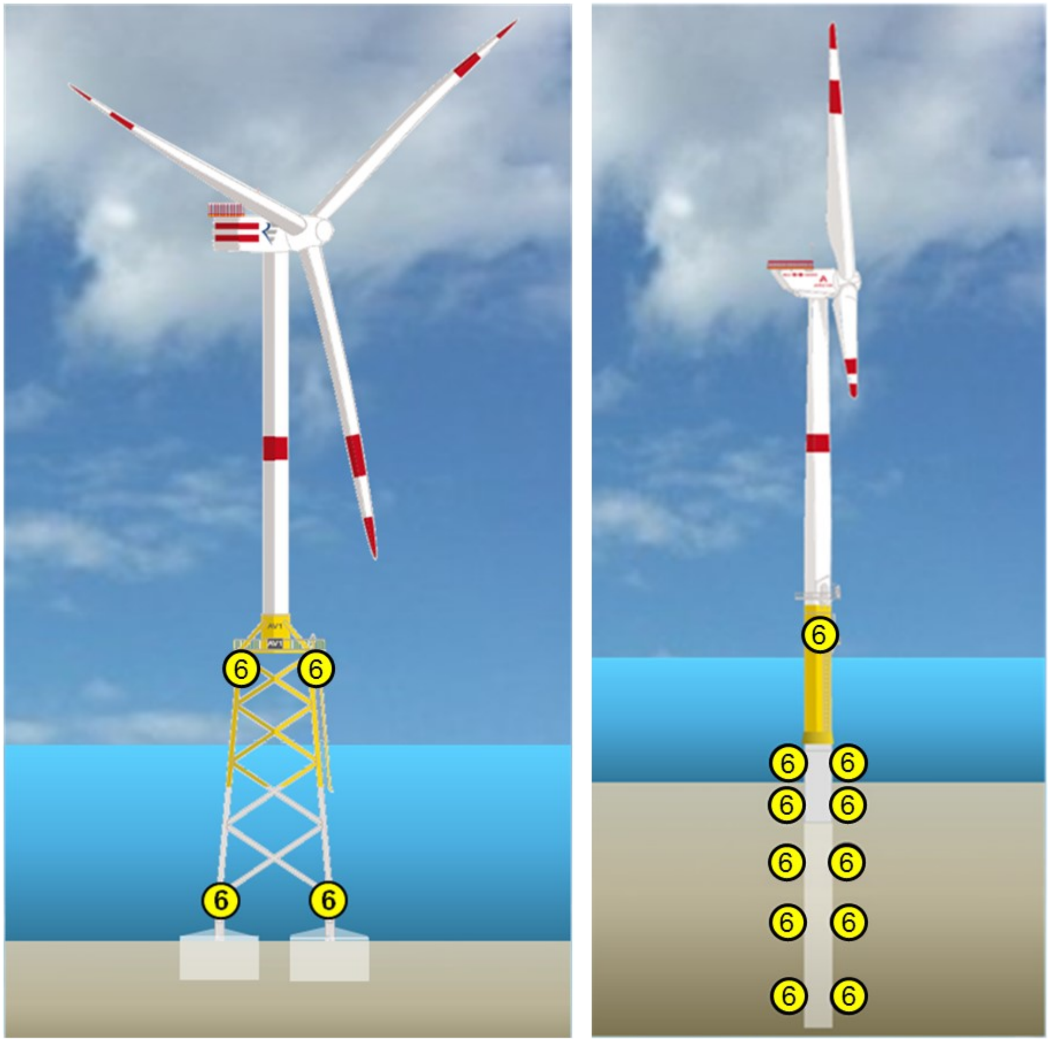


Figure 5-23 Example of structural stress monitoring. In the left figure the strain gauged sections (6) are used to monitor foundation loads distributed from the legs of a jacket (axial stress). For the mono pile (right) the strain gauges (7) are used to monitor the moment distribution with depth along the pile

5.6.1 Resistance wire strain gauges

The most common type of strain gauges are the resistance wire gauges (glued foils or spot welded). These strain gauges are applied for point measurements and must be pre-installed on the structure, see Figure 5-24.

Figure 5-24 Glued Foil strain gauge (left) and micro spot welded strain gauge (right). Some models of spot welded strain gauges have the resistance wire protected inside a water and pressure resistant tube allowing them to be immersed in seawater

In order to measure strain correctly extremely small changes in resistance of the strain wire is sensed with high accuracy using bridge measurement circuits. A strain gauge bridge circuit indicates measured strain by the degree of imbalance, and uses a precision voltmeter in the center of the bridge to provide an accurate measurement of that imbalance. The simplest bridge configuration is the quarter bridge, see Figure 5-25.

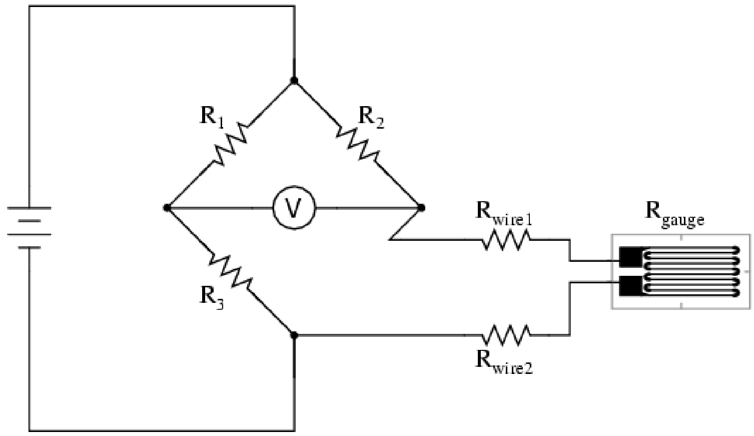


Figure 5-25 Quarter-bridge strain gauge circuit

In this configuration, the hook-up wire resistance (R_{wire}) has a significant impact on the operation of the circuit. This effect can be reduced by adding a third wire directly between the strain gauge and the voltmeter. The strain gauge is very sensitive for temperature changes, which not are compensated with this configuration. However, by replacing resistor R_2 with a dummy (unstressed) strain gauge, the effect of temperature changes can be cancelled, see Figure 5-26.

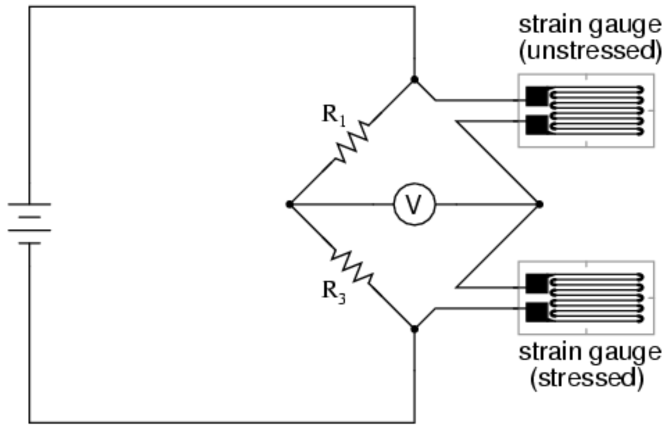


Figure 5-26 Quarter-bridge strain gauge circuit with temperature compensation

For measuring applications were the upper strain gauge is exposed to the opposite force compared to the lower gauge (i.e. when the upper gauge is compressed, the lower gauge will be stretched, and vice versa) the circuit illustrated in Figure 5-26 can be used as a half-bridge (both gauges are stressed and temperature effects cancelled). However, such configurations are normally not practical applicable for strain measurements on structures.

A full bridge configuration is when all resistors in the bridge circuit are replaced by strain gauges, see Figure 5-27. NGI use a full bridge configuration with unstressed (dummy) gauges for temperature compensation and 6 wire configuration (extra sense lines controlling the excitation voltage at the bridge for compensation of variations in cable resistance). Excitation and sense lines are twisted pairs for cancelling of EM noise in the cables. An example of a water proof full bridge and temperature compensated strain gauge assembly is shown in Figure 5-28

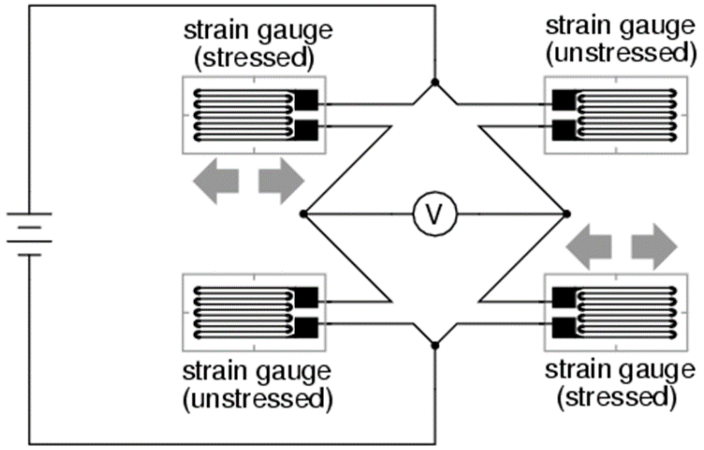


Figure 5-27 Temperature compensated full bridge configuration (4 wire system)

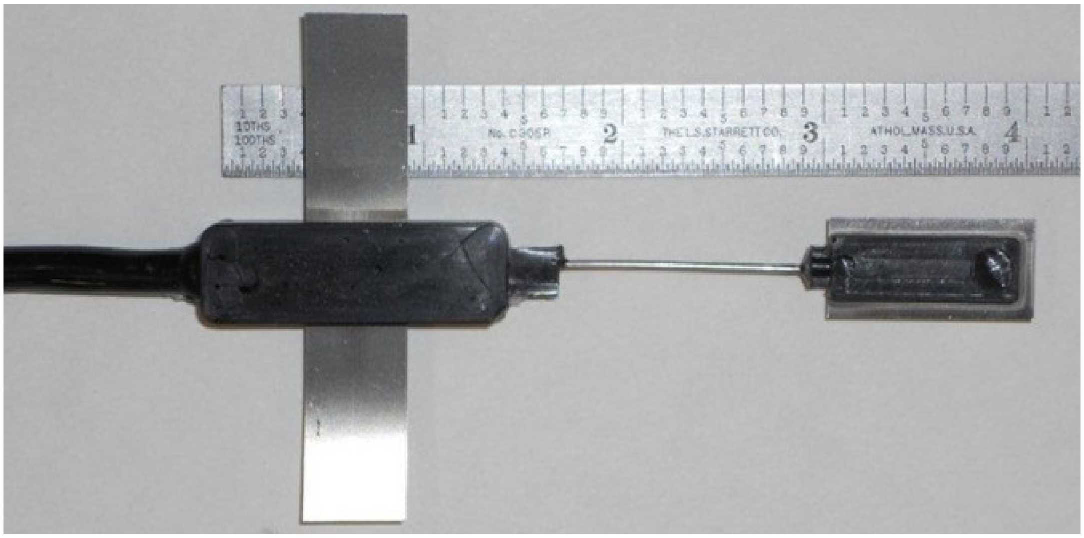


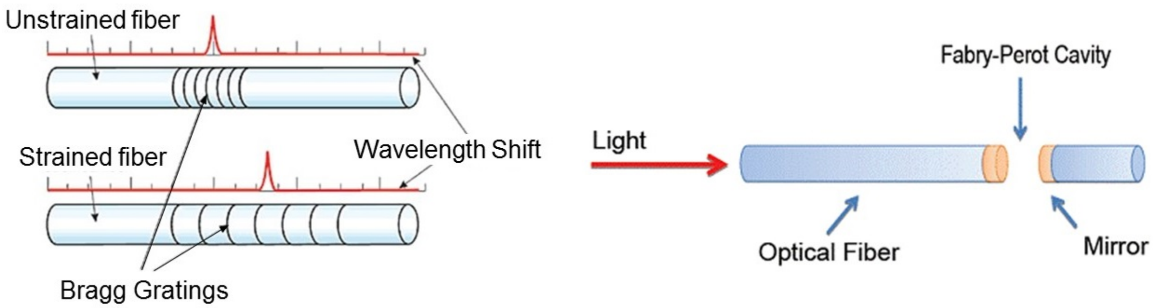
Figure 5-28 HPI waterproof strain gauge for micro spot welding. The temperature compensating elements are inside the cable transition piece to the left in the picture

For excitation of the bridge circuit and amplification/read-out of the signal, strain gauge amplifiers are used. The strain gauge amplifiers are rather costly and each unit should serve several measuring channels, normally the strain gauge amplifiers must be located remotely from the strain gauges themselves, therefore a robust bridge configuration is important at the measuring point.

5.6.2 Fiber optic strain gauges

Fiber optic strain sensors are in many aspects an advantageous alternative to the traditional resistance wire gauges. Several optical sensing principles exists, however for dynamic measurements the Fiber Bragg Grating (FBG) sensor is the most common type. By means of operating at different wave lengths several FBG sensors can be multiplexed and implemented along the same optical fiber. The Fiber Bragg Gratings are wave specific reflectors (mirrors) in the optical fiber and strain is recorded when the distance between the "mirrors" are changed, see Figure 5-29. By means of using gratings sensitive to different bands of wavelengths several FBG sensors can operate along the same fiber.

Other common types of fiber optic strain gauges for point measurements are based on the Fabry-Perot (FP) cavity sensing principle. The sensing part is essentially composed of two parallel mirrors separated by a cavity, see Figure 5-29. The spacing between the mirrors (or length of the cavity) is strain (and temperature) dependent and determined by an interferometer. These strain gauges are single ended (must be located at the end of the fiber) and use white light or low coherence interferometry which is less sensitive to dampening in connectors and splices.



5-29 Operating principles for FBG (left) and FP (right) fiber optic strain gauge

True distributed fiber optic sensor system based on Brillouin or Rayleigh scattering derives the strain data based on many repeated interrogations and are mainly used for static measurements, the long response time is not suitable for SHM on OWT foundations.

The FBG and FP strain sensors are available in different configurations and layout for similar mounting as for strain gauges, see Figure 5-30 and 5-35.

Figure 5-30 Different types of FBG strain gauges from HBM

True distributed fiber optic sensor system based on Brillouin or Rayleigh scattering can sense strain along the entire length of a fiber optic cable and can therefore contain thousands of measuring points along a single fiber. However, the signal interrogation is more complex and includes averaging of many interrogation cycles. The acquisition time for recording strain along the fiber can be from 5 to 20 minutes (dependent on required resolution). Distributed fiber optic strain systems are mainly used for static measurements, the long response time is not suitable for SHM on OWT foundations.

The FBG sensors are interfaced by an optical sensor interrogation module. The unit illustrated in Figure 5-32 can operate up to 4 FBG fiber cables, each with 20 FBG sensors (80 FBG sensors in total) at a maximum scanning rate of 500 Hz. Data from the interrogator is streamed to the Data acquisition PC by Ethernet interface.

Figure 5-31 Dynamic FBG sensor interrogation module from Micron Optics

5.6.3 Resistance wire vs fiber optic strain gauge

The **mounting and bonding** of the strain gauge to the structure is important in order to obtain representative readings, similar techniques (micro spot welding or glued) are used for both resistance wire and fiber optic strain gauges.

Figure 5-33 shows measurements of 6 FBG strain sensors installed in pairs with welded and non-welded (glued) mounting, By plotting the output from the welded gauges (WFBG) against the glued gauges (FBG), it can be concluded that in general the welded strain gauges have a reduced sensitivity compared to the glued sensors. However, for long term applications and field mounting the welded strain gauges are recommended due to a more robust fixture.

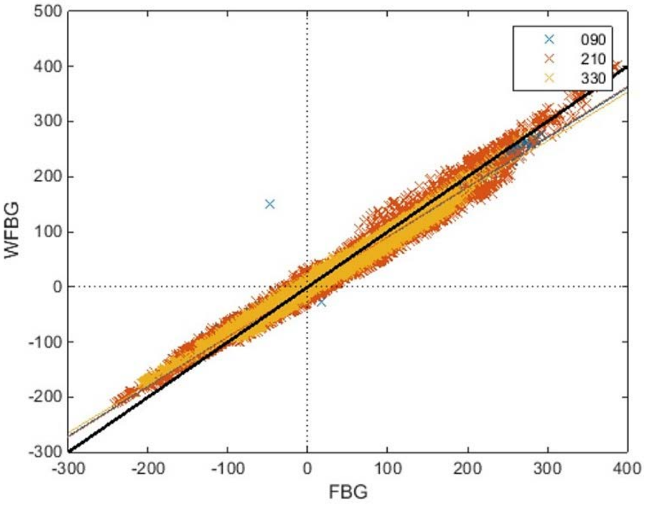


Figure 5-32 Comparison of sensitivity between welded and glued FBG SG's

Sealing against water ingress, although the fiber optic strain gauges not fail immediately if exposed to seawater, they will degrade with time according to all suppliers. Thus, the requirements for sealing of the measurement points and cable connections are similar for both optical and resistance wire strain gauges. The sealing of the measuring point is also important in order to prevent corrosion advancing into the bare steel and strain gauge bonding area, potting of the measuring points in the field requires good workmanship and patience, see Figure 5-34.

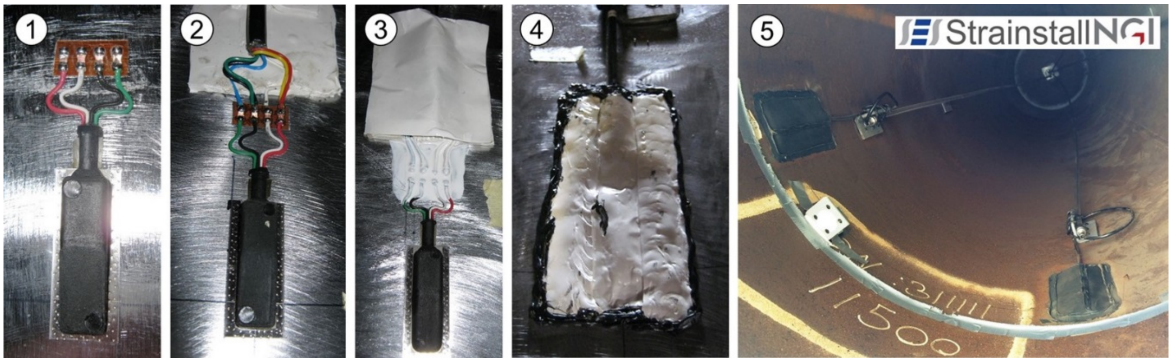


Figure 5-33 Installation of strain gauges for use under water; 1) Fix the strain gauge and cable terminal on the thoroughly prepared steel surface, 2) hook-up and fix the cable, 3) seal (pot) the cable connection and 4) Seal and pot the complete assembly, 5) is showing the completed installation (photos: Strainstall/NGI)

Cabling and hook-up, the obvious benefit with fiber optic strain gauges is that only one fiber is required for hook-up, compared to 4-6 leads required for hook up of a full bridge measuring point with resistance wire gauges. However, fiber optic cable junctions and splicing is more complicated and sensitive compared to electrical leads and continuous routing of the optical cable to the data acquisition system will make installation on the structure very challenging. The fiber optic cable is also more sensitive for rough handling at the yard. Thus, pro and cons with respect to cabling depends on the instrumentation plan. For example cabling of string with strain gauges string along a mono pile may be simpler using fiber optic sensors as they are daisy chained along one continuous cable, for a braced structure it may be the opposite as the complicated routing may call for several cable junctions.

Opsens use white-light polarization interferometry (WLPI) for interrogation of their fiber optic sensors, this technique is less sensitive for dampening/losses in fiber connections and allows for simpler hook-up. The "quick connect" adaptor allows for hook-up using ordinary fittings (Swagelock) or similar, see Figure 5-35. The "quick connector" is robust and can resist pressures up to 5000 psi and suitable for permanent subsea use. Opsens also claims that their WLPI sensors are less sensitive to temperature changes and transverse strain.

Figure 5-34 Weldable fiber optic strain gauge from Opsens based on Fabry Perot sensing principle and white light interferometry, fully submersible assembly with quick connector

Mechanical protection, strain gauge installations are fragile and must be well protected to prevent damage. This is especially important for instrumented piles or other structural elements being embedded in the seabed sediments. Normally the strain gauges are mounted inside channel protection elements with cover plates for closure of the channels after completed installation of the strain gauges and cabling. The lower end of the channel must be equipped with a driving shoe to reduce shear forces on the channel. Cables etc. must be well secured during pile driving. Figure 5-36 shows examples of protection and rigging.

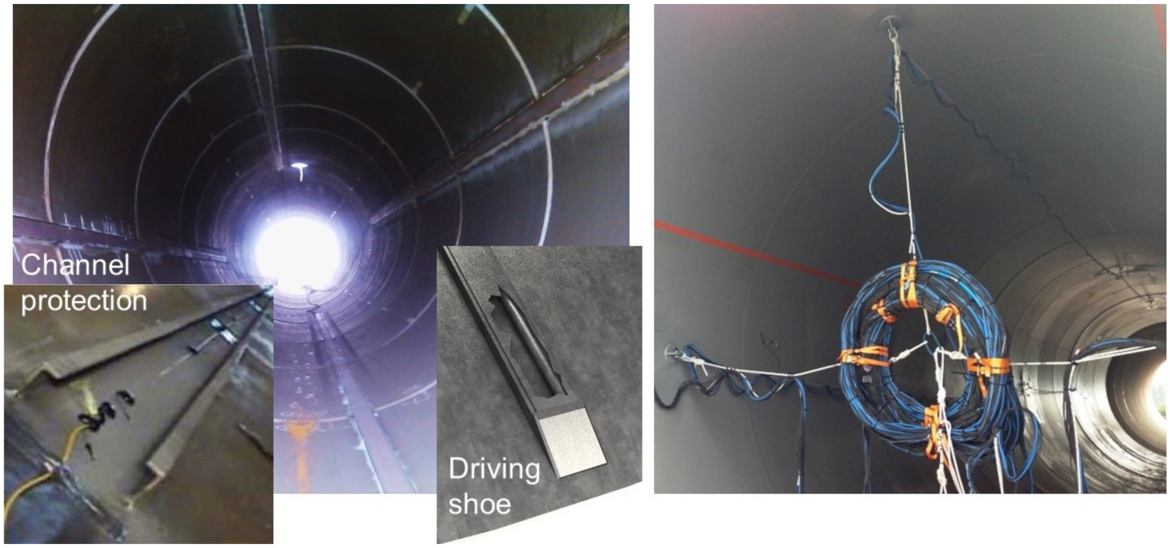


Figure 5-35 Strain gauge channels with driving shoes at the inside of a monopole and (right) cables bundles secured by ropes during pile driving

Noise, the fiber optic signals are immune against EM noise which is an advantage. However, the EM noise influence can be limited to negligible magnitudes for resistance wire gauges by means of proper configuration and wiring (twisted pairs).

Precision and drift, the overall precision in strain measurement is comparable for both types of strain gauges. They are both sensitive for temperature drift which can be compensated by using dummy gauges and/or measuring temperature in the vicinity of the gauge. They are both sensitive to transverse loads which can be compensated for by adding a transverse strain gauge in the configuration, see Figure 5-37.

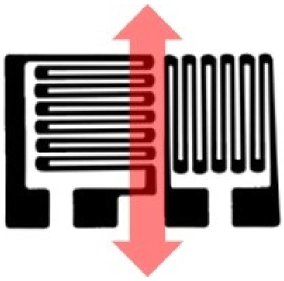


Figure 5-36 T-rosette configuration of strain gauges for compensation of transverse strain

Zero point readings, after mounting and bonding both types of gauges will read strains which to a large extent depends on the stresses introduced during mounting. Thus, both resistance and optical strain gauges must be calibrated after installation. The “as installed” offset must be determined based on comparing sensor readings in a situation when the strain in the structure is known or can be assessed theoretically. Offset readings can for example be made when the foundation is hanging vertical in a crane or vertically parked on a flat surface at the yard or feeder port. If only dynamic strain/stress variations are of interest the mounting offset does not matter.

5.6.4 Other solutions for stress and deformation monitoring

Strain gauges provide point measurements with high sensitivity. If the strain is measured across a longer base line, the deformation between the end points becomes larger and can be recorded by extensometers or other types of deformation sensors. For example, vibrating wires or long gauge fiber optic strain sensors. The long gauge type of instruments is suitable where the interpretation of point measurements is difficult due to complex strain fields or when local strain or deformation can be large or non-representative because of cracks or other inhomogeneity's, for example in concrete, see Figure 5-38.

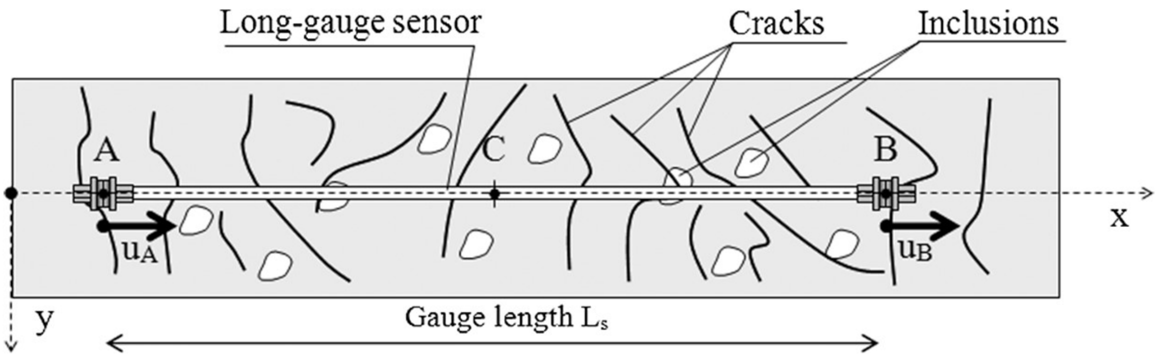
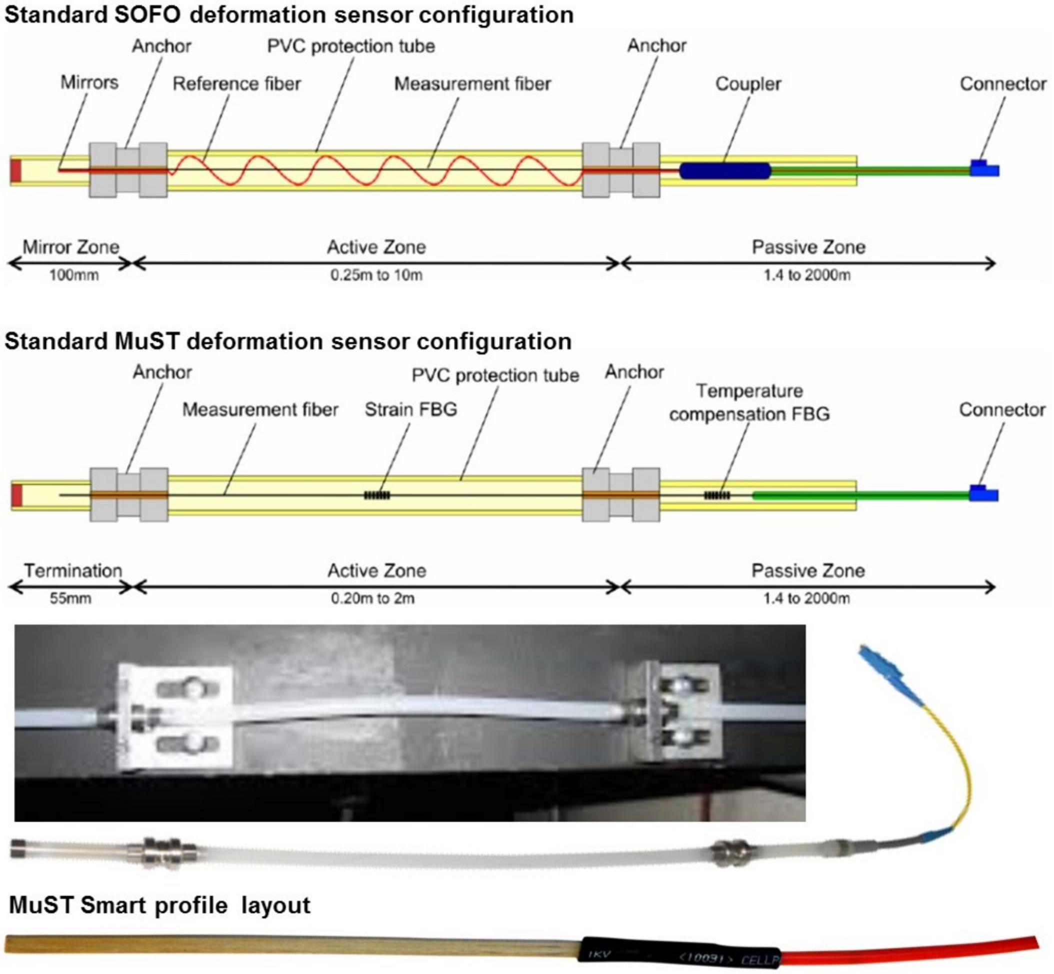


Figure 5-37 Application set-up for long gauge fiber optic strain sensor for measurements on concrete specimen. The gauge length between fixture points A and B can typical be from 0.2 to 2m

The long gauge fiber optic strain sensors transform a distance variation into a change in the balance between two optical fibers that can be measured with a read-out unit. The sensors can be based on different principles but with similar performance. Two types of long gauge fiber optic sensors are illustrated in Figure 5-39, namely:

- SOFO (Surveillance d'Ouvranges par Fibers Optiques) which is a low coherence interferometric sensor using two fibers one for measurement and one for temperature compensation
- MuST sensor is made up by two FBG sensors along the same fiber. The first FBG is located in the strained section of the fiber between the attachment points to the structure, the second FBG is located in an unstrained section of the fiber directly after the attachment point and used for temperature compensation. The outlines of the MuST sensor is similar to the SOFO sensors.


Standard SOFO deformation sensor configuration

Standard MuST deformation sensor configuration

MuST Smart profile layout

5-38 SOFO and MuST deformation sensor assemblies by Smartec, the sensors can be directly embedded in concrete or clamped externally on the element to be monitored. The Must sensor with 200mm active zone can also be fully encapsulated in a composite profile for use under water.

The sensors consist of two main parts: active and passive. The active part contains the he measurement fiber and measures the deformations between its two ends, see Figure 5-39. For the SOFO sensor the temperature compensating (reference fiber) is located in the active part (parallel to the measuring fiber) and for the MuST sensor, the reference fiber is located in the passive part (in line with the measuring fiber). Both types of sensors have similar lay out however, a SOFO sensor is single ended while the MuST sensors can be hooked up in series along the same fiber. The MuST FBG sensors also can be interrogated at high speed and is therefore better suited for dynamic measuring applications.

Other types of long base strain gauges are based on the vibrating wire principle or use of LVDT (Linear Variable Displacement Transducer) or Fibre optic extensometers based on the Fabry-Perot measuring principle. These instruments can be bolted or clamped to the structural elements or retrofitted to pre-installed mounting brackets, see Figure 5-40. Extensometer type of instruments can also be used to monitor crack propagation.

Figure 5-39 Vibrating wire strain gauge (left) and LVDT type of extensometer (right) often used as crack or joint meter (larger deformation range than a strain gauge)

For interfacing vibrating wire sensors special excitation modules must be used, this type of sensor is more common within geotechnical monitoring than SHM. The frequency signal (only two wires are required for hook-up) are however not sensitive for EM noise and suitable for long cables.

Probably the most accurate extensometers with respect to long term drift are based on magnetostrictive sensing (micro pulse transducers), see Figure 5-41. Another advantage with this type of sensor is that the sensing element is hermetically sealed and can be submerged (the moving part only consist of a magnet).

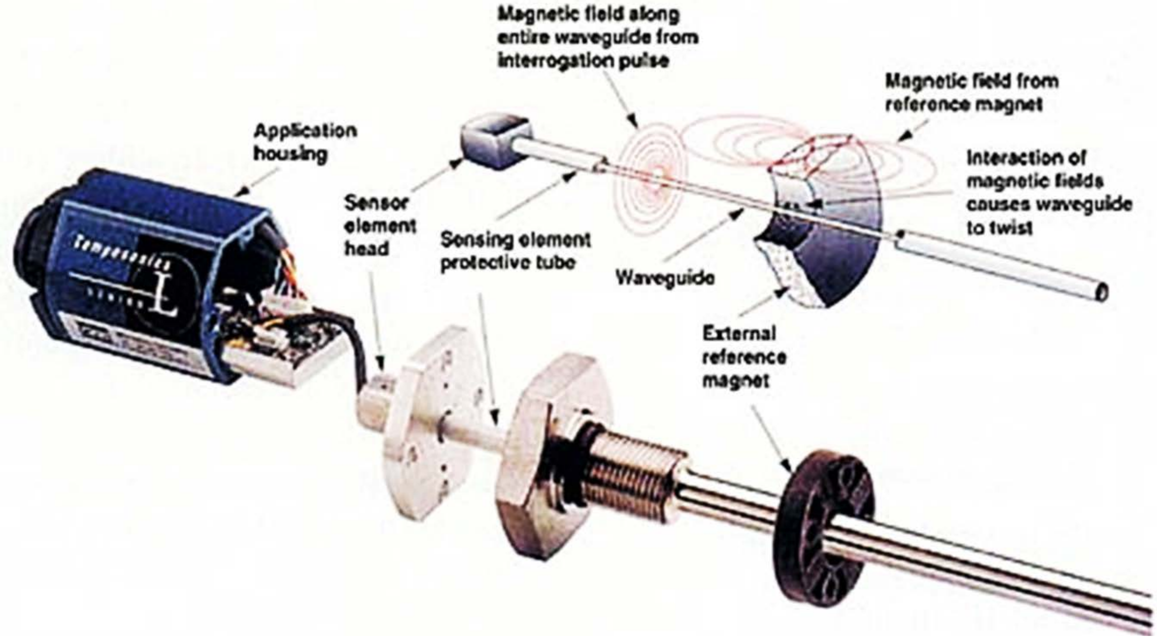


Figure 5-40 Magnetostrictive (micropulse) linear displacement transducer

Retrofitted instruments for strain/stress measurements are usually of long base extensometer type and in many cases pre-installed supports or brackets are not available. The fixture must then be customized for the application, for steel structures strong magnets can be used, see examples in Figure 5-42.

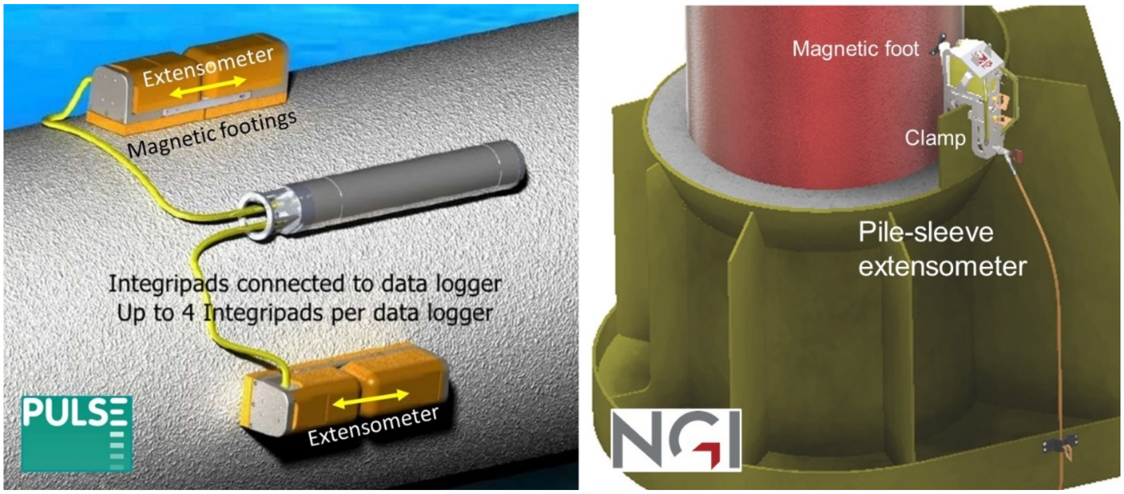


Figure 5-41 (left) Extensometers on magnet pads from Pulse and (right) combined magnetic pad and mechanical clamp fixture on NGI's pile-sleeve extensometer for monitoring of relative deformations between pile and grout sleeve for jackets

Fatigue life monitoring of the Wind Turbine structures can be carried out in two ways; firstly, by analyzing data from installed strain gauges at likely fatigue locations and generate stress cycles for estimating remaining fatigue life. Secondly, by using fatigue "pre-crack" or "weak link" sensors integrated into the monitoring system, accurate predictions of cumulative damage on welded steel structures can be made. The fatigue pre-crack sensor comprises a steel coupon attached adjacent to a critical joint. Stress cycles cause fatigue crack growth in the coupon that is detected electronically by loss of conductivity. For a typical fillet welded joint the sensor output gives the proportion of the fatigue design life that has been used. See Figure 5-43.

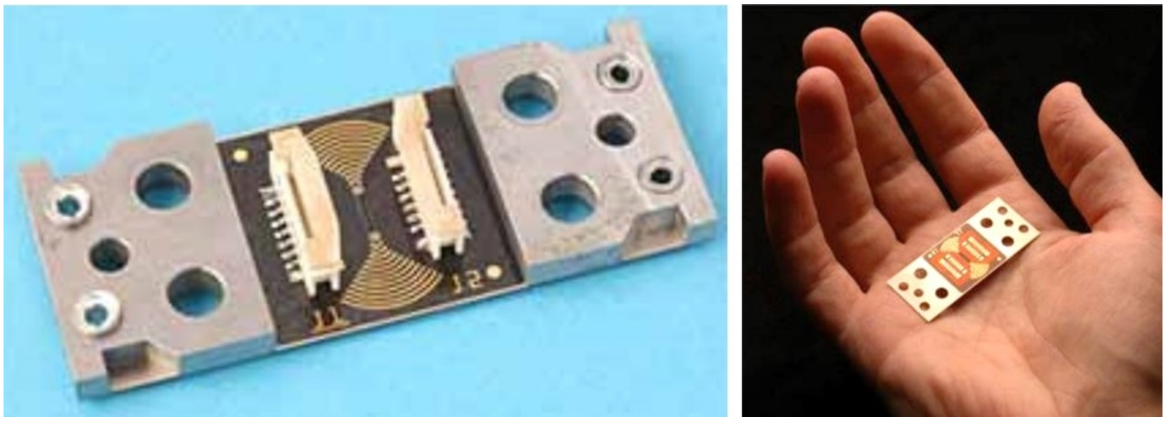


Figure 5-42 "Crack-first" fatigue pre-crack sensor from Strainstall (not for subsea installation)

5.7 Pore pressure monitoring

The pore pressure in the soil beneath and around the foundation plays a vital role with respect to strength and stiffness of the soil. The pore pressure is defined as the pressure differential between entrapped pore water in the seabed and hydrostatic (ambient) pressure at the same depth, see Figure 5-44.

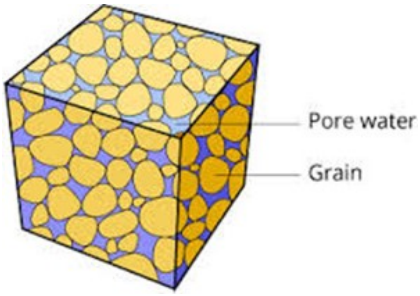


Figure 5-43 Illustration of entrapped pore water in the sea bottom sediments

A **piezometer** is the instrumentation system used to measure pore pressures in the soil. The pore pressure can be measured in three different ways as illustrated in Figure 5-45, using total or differential pressure sensors. At shallow water depths the ambient hydrostatic pressure is limited and two Total Pressure (TP) sensors can be used instead of one Differential Pressure (DP) sensor.

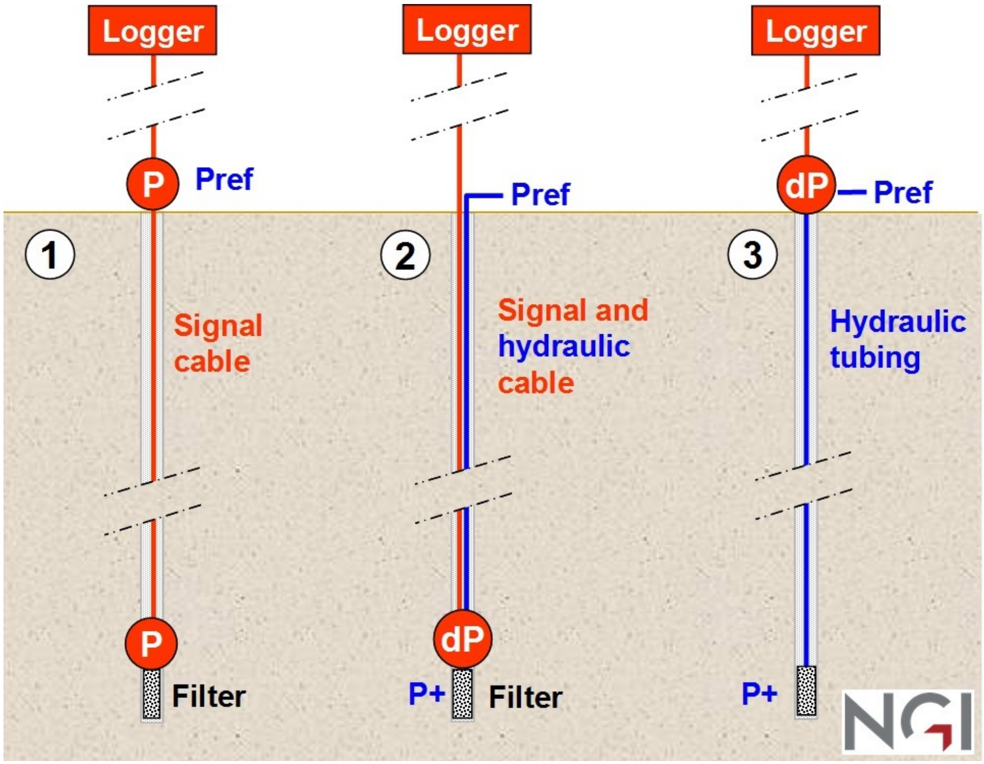


Figure 5-44 Piezometer configurations for pore pressure monitoring in the seabed (P refers to total Pressure and dP to differential Pressure sensors)

For subsea pore pressure monitoring NGI often use the third set-up with a filter inlet embedded in the soil with an hydraulic tube or standpipe routed up to the pressure port on a differential pressure (DP) sensor located in a monitoring head near the seabed. The reference port is routed directly to sea (alternatively using two TP sensors). With the sensor enclosure above ground, hook-up or replacement is possible by divers. For instrumented piles the more fragile sensor heads can be mounted after pile driving, see Figure 5-46.

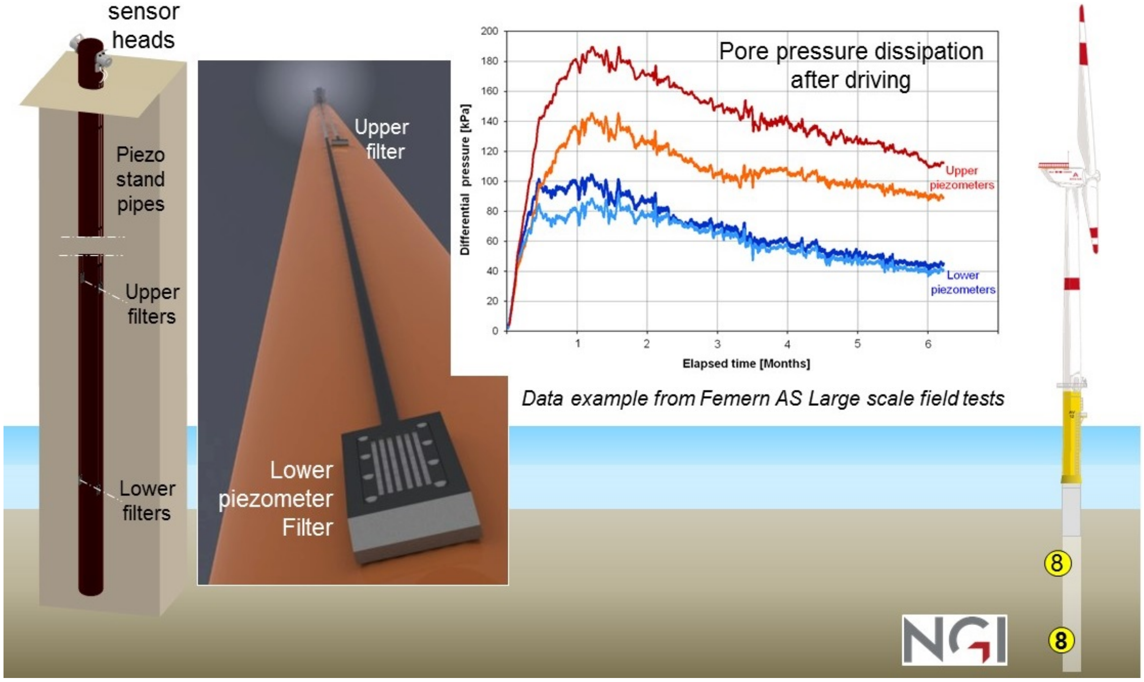


Figure 5-45 NGI's standpipe piezometer system for piles, the plot shows the recorded pore pressure dissipation after driving

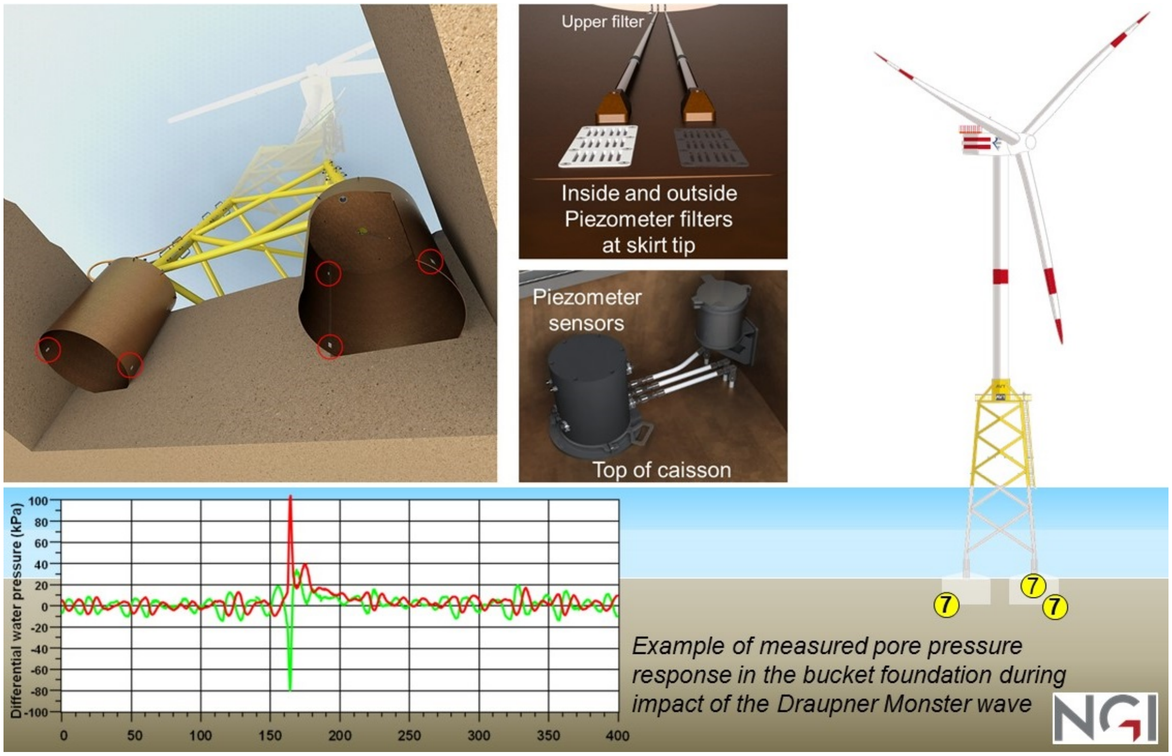


Figure 5-46 NGI's standpipe piezometer system on a bucket foundation (DONG Energy's BKR01 SBJ)

The filters and standpipes must be open to sea during installation of the foundation and flooded by seawater by means of open drainage on top (if the sensor house already is hooked up remote operated bypass valves to sea are used). By means of the bypass valve, the pressure port can also be periodically be opened to the sea allowing for zero point check of the sensor (differential pressure should then be zero) and possible de-airing of the hydraulic line, see Figure 5-48. A standpipe/hydraulic tubing system includes a larger water volume between the filter and the sensor compared to embedded sensors which can be compensated by using larger filter area and the dynamic response is sufficient to monitor cyclic foundation pore pressures generated by wave loads.

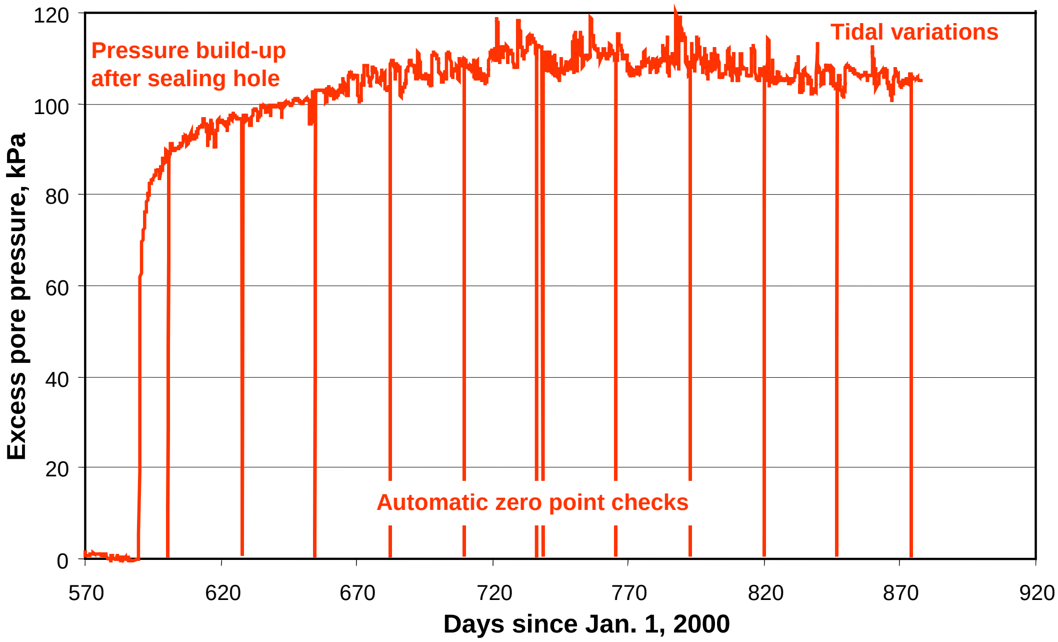


Figure 5-47 Example of down-hole pore pressure measurements (200m below the seabed) done by NGI using up-hole differential pressure sensor with automatic zero point check every month (using a solenoid operated bypass valve)

For piles and bucket foundations the pore pressures of primary interest to monitor are at the interface between the foundation and the soil and the piezometers can therefore be integrated in the structural foundation. In some cases, such as monitoring pore pressure dissipation (consolidation) beneath a GBS structure it may be important to also monitor the pore pressure below or beside the foundation. In this case the piezometers must be installed in drilled boreholes (expensive) or pushed down (similar to CPT testing). For down-hole installation beneath the foundation, pre-installed jacks may be used or drilling performed through pre-installed casings through the foundation. For installation beside the foundation, soil investigation equipment such as CPT, Vibrocorer or sampling rigs can be used for installation of the piezometers.

One issue in when integrating piezometers in foundation structures (piles or buckets), is welding or making slots in the steel walls. In order maintain the structural strength the filter elements used by NGI simply are made up from a piece with identical thickness and steel quality as the rest of the structure. By welding this piece back into the slot in the wall, the structural strength is maintained and the pore pressure filters are fully integrated with the structure and flush with the wall.

5.8 Earth pressure (effective stress)

As described in Section 4.2.3 great care must be taken for successful monitoring of earth pressure (especially the lateral stress). In order to derive effective stresses also pore pressures must be monitored in the vicinity of the earth pressure cell.

The stiffness of the earth pressure cell is very important when measuring total stress against a stiff structural element. To prevent arching effects around the cell it should not be significantly lower than the medium it is embedded in (in this case steel). It is also very important that the total stress cell is mounted flush with the structural surface that shall be monitored such that the sensor itself do not disturb the soil. Any protruding parts (conduits etc.) must be above the cell such that the sensing surface not is disturbed. Correct measurements can be difficult in granular and stiff soil, the recorded stresses are often under estimated.

The earth pressure cell can be of strain gauged membrane type or fluid filled pad connected to a pressure sensor, see Figure 5-49. In order to achieve representative earth pressure readings (limit singular effects in the soil) the cell should have a relatively large sensing surface, normally with a diameter between 90-160mm. The cells will be subjected to large forces and must be of rugged design, this is especially important for piles as the instruments must survive the driving forces (without significant changes in zero point). As for all total pressure instrument it is important to check the zero point at known reference pressure for example before the instruments are penetrating into the seabed.

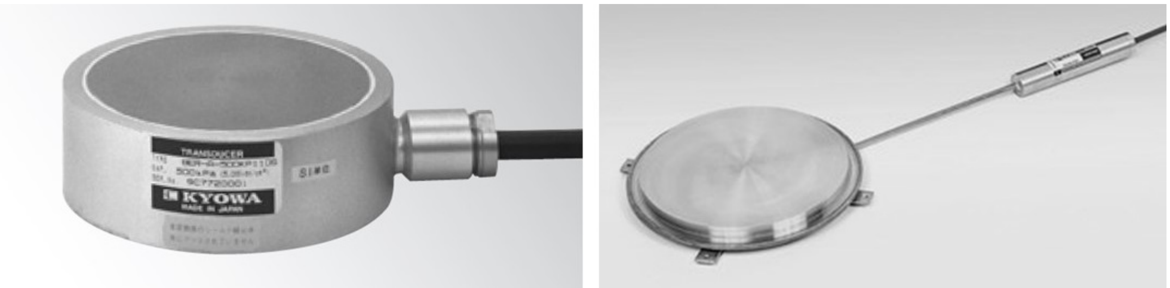


Figure 5-48 Example of membrane type earth pressure cell from Kyowa (left) and hydraulic pressure pad type from Geokon (right). Both cells have a rigid plate at the backside and are suitable for wall mounting

Examples of combined earth and pore pressure assemblies integrated in pile or skirt walls are illustrated in Figure 5-50.

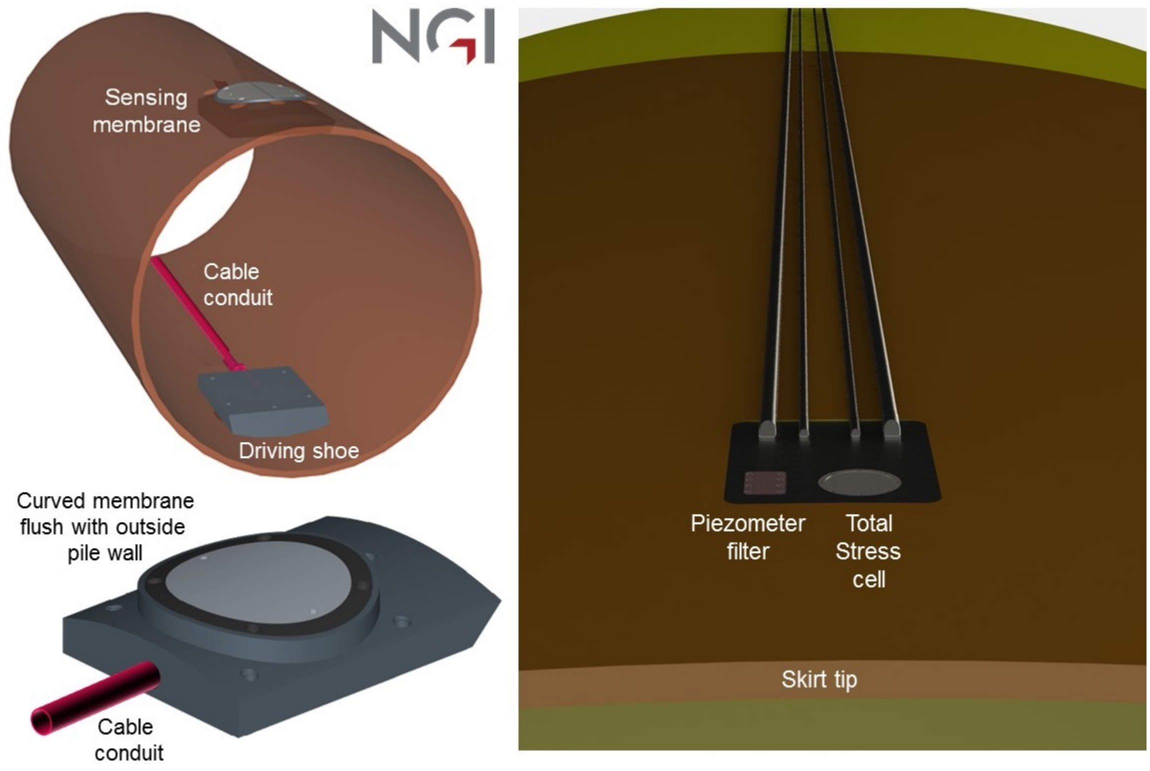


Figure 5-49 NGI Earth pressure cell for piles modified for flush fit to the external pile wall and acting as an internal driving shoe (left). Combined piezometer and earth pressure panel for integration with bucket walls

5.9 Static displacement and settlement

In general, the use of Global Navigation Satellite Systems (GNSS) offers good flexibility with respect to static displacement monitoring of structures, see Figures 5-51 and 5-53. The precision which obtained can be critical issue for fixed offshore structures and specially for settlement monitoring. The precision often depends on the distance to the reference station. Also dynamic motion and vibrations may affect the positioning accuracy (averaging may be required). The fixed reference or base station is required for corrections of the satellite positioning data which depends on atmospheric conditions such as temperature and humidity. The corrections are made based on the assumption that identical conditions apply for both the measuring (rover) and the reference stations. This assumption may become more uncertain with increasing distance to the reference station. For static events the corrections can be made during post processing.

For real time corrections which is required during offshore construction work (foundation installation) or tracking of dynamic events Real-Time-Kinematic (RTK) systems are used. The RTK reference station is continuously transmitting correction data to the measuring stations for automatic corrections in real time.

The fixed position and distance to the reference station are governing for the precision of acquired GNSS data (applies for both post processed and RTK data). The reference station can be located on a piled and stable sub-station or can be land based if the distance to shore is limited. The differential GNSS systems can use one single reference station serving a number of mobile (rover) measuring stations. The RTK reference station re-broadcasts the phase of the carrier that it observes, and the mobile units compare their own phase measurements with the one received from the reference station. Differences between the phases can be attributed to satellite ephemeris and clock errors, but mostly to errors associated with atmospheric delay significant correction of these errors can be achieved by using the data from the reference station post processed or in real time (RTK). Better precision is normally achieved for post processed corrections as more statistical data is used as basis for the correction factors.

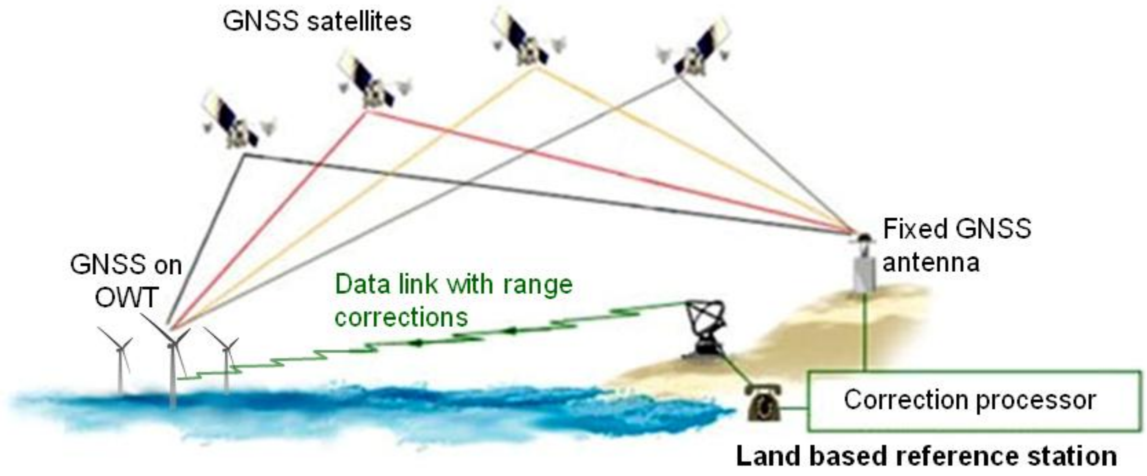


Figure 5-50 Principles of differential GNSS for offshore application with real time corrections (RTK)

GNSS based systems for deformation or motion monitoring are deployed on many major bridges for displacement monitoring. Compared to offshore wind bridge monitoring has the advantage of fixed reference stations close to the mobile monitoring stations on the bridge. The reference stations are usually installed on both bridge embankments, see data read-out example in Figure 5-52.

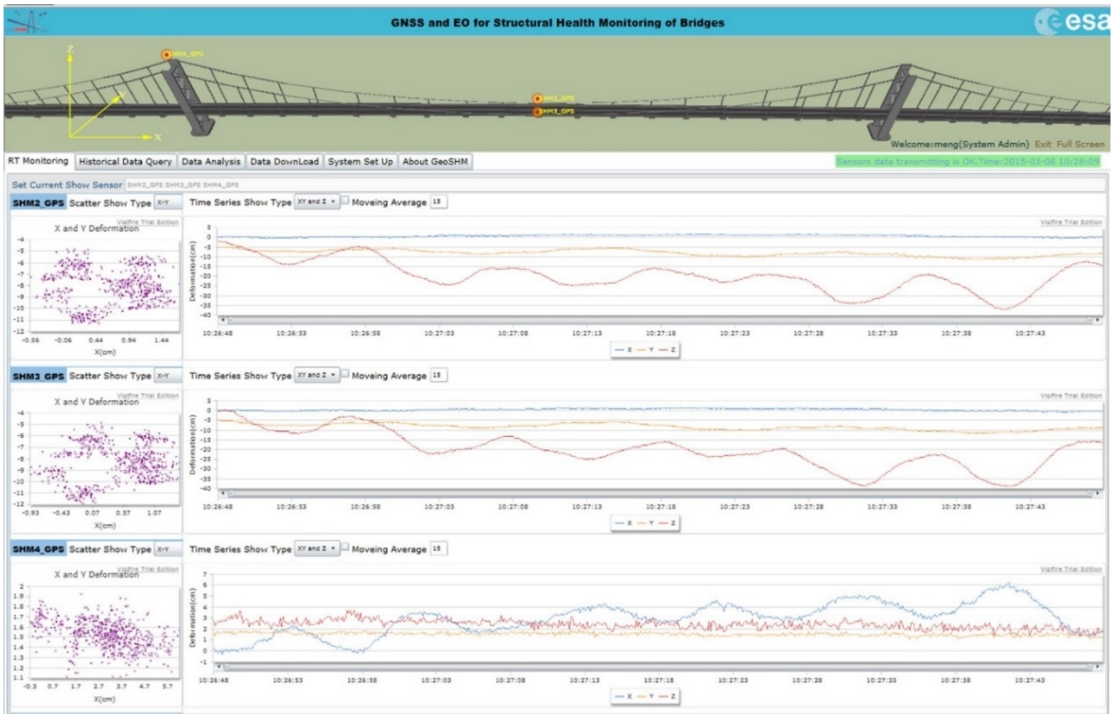


Figure 5-51 Real-time motion data provided by RTK stations on the Forth Road Bridge in Scotland

Figure 5-52 Recommended position for satellite monitoring stations (9) and settlement monitoring system (10). GNSS antenna (right) on top of Lotte World tower (Seoul) during construction, a free line of sight is required to the satellites.

It is expected that the accuracy that can be achieved using GNSS system in offshore application is within a couple of centimeters. Usually the precision is better for measurements of horizontal compared to vertical displacement. Satellite position monitoring is probably most relevant for floating OWT foundations.

Satellite positioning usually do not have the required precision for monitoring settlement of fixed OWT foundations. For settlement monitoring settlement NGI use a fixed seabed reference (for example small suction anchor/pile or clump-weight). The elevation is derived using hydraulic liquid lines connected between the seabed reference and the measuring points on the foundation and measuring the difference in hydraulic head between the foundations and the seabed reference. By means of fully isolating the hydrostatic system from seawater and using compensating lines to obtain the same reference (gas) pressure in the whole system an overall accuracy within a couple of millimeters can be obtained. The system can be configured in many ways. However, the reservoir reference must always be at the highest point, see Figure 5-54. For measurement of differential settlements within one foundation, levelling systems with reference to the liquid horizon can be used. These systems are more stable with better accuracy (+/1 mm) and less long term drift compared to hydraulic head systems. However, the range in elevation differences which can be monitored is limited (typical max. +/- 200mm deviation from the horizon), see Figure 5-55.

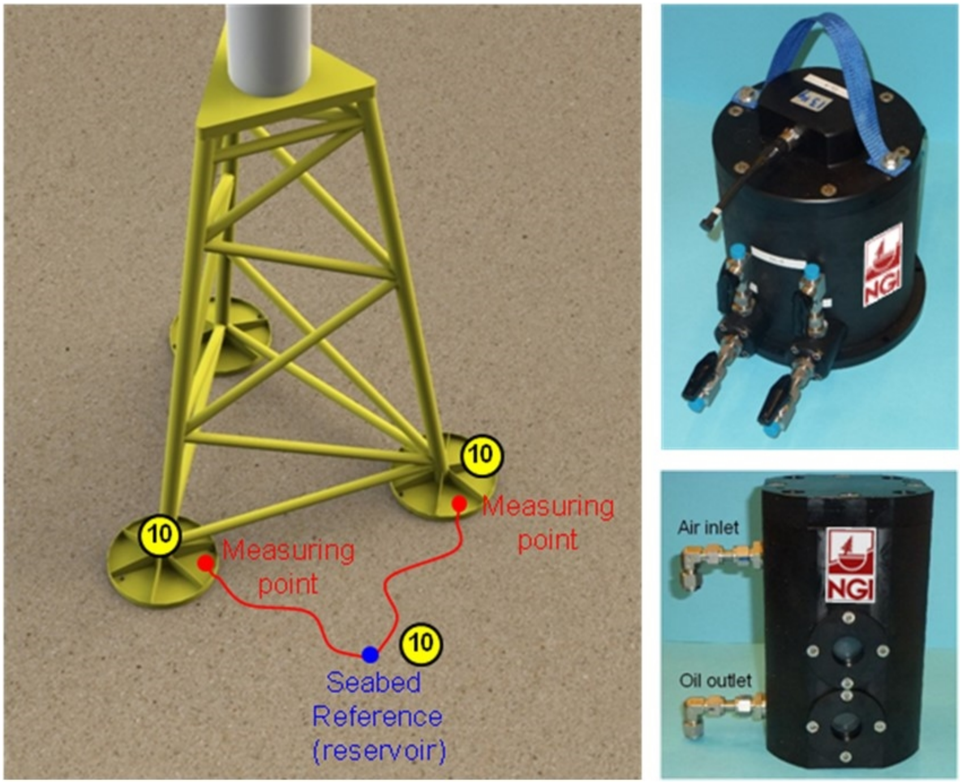


Figure 5-53 NGI's Liquid head system for settlement monitoring, measuring unit with differential pressure sensors (top right) and Reservoir reference (bottom right)

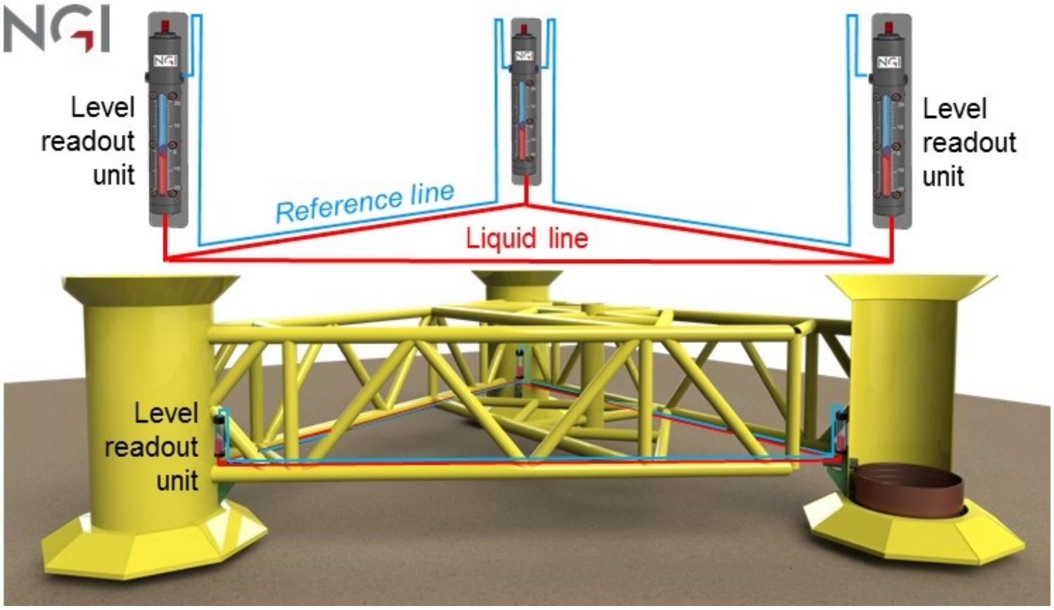


Figure 5-54 NGI' liquid level system on a pre-piling template for precise under water levelling

5.10 Mooring loads

Monitoring the mooring loads is important for understanding of the dynamic response of a floating structure. For larger floaters, the mooring chains are usually operated from deck using fairleads and windlasses for tensioning, the mooring chain are finally secured by using chain stopper, see Example in Figure 5-56.

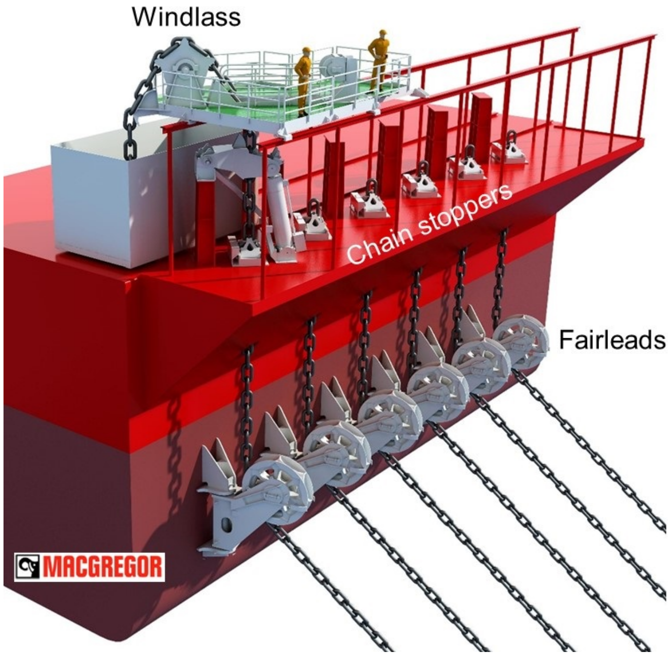


Figure 5-55 Topside arrangement for operation of mooring lines on a large floater or station keeping vessel

For OWT floaters the limited deck space (and economy) calls for a subsea termination of the mooring lines directly to the hull of the floaters. For Statoil's Hywind floater, the three mooring lines are terminated by Y-legs to the hull of the spar. One leg provides a fixed mooring strong point. The other Delta leg provides yaw stiffness to the spar floater and can be adjusted (tensioned) during installation, see Figure 5-57.

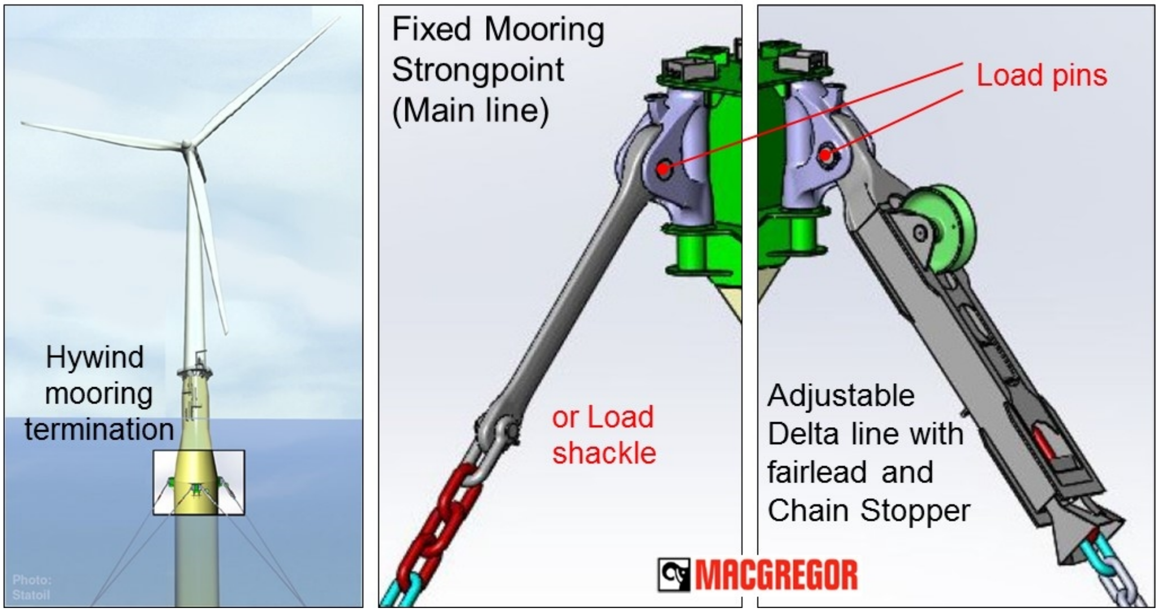


Figure 5-56 Arrangement for mooring line termination the hull of Statoil's Hywind spar floater

In order to monitor the load on mooring lines connected to the floater below, the water line subsea load shackles or load pins can be used, see Figure 5-58. The force is monitored measuring the shear forces in the strain gauged load pin, different sizes are available for load ranges up to 2000 T tension. The load pins or shackles are normally located at the upper termination of the mooring line (pad eye).

Figure 5-57 Subsea load monitoring shackles (left) and load pins (right) from Strainstall

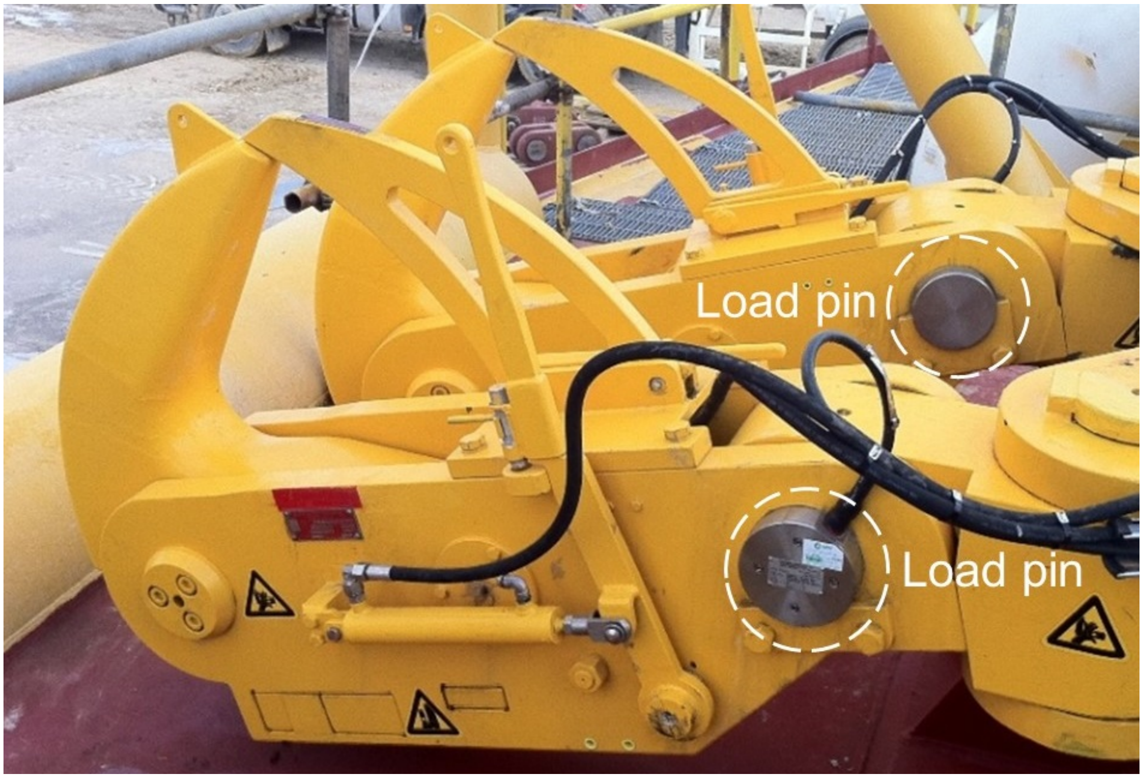


Figure 5-58 Load monitoring pins mounted on mooring quick release hooks from Mampaey

For tension leg floaters, load monitoring in the tendons may even be more important to monitor. The tendons are usually hooked up to the TLP porches by means of ballasting the hull and increasing the draught, after the tendons are hooked up the hull is de-ballasted and the tendons are tensioned based on the monitored load.

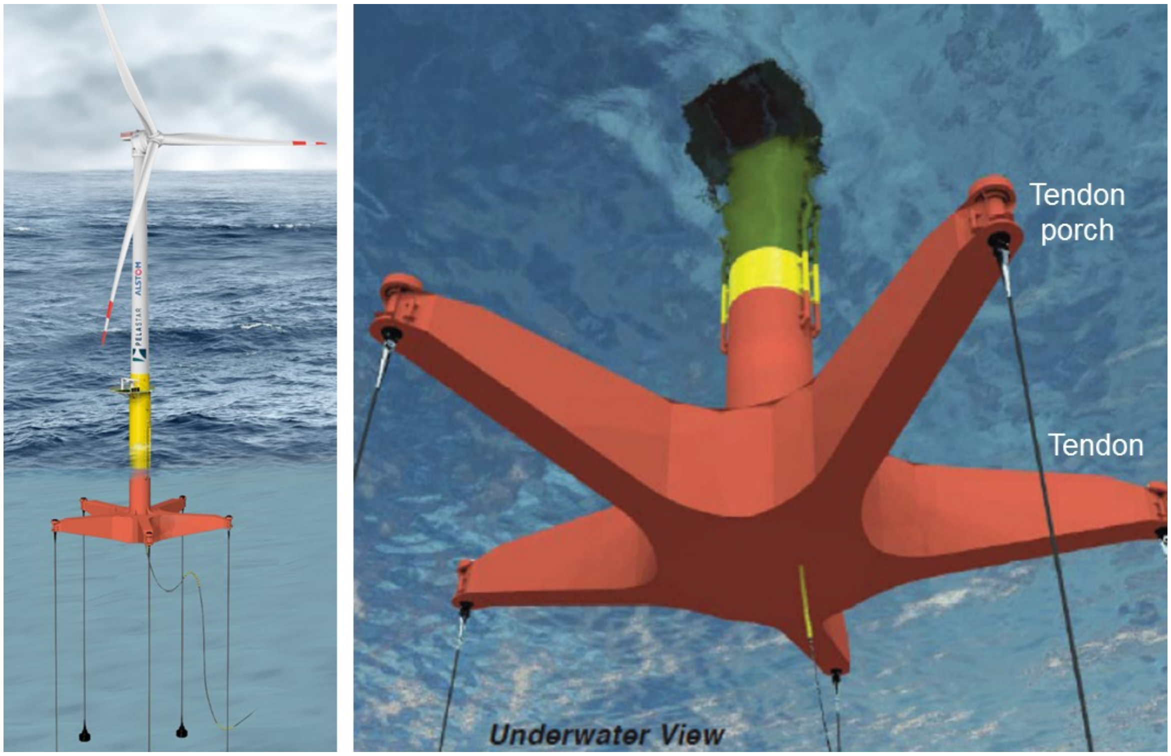


Figure 5-59 Pelastar TLP concept from Glosten Asc.

Underwater compression (column type) load cells can be used in groups of three on the porches around each mooring tendon of the TLP for measurements of the load, see Figure 5-61.

Figure 5-60 Column type under water loads cells from Strainstall

Dependent on the hook-up configuration other arrangements for load measurements may be required.

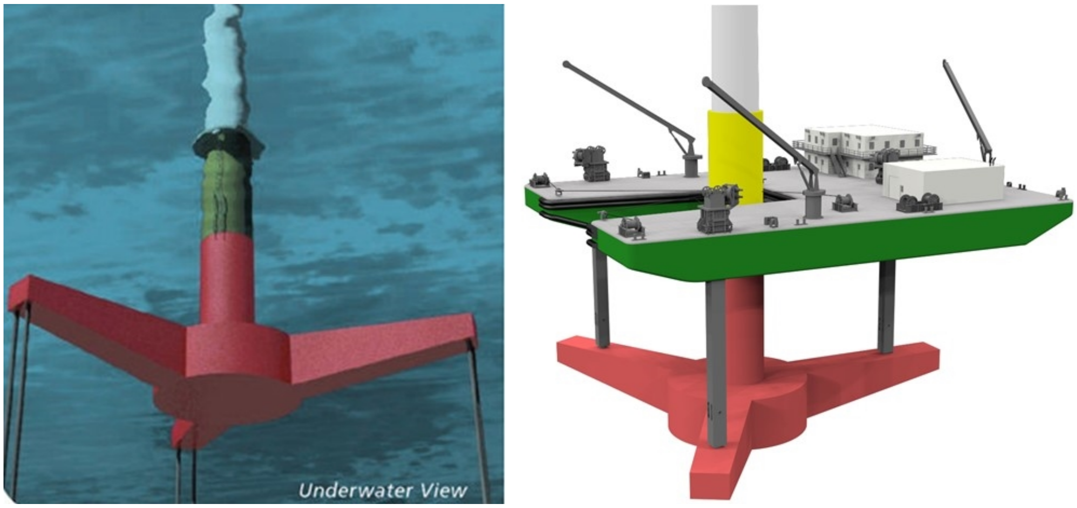


Figure 5-61 Instead of ballasting the floater, hook-up can be done with a special barge which is pushing down the TLP such that tendons can be connected. Concept: Pelastar/Geosea. Three mooring arms are replaced by five arms in figure 5-60 (redundancy?). Three tie-down points constitute a static determined system with known distribution of loads and less anchors to install

5.11 Monitoring TLP anchors

The TLP's can be anchored by piles, gravity and/or suction anchors, see Figure 5-63.

Figure 5-62 TLP suction anchors for a large floater

The suction anchors are usually designed to utilize suction for cyclic (wave) loads while the permanent tension is taken by friction and ballast. There are arguments either for further design optimization or for more conservative design criteria. It is therefore of interest to monitor the differential pressure in the headspace on top of the anchor as well monitoring possible vertical motion during storm loading. Possible settlement or pull-out can also be recorded comparing hydrostatic pressure on the anchor with a fixed reference station at the seabed. Cabling and online read-out to the surface is challenging for floaters and self-contained recording units for temporary monitoring may be a reasonable alternative. NGI has developed mobile solutions for recording differential pressure and dynamic motion of suction anchors, see Figure 5-64. These standalone units may have a battery life of 3-6 months dependent on the recording schedule. The units can be deployed and recovered by ROV and re-used on different anchors as long as they are outfitted with the required outfitting (pressure port with receptacle and docking plate)

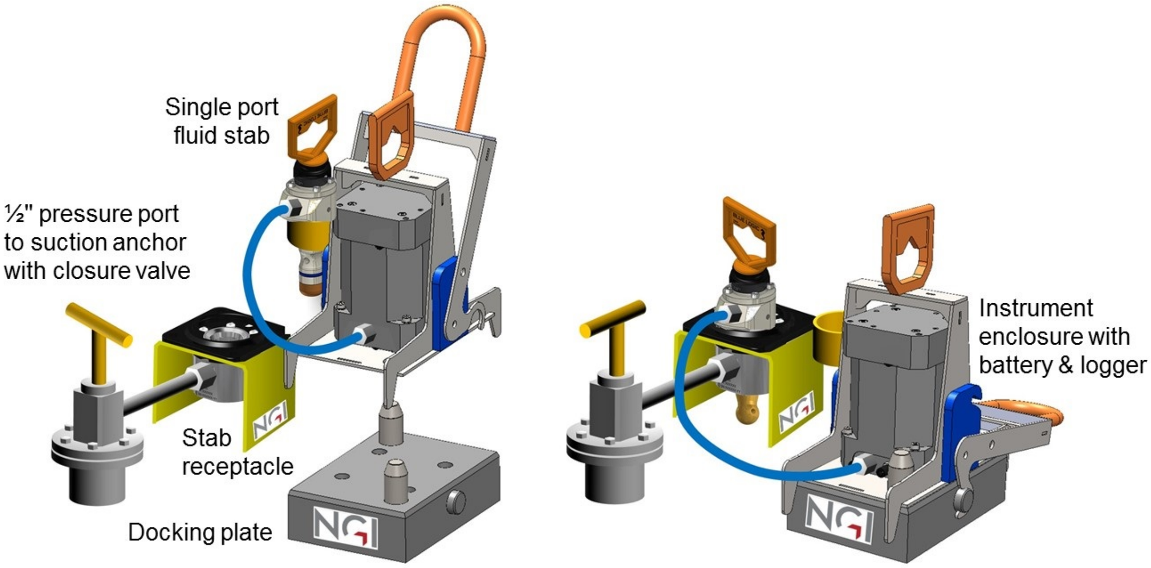


Figure 5-63 Self-contained suction anchor monitoring unit from NGI. The unit can also be used to monitor settlement or static pull-out against a reference station at the seabed.

For piles, probably only dynamic motion would be relevant to monitor. For gravity anchors dynamic motion, settlement and tilt may be relevant to monitor. The relevant sensor configuration depends on anchor type, the monitoring units may also be fixed with strong magnetic footings, see example in Figure 5-65.

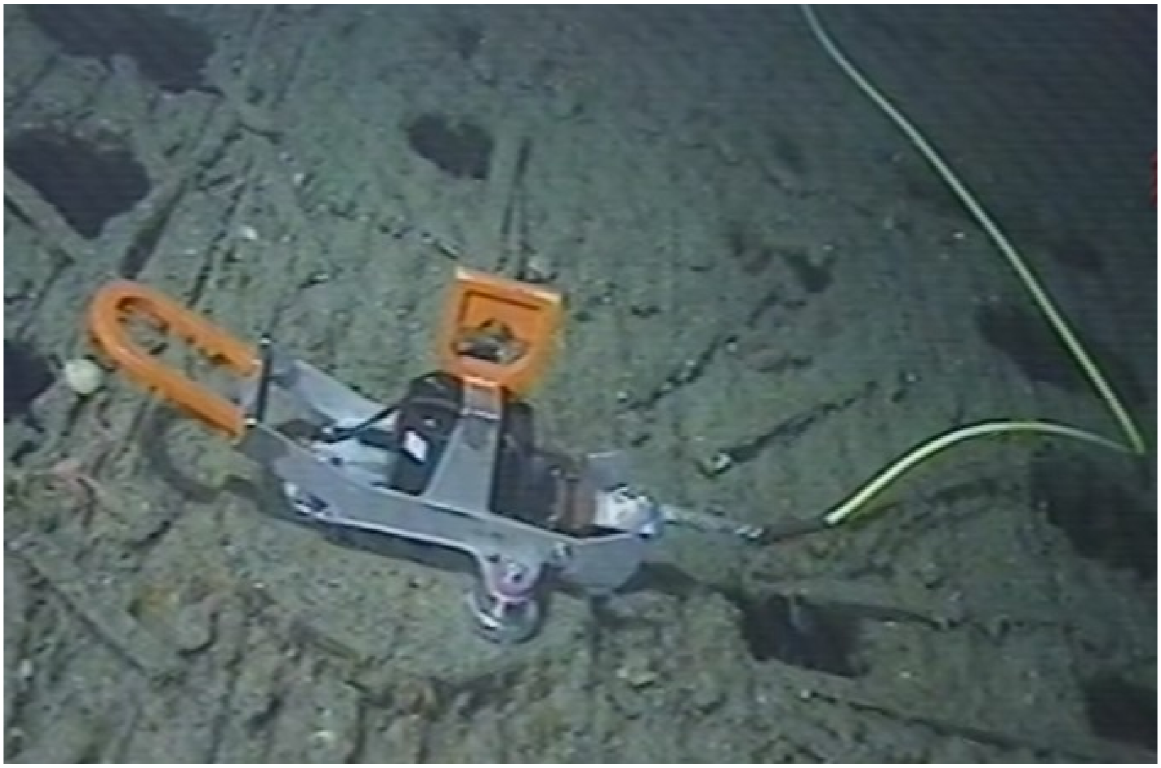


Figure 5-64 NGI's motion monitoring unit fixed with strong magnets, in this case deployed on an unstable submarine wreck to detect possible motion and tilt.

5.12 Corrosion

Based on experience from installed OWT's in Europe, the corrosion inside the mono piles is the most serious problem affecting the operational life of the foundation and consequently one of the most relevant application for remote monitoring and follow up (reducing the need for field trips and visual inspection).

Figure 5-65 Corrosion is a severe problem for long term operation in the offshore environment, the photo shows the interior of a mono pile (courtesy Force Technology)

Figure 5-66 Corrosion and coating repair in the field is extremely costly and difficult

Corrosion can be monitored on the OWT foundation by means of three approaches (usually combined):

1. Monitoring the corrosion potential (environment)
2. Monitoring of the cathodic protection system
3. Direct monitoring of corrosion rates on dummy elements

5.12.1 Corrosion potential (environment)

Many foundations are designed under the assumption that no replacement of seawater occurs in the closed compartments. However, experience has shown that seawater may enter the mono piles to a varying degree for example through the J-tube gasket. The renewal of oxygen should preferably be monitored using a **dissolved oxygen probe** because oxygen represents the driving force for corrosion. Other instruments for monitoring of environmental parameters affecting the rate of corrosion may be:

- pH meter
- H_2 and H_2S sensors (sulfates)
- Salinity probe
- Air temperature sensor (reference)
- Water temperature sensor (reference)
- Water level sensor (reference)

Dissolved oxygen can be measured either by electrochemical or optical sensors. Optical dissolved oxygen sensors tend to be more accurate than their electrochemical counterparts and are ideal for long-term monitoring programs due to their minimal maintenance requirements. They can hold a calibration for several months and exhibit little calibration drift.

Figure 5-67 Optical dissolved oxygen probe from Anderaa

Many suppliers offers multi parameter instruments with the ability to customize the parameters to be monitored using different plug-in probes.

Figure 5-68 Multi parameter seawater probe from YSI

5.12.2 Cathodic protection (CP) survey

Monitoring of the cathodic protection (CP) can be relevant due to uncertainties about regional and tidal effects on the outside, and effects from site-dependent microbiology, sediment composition and aeration of seawater on the inside. CP monitoring is based on potential measurement with durable reference electrodes and/or probes measuring the actual corrosion rate of the protected steel. The protection current running between the structure and the sacrificial anodes is also recorded as this parameter provides valuable information about development in corrosive conditions as well as anode consumption.

In the simplest form, cathodic protection surveying of fixed offshore platforms is achieved by the so called "dipping/drop cell" technique, dipping a reference electrode (drop cell) into the sea and measuring a steel/sea potential with respect to it via an indicating voltmeter and a metallic connection to the topside steelwork, see Figure 5-70. During such surveys the distance between the electrode and the structure should be limited and constant during lowering of the reference cell from the surface this is difficult to achieve in open sea but applicable inside a mono pile. Reference electrode systems for seawater are usually equipped with Ag-AgCl (sensitive) or Zink (robust) electrodes.

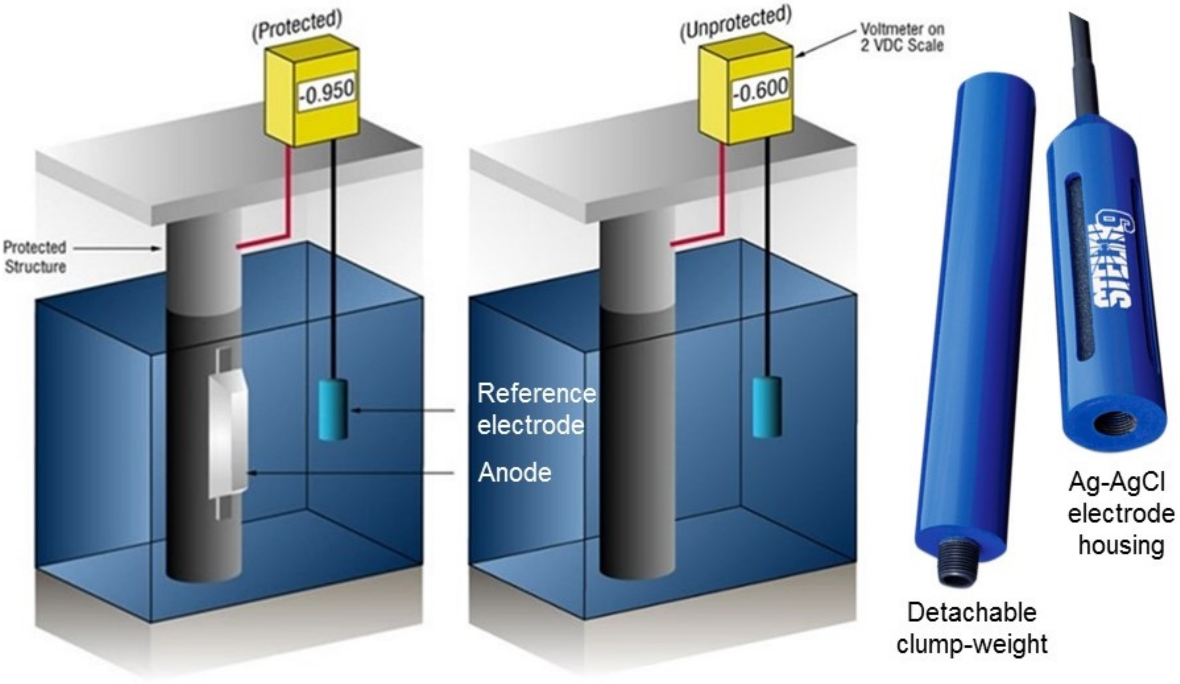


Figure 5-69 Principles for CP survey using reference electrode (drop cell), Illustration (left): Stoprust.com. Seawater Ag-Ag-Cl Reference electrode from Borin (right)

For better precision the reference electrode can be positioned with divers or an ROV, see Figure 5-71. The "Bathycorrometer" or "CP-gun", has a stainless steel tip for subsea ground contact and a reference electrode 1"-2" from the ground, the potential is recorded by internal voltmeter with readout. Most instruments have two reference electrodes such that faults can be detected immediately (the same potentials should be read for both electrodes).

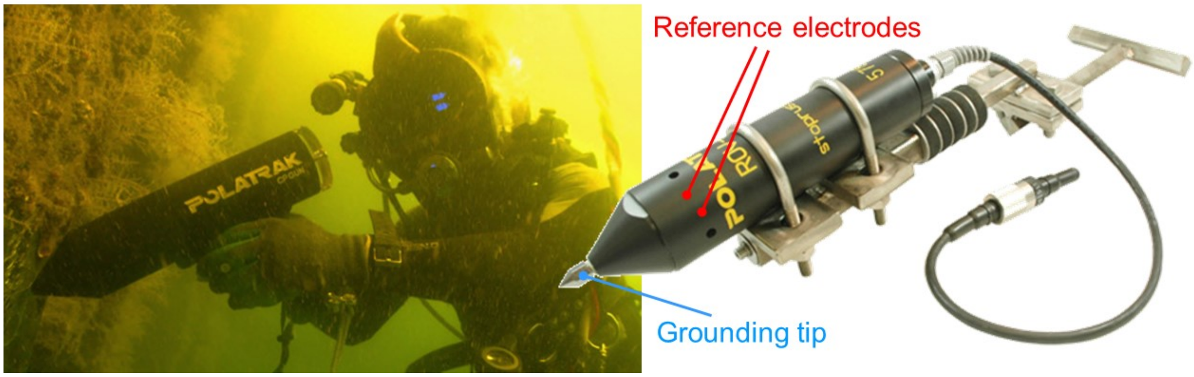


Figure 5-70 Diver operated CP gun from Polatrak (left) and ROV operated version (right). Remote readout of the voltmeter is then usually arranged via the ROV's communication system

The Field Gradient Sensor (FiGS) developed by Force Technology is a non-contact CP inspection tool that performs highly accurate measurements of electric currents in seawater, see figure 5-72. The system is suitable for external CP survey with an excellent resolution and detection level. The sensitivity enables the identification of corrosion problems and the characterization of CP system status on pipelines and subsea structures, even when buried. The electric fields (strength and direction) set up by the cathodic protection system are. It can also quantify the current flow to buried parts of the mono pile. With this information, the level of protection and remaining lifetime of the CP system can be evaluated. The survey is quick and can be conducted by ROV's, divers or from the surface in calm weather.

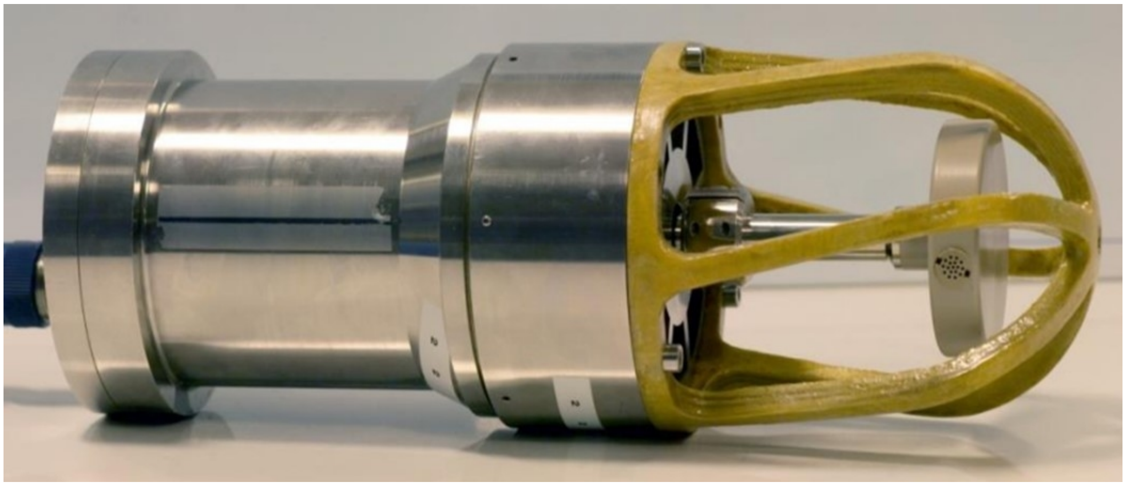


Figure 5-71 Field Gradient Sensor from Force Technology

Reference electrodes for permanent use must be fixed to the structure if located externally, see Figure 5-73. Permanent reference electrodes should always be equipped with dual element electrode for redundancy. If combined with current density monitoring, the polarization of the structure can be monitored. The permanent units are hardwired to the voltmeter and data acquisition unit topside, thus it is important that the cable is of adequate quality for permanent immersion in seawater (nothing lasts longer than the weakest part). An Ag/AgCl reference electrode provides very accurate potential data for monitoring polarization of the structure. A heavy-duty zinc-electrode element provides a reliable, long-term data source alongside the more accurate, but less stable, silver chloride.

Figure 5-72 Permanent reference electrodes for external use from Polatrak, the (right) version is equipped with a 1m^2 current density monitor.

For corrosion protection of larger steel structures, Impressed Current Cathodic Protection (ICCP) are often used instead of passive CP with sacrificial anodes, see Figure 5-74. The ICCP anodes are connected to a DC power source. An essential feature of ICCP systems is that they constantly monitor the electrical potential at the seawater/hull interface and carefully adjust the output to the anodes in relation to this. Therefore, such systems may be more effective and reliable than sacrificial anode systems where the level of protection is unknown and uncontrollable. The placement of the active anodes is however very important, these should be located at some distance from the structure for better distribution of the current field. Local concentrations of the current will reduce the overall protection of the structure and may cause cracking of the coating (if present).

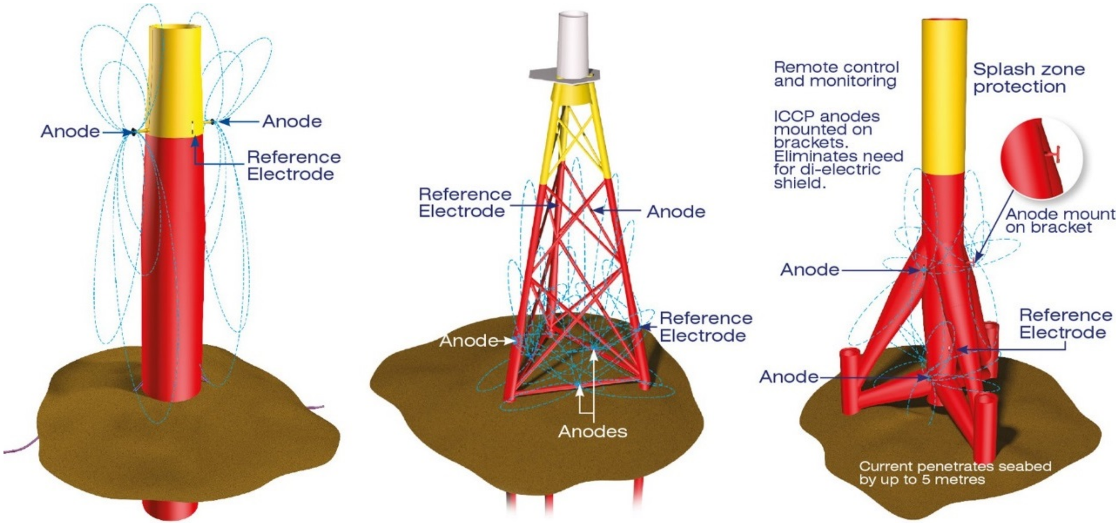


Figure 5-73 Impressed Current Cathodic Protection (ICCP) system for active corrosion protection on OWT foundations (Illustration Cathelco)

The thyristor based control panel supplies an impressed current which provides the driving force ‘potential’ which ensures protection of the whole submerged structure and also extends beneath the mudline.

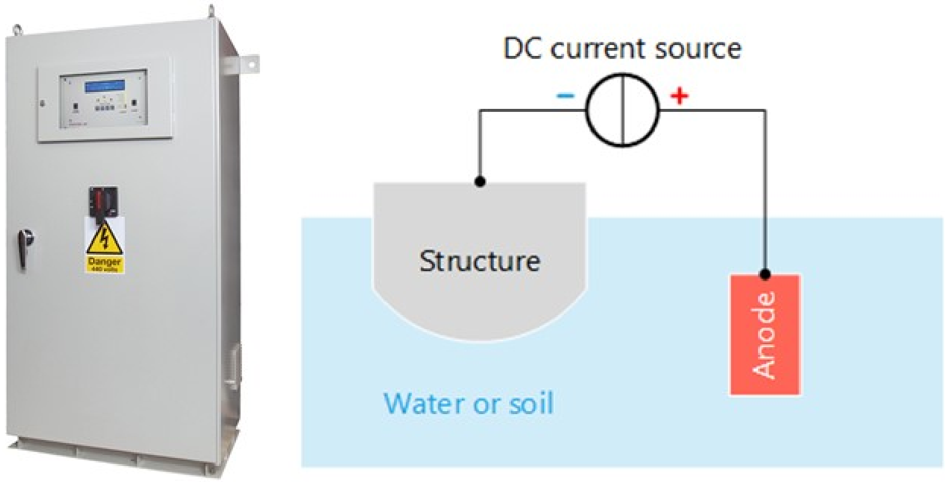


Figure 5-74 Thyristor based ICCP control panel from Cathelco

Stand-off disc anodes are typically used for mono pile structures where the bracket can be mounted on the transition piece. As the anode is at a distance from the structure the need for a di-electric shield is eliminated. In other cases linear surface mounted anodes can be used where the backing shield provides di-electric protection, see Figure 5-76. Ag-AgCl reference electrodes are commonly used in ICCP systems on fixed foundations as they are highly accurate and more stable at higher negative potentials. The reference system monitors the potential gradient between two electrodes which are mounted on a bracket fixed to the structure.

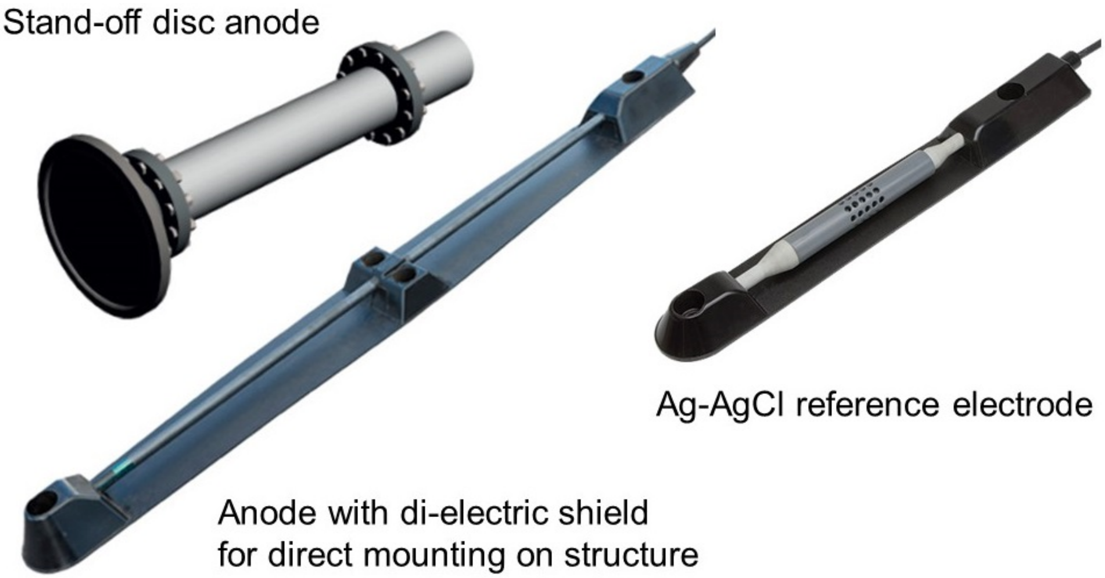


Figure 5-75 Examples of ICCP anodes and reference electrodes from Cathelco

At any time the performance of the system can be checked and controlled from an on-shore control room or on PC via internet link. If the environment below the waterline changes the ICCP system can be immediately adjusted to take account of this. Secondly, a record can be kept of the performance of the system demonstrating the integrity of the foundations. This avoids the time and expense of carrying out offshore surveys.

ICCP systems have a much higher driving voltage than sacrificial anodes enabling the current to reach a depth of up to 5 meters below the sea bed (mudline). This extends corrosion protection to the buried foundations of the structure and combats microbiological influenced corrosion (MIC).

5.12.3 Corrosion rate monitoring

Coupons (weight loss) are the direct technique providing reliable data including the option of examining scale and corrosion attacks. The only drawback is the need for retrieval to obtain data, slow response rate, and that only historical data are obtained, not real time data. Corrosion rates vary in time so, in order to measure the actual corrosion rates and record changes, techniques such as electrical resistance (ER) or electrochemical corrosion rate measurements like linear polarization resistance (LPR) can be introduced. Even if remote monitoring methods are applied, coupons should be installed as a reference and back-up solution, see Figure 5-77.

Figure 5-76 Coupons rigged inside a mono pile above and below the water line for direct monitoring of corrosion rates

Remote monitoring of corrosion rates are based on measurements on electrodes exposed to the corrosive media and not on the foundation structures.

Electric resistivity (ER) probes are equipped with an element that is freely "exposed" to the corrosive fluid, and a "reference" element sealed within the probe body. Measurement of the resistance ratio of the exposed to protected elements is made as shown in Figure 5-78. Reduction (metal loss) in the cross section of the structural element due to corrosion will be accompanied by a proportionate increase in the element's electrical resistance.

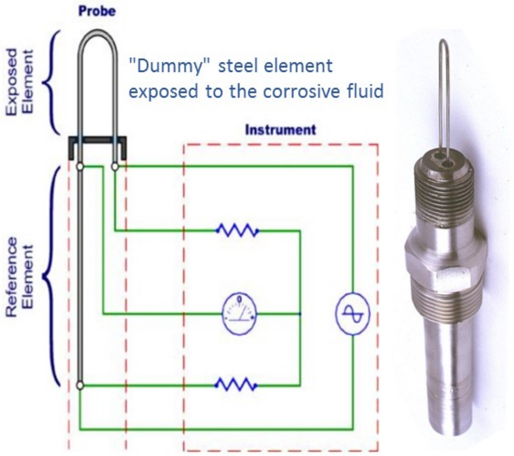


Figure 5-77 Example and working principles for ER probe

The Linear Polarization Resistance (LPR) measurement technique is based on the fundamental concept that when a test electrode in an aqueous environment is polarized by a small voltage, the apparent resistance measured from resulting current flow is inversely proportional to the corrosion rate. The advantage with the LPR probe compared to the ER probes is that the corrosion rate is measured immediately as for the ER probe metal loss must occur before the corrosion rate can be determined. The LPR probes have two polarization electrodes (anodic and cathodic sides), by introducing a third electrode the probe can be calibrated/tested, three element LPR probes are therefore recommend for long term operation. When immersed in water without currents, for example inside a mono pile, protruding electrodes are recommended, see Figure 5-79.

Figure 5-78 Examples of 3 and 2 element LPR probes

If corrosion rates are low, ER and LPR probes will generally have a long functioning time – whereas in the case of high corrosion rates or localized corrosion, the service life of the sensor is shortened.

The galvanic probe (Figure 5-80) is an indirect measurement very sensitive to oxygen ingress, based on zero resistance amperemetry between a steel probe and a noble copper or brass probe. When installed just below the water level, it will be sensitive to ingress of oxygen from both top and bottom. The recorded output of this probe type is galvanic current which can be transformed to an approximate corrosion rate (mm/y). Rapid changes in the oxygen level will be registered and the design life of this type of probe can be long. Reduction (metal loss) in the element's cross section due to corrosion will be accompanied by a proportional increase in the element's electrical resistance.

Figure 5-79 Galvanic probe from Emerson process

The mud line inside mono pile foundations may represent a risk of highly localized corrosion due to the combination of bacterial activity in the mud and macro galvanic elements between the oxygen-containing bulk media and the oxygen-depleted mud zone. There is no straight forward and standardized way of measuring corrosion in mud lines, and exposure of simple coupons may overlook critical effects. Specially designed probes are required such as full-length corrosion coupons or real-time monitoring devices that assess the risk of macro galvanic effects, microbial corrosion (MIC) or Hydrogen Induced Stress Cracking (HISC).

As discussed in the introduction to corrosion monitoring. One type of sensor or parameter and one monitoring position or elevation are usually not sufficient in order to obtain a clear picture about the corrosive state of the foundation. Therefore a set of sensors are usually deployed and hooked up to a common data logger, see Figures 5-81 and 5-82. The most common and important measurements/instruments in such systems are dissolved oxygen, corrosion rate (ER or LPR probes) and reference electrodes.

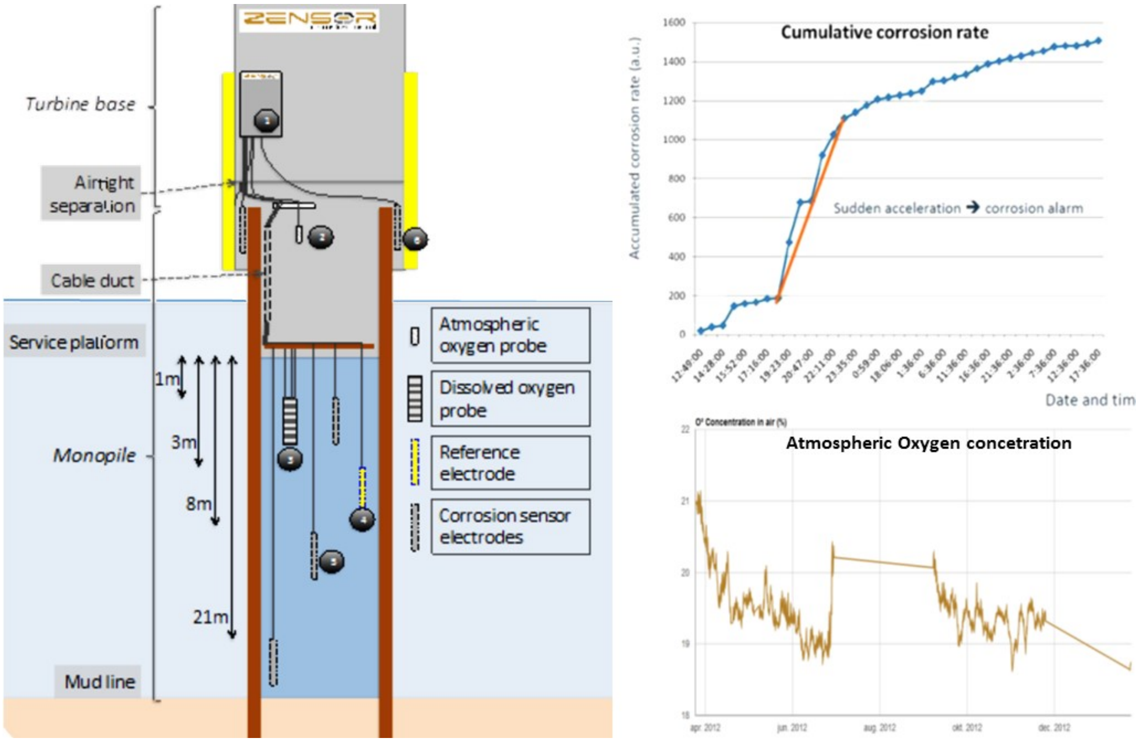


Figure 5-80 Instrumentation system and data examples for corrosion monitoring inside a mono pile from Zensor

Figure 5-81 Permanent corrosion monitoring panel from MetriCorr containing different types of corrosion sensors

5.12.4 Ultrasonic thickness gauging

The most common method for in-situ measurements of thickness is by Ultrasonic Thickness (UT) inspection. By UT gauging determine the local thickness of a solid element (typically made of metal or concrete) is determined based on the time taken by the ultrasound wave to return to the surface. Dual element transducers are recommended for corrosion inspection. These transducers generate sound waves with one element and receive with another – in a 'V-path' orientation, which increases sensitivity when examining corroded or pitted back walls, see Figure 5-83.

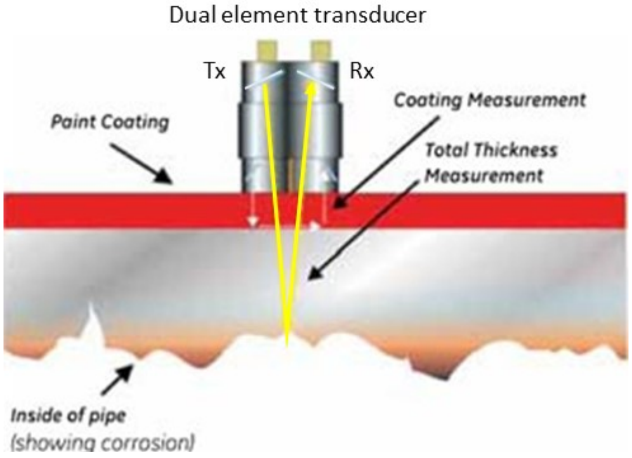


Figure 5-82 Principles for Ultrasonic thickness gauging (Illustration INTECH NDE)

UT gauging requires good contact with the material (usually gel), however for practical field work dry coupling is used by adding a soft material such as neoprene rubber to the face of the transducers. The UT accuracy is good (0.1 mm and less) and can be achieved using standard timing techniques. There is no need to remove the coating of the metal however measurements are affected by rust and are therefore made from the intact or cleaned side (usually the coated outside) to determine how much metal has been corroded at the back wall.

UT spot checks can be done manually were access is possible, for scanning of larger sections crawlers are normally used, see Figure 5-84. By means of robotic scanning inaccessible sections can be inspected and the surface coordinates for the mapping are recorded automatically.

Figure 5-83 UT Crawlers for UT scanning (inserted pictures). The outside of for example the TP is not easily accessible, the large photo shows sand blasting at Scroby Sands wind farm with tie-back to the structure by a magnet system from Abfad. UT crawlers can be used for external UT scanning of TP's provided calm weather.

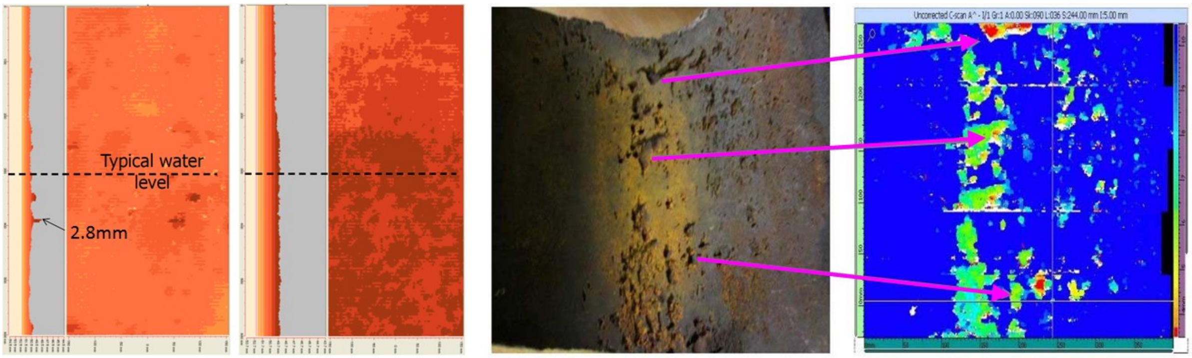


Figure 5-84 UT Data from Crawler scans, the left example is a 2D presentation from two scanned profiles along the TP waterline. A maximum pit depth of 2.8mm is observed on the inside of the left scan (UT scans performed by Force Technology). The right example shows 3D UT mapping of corrosion (C-scan) compared with observations at the back wall (Courtesy: James Fisher NDT)

UT measurement can be performed under water, diver or crawler operated, see Figure 5-86.

Figure 5-85 Diver operated ultrasonic Thickness Gauge from Cygnus instruments

Electromagnetic Acoustic Transducer (EMAT) is a transducer that employ a magnetostrictive effect to transmit and receive ultrasonic waves. EMAT is an ultrasonic testing method which does not require direct contact or coupling substance, because the sound is directly generated within the material (steel to be tested). As an emerging ultrasonic testing (UT) technique, EMAT can be used for thickness measurement, flaw detection, and material property characterization. However, limitations may apply for thicker steel elements.

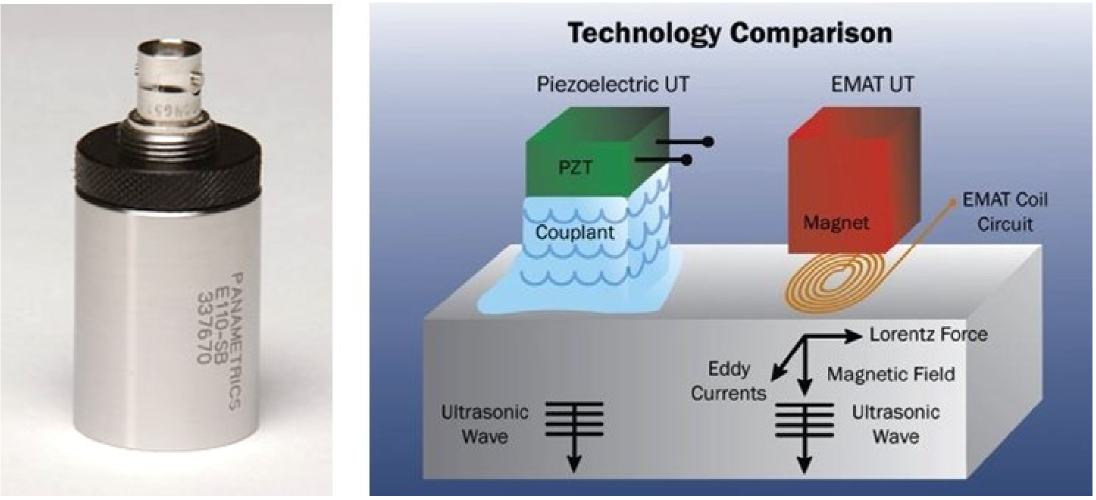


Figure 5-86 EMAT Transducer from Olympus (left) and comparison between traditional piezoelectric and EMAT UT. Non-contact EMAT measurements can be done from the corroded side

5.12.5 Acoustic Emission Monitoring

An alternative and relatively new approach for corrosion monitoring may be acoustic emission measurements (AEM) for corrosion fatigue monitoring. AEM can be utilized for both active **corrosion** and active **crack growth monitoring**.

Discrete acoustic events can be located by time of flight, (similar to seismic activity monitor for earthquakes) and clusters of high location densities can be found immediately, also low level corrosion can cause non-locatable Acoustic Emission activity. Acoustic waves caused by active corrosion and/or fatigue cracks can propagate either in the metal to an acoustic emission sensor being directly mounted on the surface or through the liquid to an acoustic emission sensor immersed into the liquid. The sensors are normally of low cost piezo-electric type, see Figure 5-88.

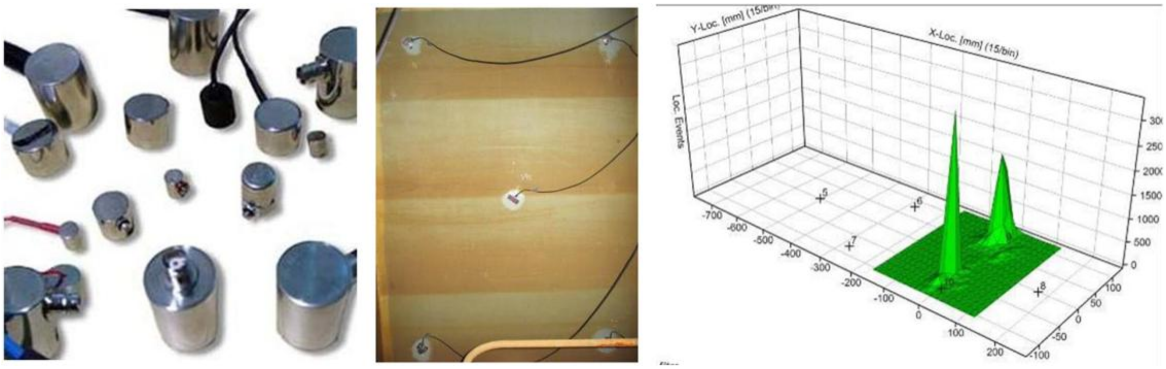


Figure 5-87 Piezo-electric AEM transducers (left), array of transducers mounted on a tank wall and 3D plot showing intensity and location of recorded acoustic emissions

6 Data acquisition system and interface electronics

The data acquisition system and interface electronics provides power and reads data from all sensors. The data is stored on disc and/or transferred to shore by available links installed for operating the wind turbine, see Figure 6-1.

Sensors with analogue output must be interfaced with AD’s and multiplexed, SHM instrumentation usually includes a mix of analogue and digital sensors, special sensor systems such as resistance strain gauges or vibrating wires may require special interfaces (preamps, excitation and counting modules, etc.). In some cases, it may be cost effective to use subsea AD/MUX in order to reduce the extent of cabling to the surface and obtained better noise immunity.

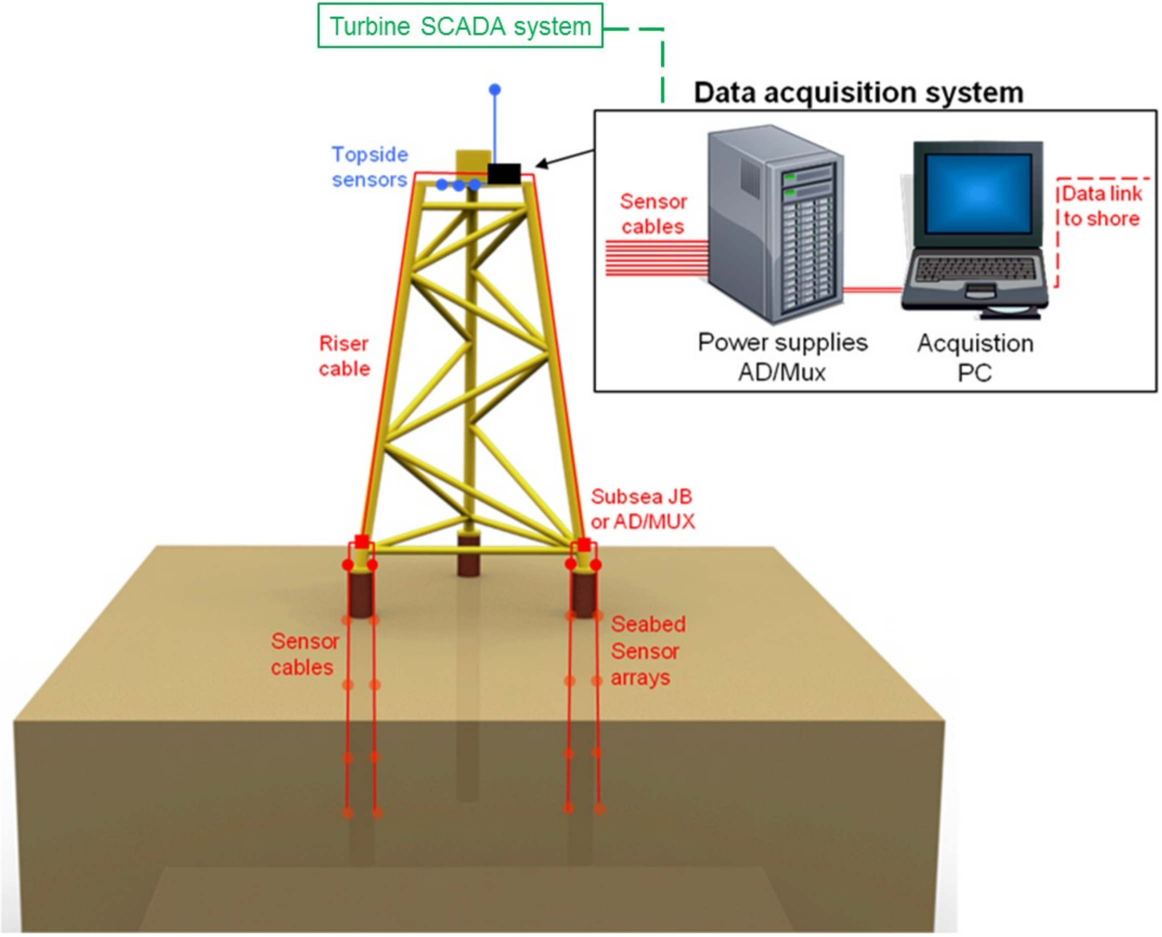


Figure 6-1 Components and hierarchy for a SHM data acquisition system on an OWT foundation

6.1 DAQ system

Low pass filtering, re-sampling and processing of statistical data is performed in the topside Data Acquisition (DAQ) computer in order to condition and reduce the amount of data transferred to shore. Note for dynamic SHM parameters a minimum re-sampling rate of 20Hz is recommended.

A local data storage and battery UPS (Uninterrupted Power Supply) should also be included in the offshore Data acquisition system in case of power or data link failures. Sensor configuration including settings of conversion factors such as sensitivity and offset can be performed from the data acquisition computer. Other logic functions may be time synchronization, statistical data reduction and control of re-sampling rate. For example, more frequent logging of recorded sensor data and storage of complete time series in stormy weather. SHM recording schedules may also be linked to turbine operation settings (SCADA system).

If possible, all relevant data for SHM should be merged, this includes relevant turbine data from the SCADA system (if possible) and Metocean parameters from other systems onboard. These data can either be imported directly to the SHM data acquisition system in order to provide common and synchronized data files or merged via land based servers. In some cases, the opposite requirement may apply, namely exporting the SHM data to the SCADA system such that the same data transfer link to shore can be used. Some SCADA suppliers are aiming for integrating the SHM system with the SCADA system which is challenging as the type of measurements and analyses required for complete SHM (including the seabed foundation) is very different from condition monitoring of the drive train.

Depending on the bandwidth of the data transmission link to shore, data reduction may be required, especially if traditional GSM modems are used. If data is transmitted through optical fiber cable usually no practical bandwidth limitations applies for transfer of SHM data. An onshore server receives the data for further distribution and processing. How to handle large amount of SHM data is a very important and big topic in itself, which may include both neural networks and machine learning. The data processing part is however not addressed in this study.

For remotly operated small to medium size SHM systems with standard sensors the acquistion system can be based on smaller loggers such as the CompactRIO from National Instruments, see Figure 6-2. This system has embedded controllers with two processing targets: (1) a real-time processor for communication and signal processing and (2) a user-programmable to implement high-speed control and custom timing and triggering directly in hardware.

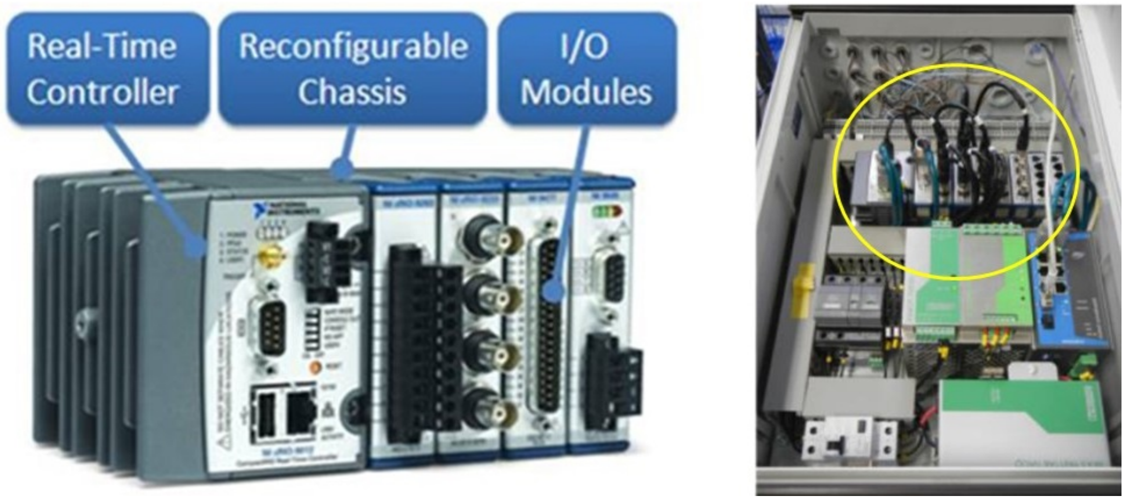


Figure 6-2 Small scale DAQ system based on CompactRIO logger from National instruments

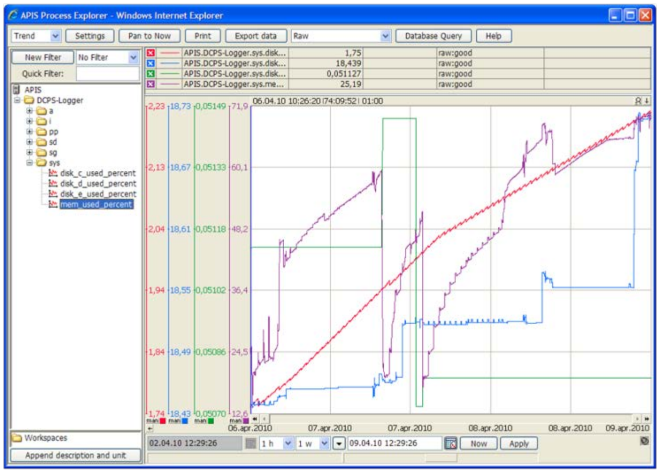
It should be noted that space is often limited on board the OWT foundation and handling can be difficult. It is therefore important that the data acquisition cabinets are as compact as possible or split into smaller modules

Figure 6-3 Example of compact wall mounted data acquisition cabinet inside TP serving small scale SHM systems (Force technology)

Data acquisition for larger SHM system (100 + sensors) must be based on logging system capable to interface and process large amount of sensor channels and small loggers (type CompactRIO) become insufficient. Figure 6-4 shows a high-end data acquisition system delivered by NGI based on HBM's QuantumX data acquisition modules and an industrial grade computer. The system is fully remote operated and can handle hundreds of sensor channels with different output signals and logging rates.

Figure 6-4 Large scale and modular SHM data acquisition system from NGI. Right, termination of strain gauges cables requires space and focus (Photo NGI archives)

Although the Data acquisition systems are remotely operated, a local operator station is usually integrated in the on-board system for checks during installation and service.



APIS Process Explorer - Windows Internet Explorer

APIS.DCPS-Logger.sys.disk...	1,75	raw:good	
APIS.DCPS-Logger.sys.disk...	18,439	raw:good	
APIS.DCPS-Logger.sys.disk...	0,051127	raw:good	
APIS.DCPS-Logger.sys.me...	25,19	raw:good	

Figure 6-5 Example of processed data trends (NGI-VISMON) for local and remote visualization of data and system configuration

To allow for data conditioning, the sensor signals should be over sampled. The actual sampling rate depends on the monitoring application. As a rule of thumb dynamic data should be sampled at 20-25 times higher rate than the typical frequency of the measured application in order to properly track the dynamic response and avoid aliasing errors, see Figure 6-6. For a mono pile the dynamic response of interest covers frequencies up to 1 Hz, dynamic data should then be logged with minimum 20 Hz sampling rate. As a rule of thumb static data such as settlement and tilt can be logged at 1-2 Hz sampling rate, whilst cyclic/dynamic data should logged at minimum 20 Hz. If vibrations are of interest logging may be performed at even higher rates. Over sampling also provides better basis for conditioning (filtering) of re-sampled data.

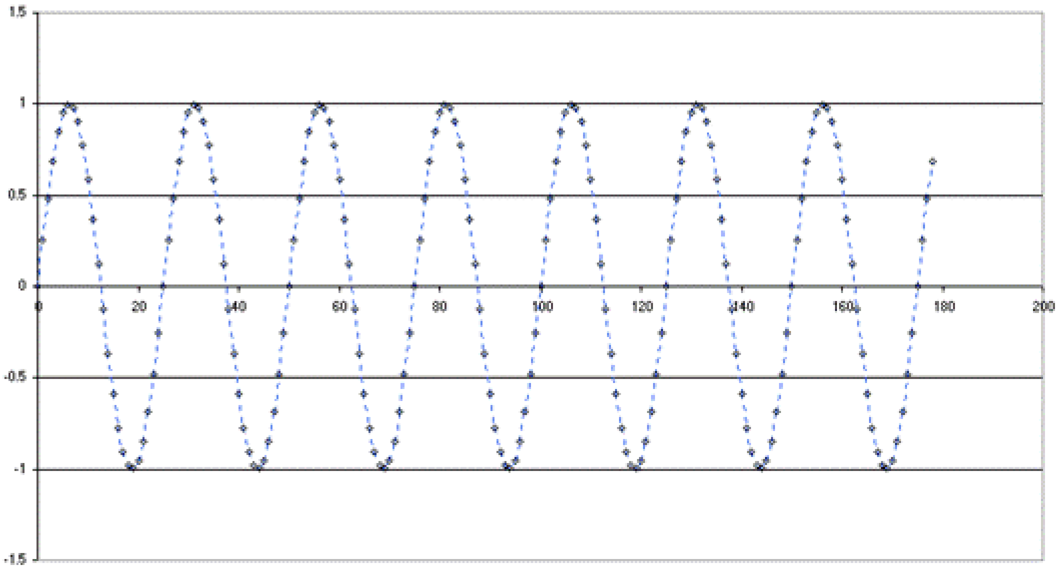


Figure 6-6 Real-time trace of a cyclic signal based on a logging rate corresponding to 25 samples per period

General considerations when planning a data acquisition system:

- Parameter(s) to be measured (analog or digital sensor interface)
- Duration of measurement and power requirements
- Environmental (EM noise, IP protection)
- Resolution, e.g. 8, 10, 12, 16 bits logger and number of channels
- Interface type / communication
- Logging rates
- Embedded processing, data reduction
- Storage capacity
- Size
- Programming interface
- Costs

The Analog-Digital converter connects analog sensors to a data logger. There are several analog sensors with voltage or current output. As the A/D converter only converts voltage to digital numbers, sensors with current output have to be converted to a voltage signal by using a resistor. High quality resistors with low thermal drift and good long-term stability should be used in order to maintain the accuracy in the measurements.

Most A/D converters can be used as single ended (typical for 2 wire sensors) or fully differential inputs (typical for full bridge sensors). A 24 bit A/D converter may increase the sensor resolution but not the sensing accuracy. A rule of thumb is to choose an A/D converter giving a resolution 10 times better than the sensors accuracy.

6.2 Signal transmission

The following analogue sensor signals are relevant for SHM sensors:

- Voltage, usually ±5 or 10 V, sensor with low voltage output are EM; noise sensitive and should not be used)
- Current loop, normally 4-20 mA
- Frequency, vibrating wires or quarts resonators

The current loop and frequency signals are not affected by cable resistance and suitable for transmission through longer cables. In some applications, the analog sensor signal has to be amplified or reduced before logging. The main reason may be to adjust the sensors output to the A/D input. Avoid analog sensor signals exceeding the range for the A/D as this may fail the unit and the readings will be out of range (clipped).

Many sensors have serial I/O (Input/output) and communicate by using special protocols. Serial data transmission has better immunity to EM noise than analog signals. The traditional serial signal formats are RS232 (only for short cables) or RS485 lines (balanced signal for transmission in longer cables). A range of different protocols exists for serial data communication, the most common for sensor communication and interfaces are RS422, CANbus, Profibus, HART and USB. For digital signals, the data logger must have a digital interface and driver software installed fitting the used protocol. For rare protocols implementing the driver software may be time consuming if the documentation from the supplier is limited. It is becoming standard that sensors and/or interface modules have Ethernet output with larger bandwidth allowing for faster sampling. A data acquisition system based on network interfaces is flexible and enables easy to hook-up different interface modules with Ethernet output (IP address) such as FBG interrogators or other streaming units. As discussed earlier, fiber optic sensor signals are completely immune to EM noise and suitable for longer cables. However, splicing and amount of connectors must be limited as signal loss may occur.

In addition to the EM noise from the power grid (50-60 Hz), near-field electromagnetic fields with higher frequencies is emitted by the generator and switching components in the turbine. The electromagnetic interference (EMI) from the high frequency components may disturb signals in the kHz band. For most SHM monitoring applications frequency components above 50 Hz are not relevant and EM noise can be removed by Low pass filtering, for examples with 25 Hz cut off frequency. It is however important that the amplitudes of the noise frequencies above the filter cut off do not saturate the transmitted signal as this will make signal conditioning useless. As long as shielding (for example twisted pairs) and robust signal format is used NGI has not experienced any problems with EMI for SHM systems installed on offshore wind turbines. Also note that the attenuation of EM fields is strong in seawater. Consequently submerged instruments are subjected to very low EMI, though the cable connection to topside may be exposed.

7 Practical advices for SHM instrumentation of OWT foundations

7.1 Introduction

A successful instrumentation project is when the monitoring system provides the data required by the end user. This involves multidisciplinary coordination and understanding, the main considerations and disciplines such as:

- Proper definition of objectives for monitoring (what data is needed?) and realistic expectations of what can be achieved
- Identifying appropriate monitoring approach and linked parameters
- Type of sensors and data recording infrastructure (instrumentation hardware and DAQ system)
- How and when to install the instrumentation
- End users and interpretation of data (Metocean, Geotechnical, Structural and Environmental disciplines)

All links in this chain are equally important. The instruments can work perfectly but the output can be worthless as the installation changed the in-situ conditions. The selected hardware may not be adequate for the monitoring application or simply not mounted properly on the structure or at a position which not is representative for the desired monitoring purpose.

It is important to maintain focus on all components in the instrumentation system such as:

- Sensing mechanism (interface to the media to be measured)
- Sensor (type of instrument)
- Location and configuration of sensors
- Permanent, temporary or mobile system
- Power supply
- Signal transmission (analog, digital, fiber optic, wireless, required baud rate, EM noise, environmental aspects dry/wet)
- Installation method and place (yard, in the field, retrofit, under water, etc.)
- Operational life (protection, waves, corrosion, biofouling....)
- Data acquisition system
- Data base and interpretation

The balance between costs, backup and reliability of the monitoring system usually depends on how important the measurements are for the operator and how much risk the contractor is prepared to undertake. Due to demanding environmental and operational conditions as well as interface constraints, the instrumentation design must often be custom made for the application.

For SHM instrumentation the main factors affecting the design may not always be to obtain measurements with the highest precision but rather:

- Limited time for design and manufacturing the monitoring system (delivery times from sub- suppliers).
- Minimized time for installation in the yard or in the field (being at the critical path can be expensive).
- Handling and installation constraints, such as deployment in the sea water.
- Accessibility and safety (especially under water and also at heights).
- Retrofit required to structures already installed at the field.
- Constraints for cable routing on the structure.

Offshore operations are costly. As a rule of thumb the costs for offshore and subsea operations are three orders more expensive than on land. The offshore installation work can cost more than the instrumentation hardware itself. Thus, as much as possible of the instrumentation should be prepared and installed at the yard, bearing in mind that many times the instrumentation (especially cables) might be exposed to the highest risk of damage at the yard. For critical monitoring system, the instrumentation must include a robust strategy for backup and redundancy.

Figure 7-1 The yard can be a dangerous place especially for unprotected cables (photo: NGI)

Although a successful installation of a permanent monitoring system many times depends on the “Mood of Mother Nature” during offshore operations, the human factor is still probably the most frequent reason for failures. Skilled and thorough instrument engineering supporting during the installation is a paramount factor for a successful monitoring project, comparable with the importance of a qualified pilot for a safe flight. The true skills of the supplier are proven when things fail or do not happen according to the plan and judged by the ability to rectify the problem in a stressful situation.

7.2 “Ten Commandments” for offshore and subsea instrumentation

Some of the most important aspects and recommendations for successful execution of a monitoring program are summarized in the following sections.

7.2.1 Planning and Design

The first thing to be done is to perform a thorough analysis of sensitive/critical parameters: Where-, what- and how to monitor; i.e. develop an instrumentation philosophy for the project. Budget constraints may set limitations to the amount of hardware available, and it is therefore very important to have a clear opinion with respect to priorities, i.e. where money **can** be saved and where money shall **not** be saved.

It is almost impossible to do a “Fit for purpose” design without having first-hand experience from offshore installation work and subsea operations. As the development time usually is limited for working prototypes, the planning and considerations of all installation steps and contingencies is very important. Many times the evaluation of “What will work and what will not work” is purely based on experience. The measuring system “surviving” the construction work and offshore installation, i.e. ensure it works offshore, has first priority and many times an optimal setting for the best measurements must be sacrificed. Probably the most demanding application with respect to system “survival” is pre-installed instrumentation of driven piles. Not only the sensor integrity is important, cable protection is often more critical.

For both yard and offshore installation works, proper planning is essential as the given time slots for doing the job often are limited. This also includes taking into account the Environment, Safety, Access and Training required. It is essential that the design of the system allows the onsite installation and commissioning to be carried out as smoothly as possible. Offshore retrofit of instruments is challenging (especially under water or at height) therefore the instrumentation should if possible be installed in advance, preferable at the yard were access and handling assistance can be provided (cranes, scaffolding etc.)

7.2.2 Harsh conditions and Robustness

The conditions at offshore wind farms are usually rough and the environment that the SHM systems have to be installed and commissioned in is difficult and hazardous, each turbine is subject to potential extremes of wind, wave and temperature parameters which can change quickly. Instrument pre-installed on the foundation structure may imply that the instruments will be subjected to large forces and vibrations for example during pile driving, see Figure 7-2.

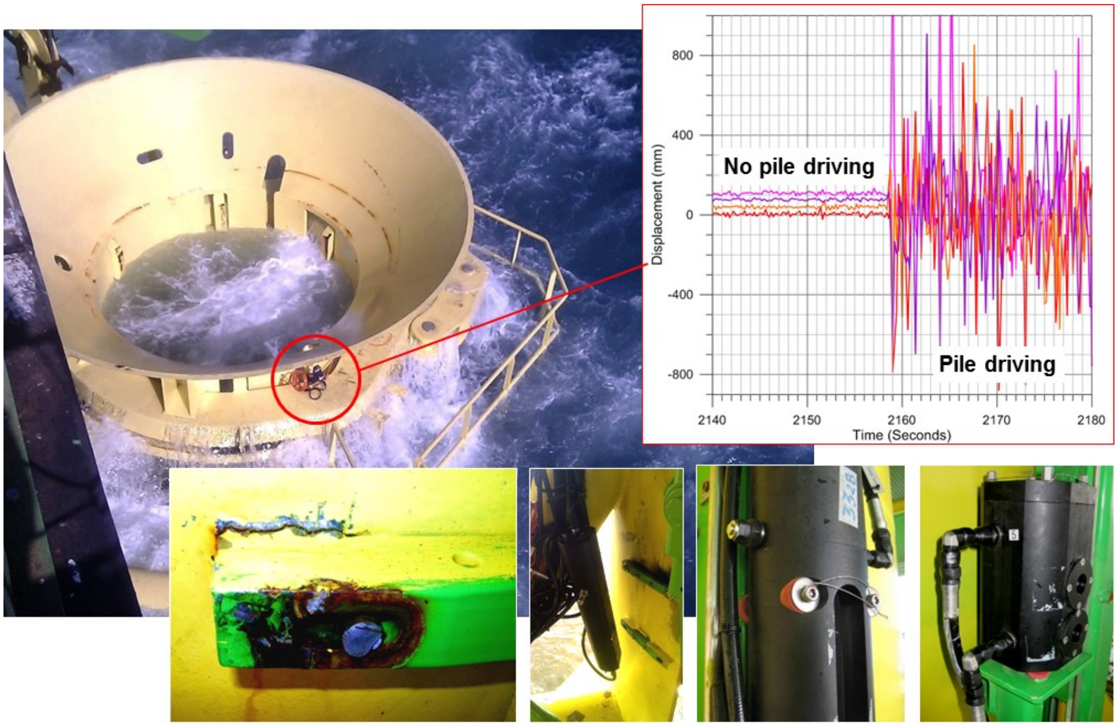


Figure 7-2 Instruments mounted on a pile driving template. The bolts on the mounting bracket where eventually sheared of during pile driving, however the instrument survived. Loosening of bolts and fittings were observed and special arrangement to secure all fixtures was required. If the OWT foundation is towed in the water submerged instrument will be exposed to large drag forces and vortex vibrations (source NGI archives)

For typical wind farm locations, the waves may not be the critical factor for subsea intervention by ROV but rather the underwater currents (tidal) and poor visibility. The experience from many European sites is that subsea intervention is only possible when the tidal current is turning i.e. two times a day during slack tide. For safety reasons diver intervention should be avoided. A diver usually has better control than a ROV but the working conditions and abilities cannot be compared with installation work at the surface.

Figure 7-3 Do not trust this fellow for fine tuning your subsea instruments

7.2.3 Backup and contingency

Sensor costs are usually small compared to infrastructure for the instrumentation (pressure enclosures, cabling etc.) and the operational time for replacement is expensive. Therefore, cutting costs by eliminating back-up sensors may not make any big difference in total costs but regrettable if something goes wrong. Consequential failures must also be considered, such as configuration of cables and sensors, how much of the system is affected by one ruptured cable? Contingency is a popular word for offshore operation schemes, there must always be a plan for what to do if things do not happen according to the plan.

7.2.4 Pressure integrity and corrosion

Pressure integrity of sealed components is obviously important for subsea applications. This aspect can be divided into two categories:

1. Leakage (water ingress)
2. Structural integrity (pressure collapse)

Most failures related to pressure integrity occur due to leakage and the risk for water ingress may even be bigger in shallow water compared to deep as many sealing parts (O-rings, connectors, etc.) actually seal better at higher pressure. Structural collapse often occurs because it was not considered. For example forgetting to drill vent holes in tubular members for pressure compensation when deployed in deeper waters. However, for subsea instrumentation related to offshore wind turbines, the water depth is limited and structural collapse due to the external pressure is less of an issue.

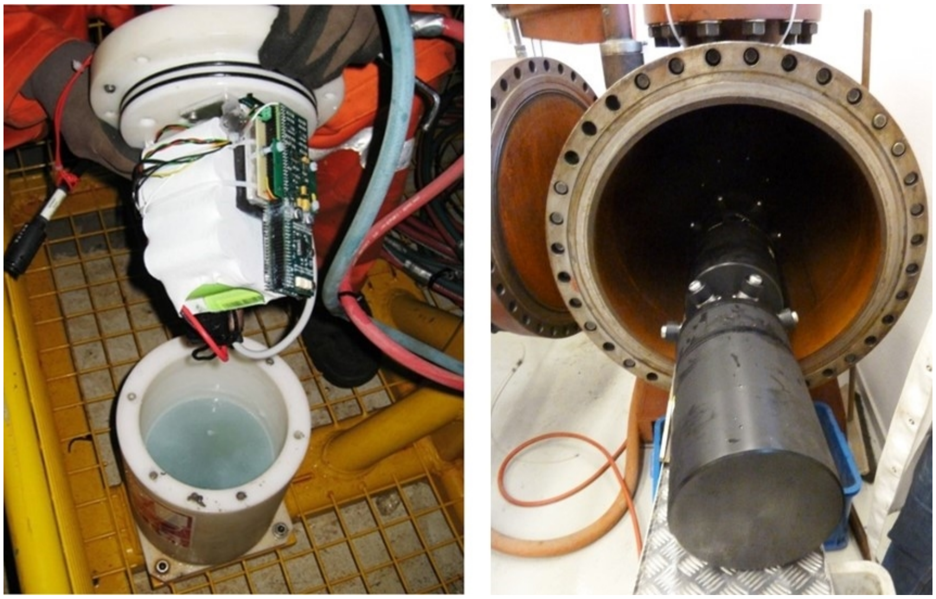


Figure 7-4 Water ingress into a subsea instrument enclosure (left) and pressure integrity test (right) in a tank filled with water normally at 1.5 x the ambient pressure at site (Photos: NGI archives)

The offshore environment is very corrosive both above the sea level and in shallow water, especially in the splash zone. Corrosion is therefore important to consider in design of the instrumentation hardware, especially for long term deployment. Even if the rules of thumb are followed such as using noble metals in the galvanic series, not mixing metals with different galvanic potential or using cathodic protection, the results may be discouraging. Scratches in the anodized aluminum surface or anodes with oxidized surface may compromise the protection. Mixing of metals or fixture to larger steel structures without galvanic isolation can result in rapid corrosion even if the metals themselves are corrosion resistant. NGI's practice is to keep it simple and only use for example stainless steel in combination with thermoplastic materials such as Delrin, see Figure 7-5.

Figure 7-5 "Bright and shiny" instrument unit mainly in stainless steel prior to deployment (left) The same unit heavily corroded after 2 years deployment in seawater (middle). Corrosion "safe" instrument housing made of Delrin with outfitting in stainless (right)

7.2.5 Functional Testing and calibration checks

The importance of functional testing can never be exaggerated. If possible, hooking up the instruments in a representative configuration can save time for fault seeking and prevents uncertainties during field installation (especially for signal addressing and sign convention). Many times the obvious is forgotten or wrong. These checks are therefore nicknamed as the "idiot test" internally at NGI.

Other instruments such as Inclinometers are simply difficult to calibrate (offset) offshore when things are moving on the vessel and must thus be checked at the quay before leaving port.

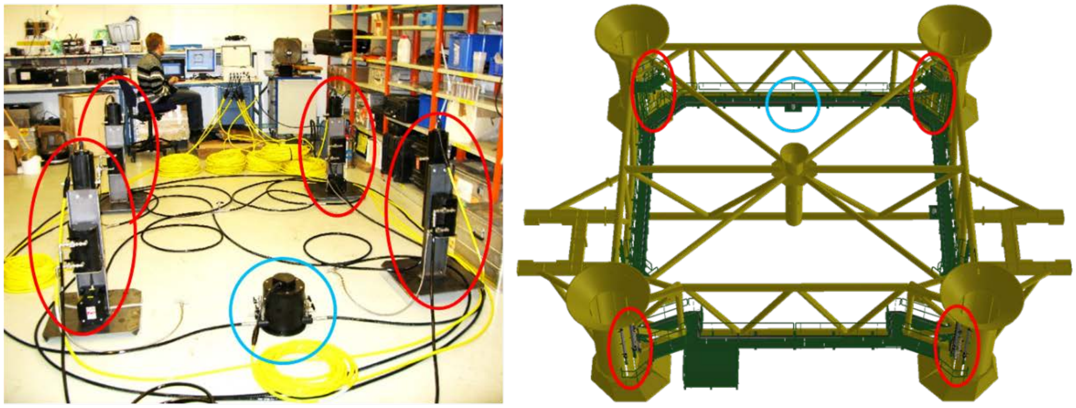


Figure 7-6 Ex works functional testing of NGI's level monitoring system mimicking the configuration and use on a pre-piling template (Geosea)

7.2.6 Flexibility and Installation friendly

As offshore installation time is expensive it is important to simplify the operations as much as possible minimizing the time used offshore. This is especially crucial when under water intervention is required for retrofit applications. Flexibility implies options to adapt the equipment for unexpected conditions or changed set up for installation as well as access for easy replacement of damaged parts.

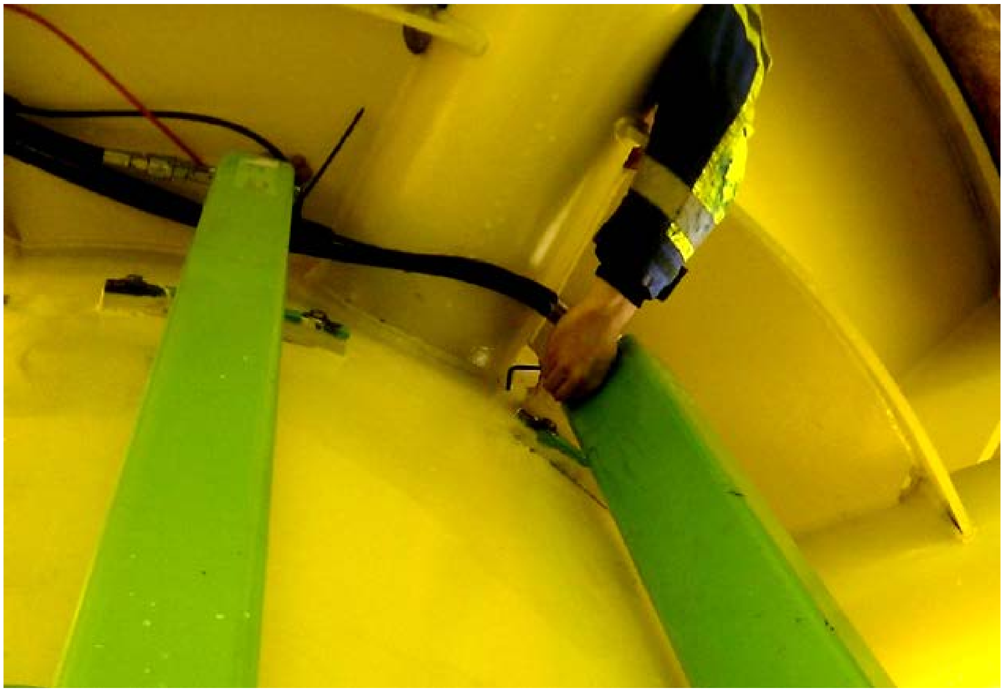


Figure 7-7 Accessibility is important for maintenance and replacement (photo: NGI archives)

7.2.7 Safety during Onshore and offshore installation works

Safety is a paramount issue when working on wind turbine structures, this applies both on the construction yard and offshore. There are many hazards around when working on or accessing these structures. In Europe, the following training is required:

- Offshore survival training and medical (offshore works)
- Offshore access (offshore works)
- Confined space training (offshore and yard)
- Working at heights (offshore and yard)

Special training is also required for access to the turbine. Due to many activities performed simultaneously at the yard such as lifting operations, grinding, welding etc. special attention must be paid. As instrument technicians/engineer normally only pays shorter visits to the yards, familiarization is important. The offshore wind turbines are remote in location and have to be accessed by work boat, the transfer from the boat to the turbine tower can be difficult and there are vertical ladders to climb both externally and internally to gain access to the necessary parts of the structure.

Figure 7-8 (above) A dangerous and uncomfortable workplace. (right) Offshore access to the OWT foundation requires physical fitness and high safety awareness.

Often the installation work has to be done inside confined spaces or at height, appropriate safety equipment is then required, see Figures 7-9 to 7-11.

Figure 7-9 Access for installing sensors at the yard: Left, inside mono pile (photo: Allnamics) and right, on top of suction buckets (photo: NGI)

It is important to involve the construction yard and/or offshore contractor for review of and input to the installation plan and interfaces. Usually, the rate of success can be raised significantly if the important details are thoroughly explained and understood by the contractor. Some requirements for installing the instruments can indeed appear as weird and easily neglected for someone who is not familiar with the “Art of instrumentation”.

Figure 7-10 Left, darkness and confined space when installing extensometers inside the TP just above the sea water level (Photo: Strainstall) or right, when strain gauging a jacket leg (photo: NGI)

Figure 7-11 Great view when working at height installing a wave radar on TP deck (Photos: NGI)

In order to fulfil the safety requirements, significant and costly training is required (in Europe) to be undertaken by personnel that are involved in the installation and commissioning of the SHM systems on the Wind Turbine structures. Still the alertness and judgement of the field personnel themselves are the most important factors preventing accidents.

7.2.8 Delivery time and coordination of installation work

Installing instrumentation at the construction yard or offshore is usually a small part of a bigger scheme and the logistics involved must fit the overall plans. Waiting must be expected for access but do not expect the yard or installation vessel to be waiting for you. As cables are usually fabricated in batches and many times is the first item required for installation, delivery times are often on the critical path.

7.2.9 Cable routing

Cable routing on the structure is usually the trickiest part with respect to coordination and interfaces, usually instrumentation and cables are not included in the structural fabrication drawings and plans. Although many times the cable routing ends up with ad hoc solutions the general cables routes must be defined such that sufficient cable lengths can be ordered. If possible the cables should be installed after grinding, welding and painting is completed at the yard. It is strongly recommended to visit the yard in advance and discuss routing details, sketches on photos are useful but still (unless incorporated in the structural fabrication drawings) expect that details must be adapted on site, see spFigure 7-12.

Figure 7-12 Example of cable routing details indicated during yard visit (left) and final installation (right), photo from NG's archives.

Challenges with cable routing can be avoided using wireless sensor systems, however wireless communication do not work well between closed steel compartments and battery power supplies would be required. For under water communication acoustics, EM or optic (OLED) data transmission can be used, but such systems are either power hungry or have limited transmission range in addition they are more complicated and expensive compared to direct cabling. For retrofit under water it may however be the only option, unless standalone systems with integrated data loggers ("black boxes") are used.

Figure 7-13 Long cables makes big bundles and even less work space before final routing (photo from NGI archives)

External cables must be properly fixed to the structure, this is especially important for cables routed through the splash zone as the slamming forces from waves will impose violent battering on the cables, see Figure 7.14. Normally the cables are routed through a solid steel conduit through the splash zone.

Figure 7-14 Battering wave action which can be expected in the splash zone (in the North Sea)

7.2.10 The Devil is in the details and Murphy's Law

It is a fact that most problems or malfunctions are caused by small details rather than major faults in design or hardware. Therefore, "Paying attention to the details" is necessary for all instrumentation tasks and especially important for monitoring systems which not are accessible after installation and consequently not possible to repair or rectify when in operation. According to Murphy's law, "*Anything that can go wrong, will go wrong*". Therefore, plan for the unexpected, double check and check again.

The following example is taken from the internet (http://www.fino3.de/en/research/pillar-foundation). A comprehensive research program was executed for the mono pile Metmast (FINO 3), the project included extensive monitoring of the embedded pile both during driving and operation. The pile was extensively instrumented with Geotechnical Measurement Stations for Offshore Ground Structures (GEMSOG's), containing inclinometers, piezometer and total stress cells. The GEMSOG's were mounted along the outer pile wall in rows above each other, see Figure 7-15.

The instrumentation was nicely done with a completion which should survive driving and under water long term immersion. However, the readings of total pressure during driving quickly revealed an important detail for successful measurements of radial earth pressures (effective stress) which was not taken into account when designing the monitoring system, see figure 7-16.

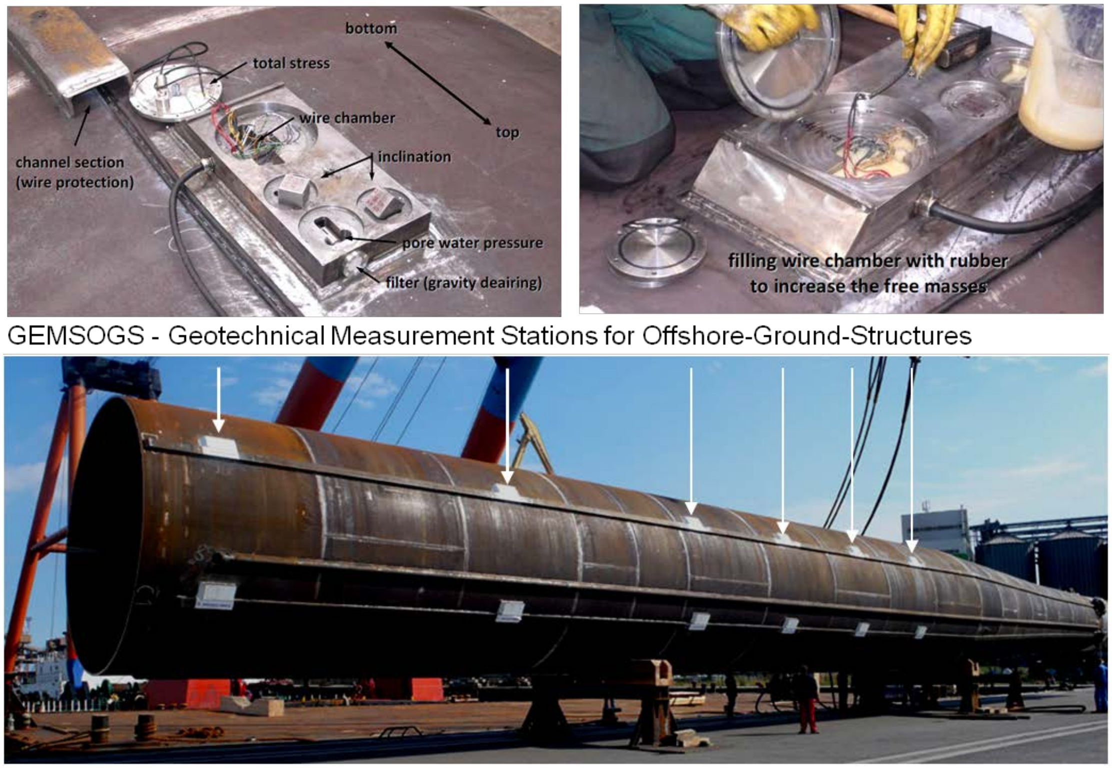


Figure 7-15 FINO 3 Mono pile with "GEMSOGS" instrumentation

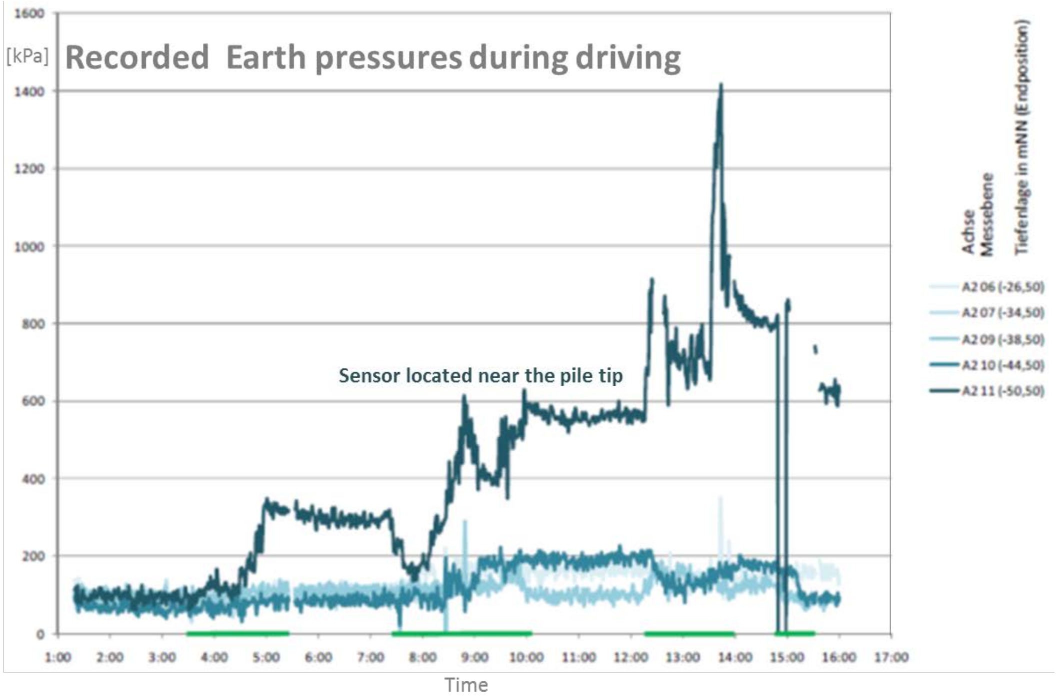


Figure 7-16 Recorded radial earth pressures during driving of FINO 3 mono pile

As seen from the plotted earth pressure recordings along one instrumented section of the pile (Figure 7-16), only the instrument close to the tip is reading increased earth pressure when the pile is driven deeper into the ground. All sensors above show more or less a constant value (not representative for the effective radial stresses around the pile).

The explanation is straightforward as the "GEMSOG's" instrument units were fixed and protruded outside the mono pile (acting as driving shoes) a slot was generated in the soil above when the pile was driven. Consequently, only the deepest GEMSOG did measure representative earth pressures as the units above were affected by the groove created in the soil when the sensor unit at the tip was penetrating. ***Earth pressure cells must be mounted flush with the pile wall.***

More details about lateral earth pressure instrumentation are discussed in Section 5.8.

7.3 Executing a larger SHM project

As discussed earlier there are many items to consider executing a monitoring project and the solutions which work best are many times based on long term experience (including failures). Thus, for larger projects competent expertise is required, usually organized as a System integrator or Main instrumentation contractor.

The purpose with this role is to design and integrate a system which will provide an integrated monitoring solution meeting the objectives and requirements for data as specified by the client. The system integrator should be able to select the most suitable components from different sub-suppliers, design a suitable configuration, test and install the system on the structure.

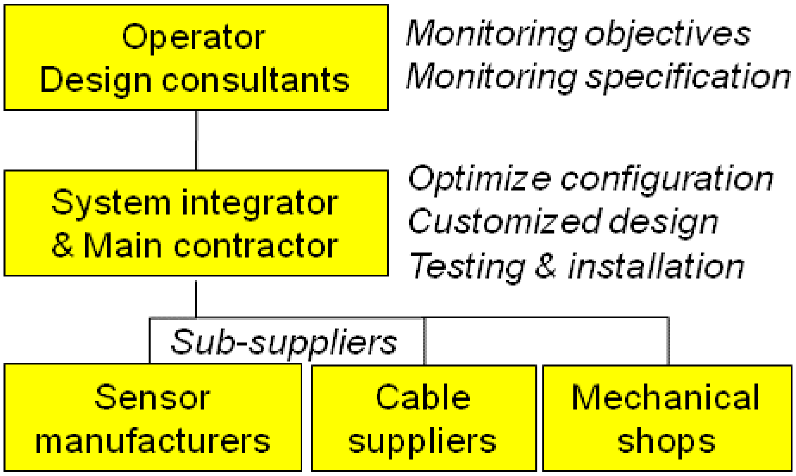


Figure 7-17 Organizaton and flow chart for execution of a monitoring project

7.4 Guidelines for selection of sensors

7.4.1 Basic considerations

- **Parameter to be measured:** Determine the best method to obtain the required parameter(s) including how to get the desired accuracy.
- **Specifications:** Range, resolution and accuracy required. Cost is usually a function of the specifications - choose the specifications appropriate for the requirements and not simply the very best sensor on the market.
- **Signal type:** Which signal type (voltage, current, frequency, digital or optical) is best suited for this particular application? This has implications also for choice of cabling and interface electronics.

- **Priority:** Which priority do you give to this particular measurement? This may govern the type of equipment you choose w.r.t. price and quality.
- **Environmental:** The environmental conditions must be taken into account when choosing materials, ruggedness of enclosures and mounts etc.
- **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 prolonged. Apply a reasonable safety factor.
- **Sensor materials:** Requirements regarding corrosion, pressure, size, electrical effects etc.
- **Sensor manufacturer:** Previous experience with supplier.
- **Cost and delivery time**: Always to be considered.

7.4.2 Sensor accuracy

Sensor accuracy is often specified as the sum of the following errors, see also Figure 7-18.

- Non-Linearity
- Hysteresis and repeatability
- Drift

Note that the sensor resolution does not give any information about the accuracy. In many cases mounting and how the sensor is used are more important for the overall precision in the measurements than the sensor accuracy.

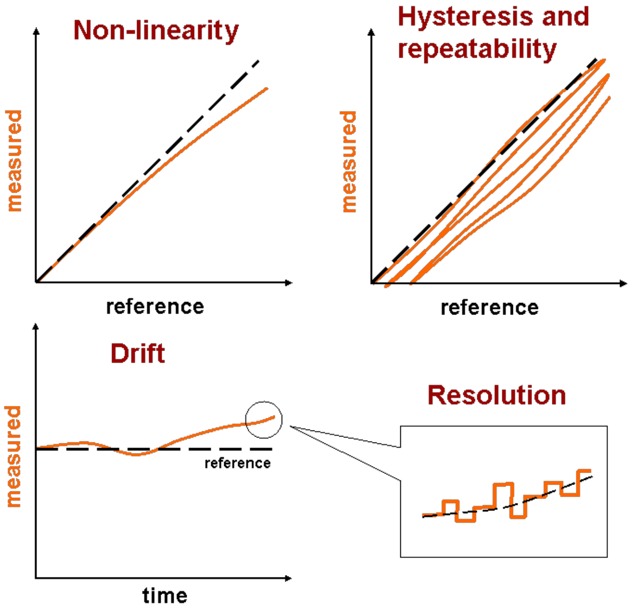


Figure 7-18
Definitions of sensor specifications affecting the overall accuracy

The maximum error is stated as an Engineering value or as a percentage of sensor full range/scale (FS). If only a portion of the sensor full range is utilized, better accuracy can often be obtained by re-calibration for the utilized (limited) range or taking reference or offset readings.

In conjunction with deformation and position measurements it is very important with minimum slack in the attachment point and/or that the reference position/or environment does not change. For example, the use of high precision inclinometers is meaningless if the alignment and fixture to the structure not is appropriate.

7.4.3 Sensor backup and redundancy

Back-up is defined as an identical extra system in case the main system should fail. Redundant system is different (maybe simpler) but shall provide similar functions as the main system.

Executing a long-term monitoring project in deep waters involves a significant amount of money. The costs of for example extra sensors (back-up or redundant) is often minor compared to total costs. It is therefore strongly advised to not compromise on back-up/redundancy in order to save costs as that will increase the risk failing with the monitoring task.

Identify which parts of the system which requires redundancy. This is usually related to risk of damage and accessibility for repair. e.g.:

- Sensors embedded in the seabed (not accessible): Need redundancy
- Topside and subsea sensors accessible for replacements: May not need redundancy
- Topside Logging cabinet: Does not need redundancy.

Also sensor redundancy or supporting instrumentation will enhance the quality of the data readings. For example if one sensor shows a trend development the possibility of drift in the sensor cannot be disregarded, see Figure 7-19. However, if two different sensors show the same trend it is more or less certain that the response is real.

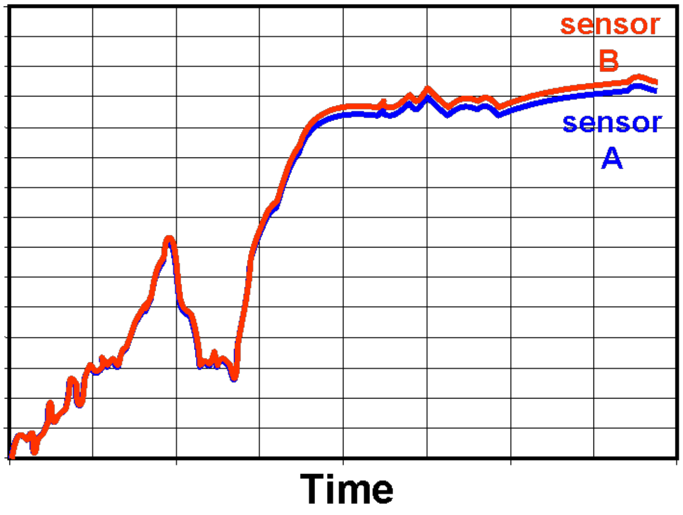


Figure 7-19 Redundant sensors (A and B) - increased data reliability

7.5 Guidelines for purchase and calibration of sensor systems

7.5.1 Receipt of sensors

Most sensors that are commercially available come ready calibrated from the manufacturer. However, errors by the manufacturer and transport damage may occur, and it is therefore important to check the sensors on receipt.

Function test the following on receipt of equipment (do this immediately when receiving equipment):

- Visual signs of damage
- Power up sensor and check signal
- Sign checklist after completion for Quality Control (QC) documentation

Calibration checks:

- Calibrate 1-2 steps within range, check signs and zero point
- Verify this is in accordance with specifications from manufacturer
- Sign checklist after completion for QC documentation

7.5.2 Customized calibration

For instrument systems where high accuracy is required and only a limited part of the total range will be used, it is often advisable to perform a re-calibration of the sensor within the limited range which is relevant for the application. Special calibration may also be advisable when operating at for example low temperatures, usually it is sufficient to check temperature offsets. In some cases, the fixture or measuring arrangement may be the critical factor for the overall measuring accuracy, in such cases it is recommended that a calibration check is done on the complete system is performed (if possible) on a dummy set-up.

7.5.3 Functional and in-situ calibration tests

For sensors built into a system, calibration simulating the use and function of the system should be performed as this will be representative for the monitoring application and include all aspects affecting the overall accuracy. This type of functional testing/calibration is often the most important check of the measuring system. In some cases, field calibration is required. This is normally limited to in-situ zero point check of for example systems based on pressure measurements (piezometers) or offset readings after inclinometers, extensometer or strain gauges have been mounted on the structure.

If possible, the sensors should be in operation and data recorded during installation. The sensor response should be carefully logged and as observed values may be used directly as new offsets in the data acquisition configuration files. Many times the readings taken during installation provides an important baseline for later monitoring and data interpretation. See Figure 7-16.

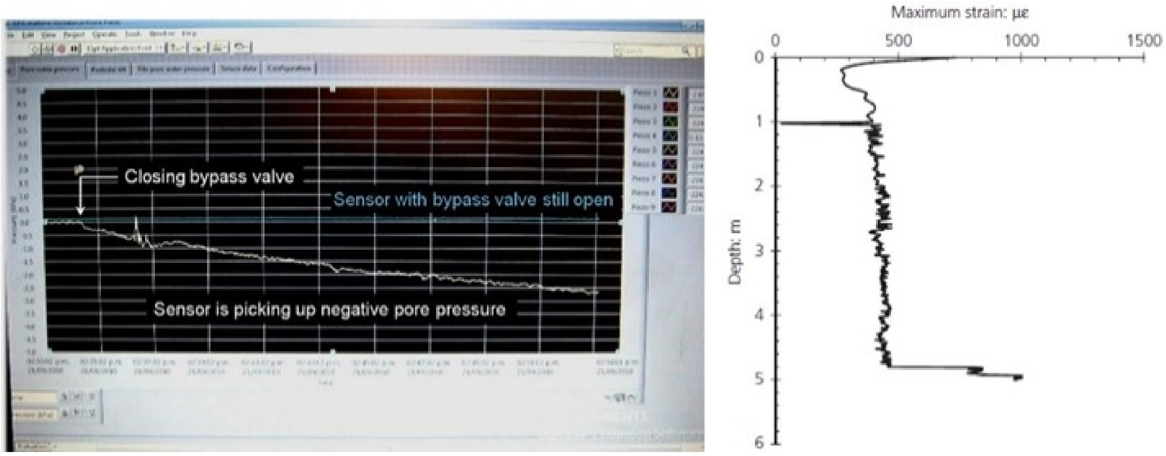


Figure 7-20 (left) Real-time display showing piezometer response directly after seabed installation (in this case negative pore pressures were expected as the instrument was installed in swelling clays). From NGI archives. (right) Tracking of fiber optic strain gauge during pile driving, these records provide important information about sensor integrity after driving and the recorded stresses provides an essential baseline for subsequent strain recordings during loading, Example from validation tests of FBG sensors performed by UCD Doherty et al.

For larger instrumentation systems, it is required that the sensors ID’s and line/cable routing is properly described in hook-up diagrams with sensor, cable and channel ID’s. A master list showing all ID’s, as well as conversion factors is essential for hook-up and configuration of the data acquisition system. Sensors and cables should be properly tagged, it is useful to show the sign convention on sensor enclosures (for example inclinometers) and tag long cables in both ends. Even with careful documentation and marking it is strongly recommended that the sensor response is checked during field hook-up making sure that both signal address and sign convention are correct. This may save a lot of questions when reviewing and interpreting data during later operation.

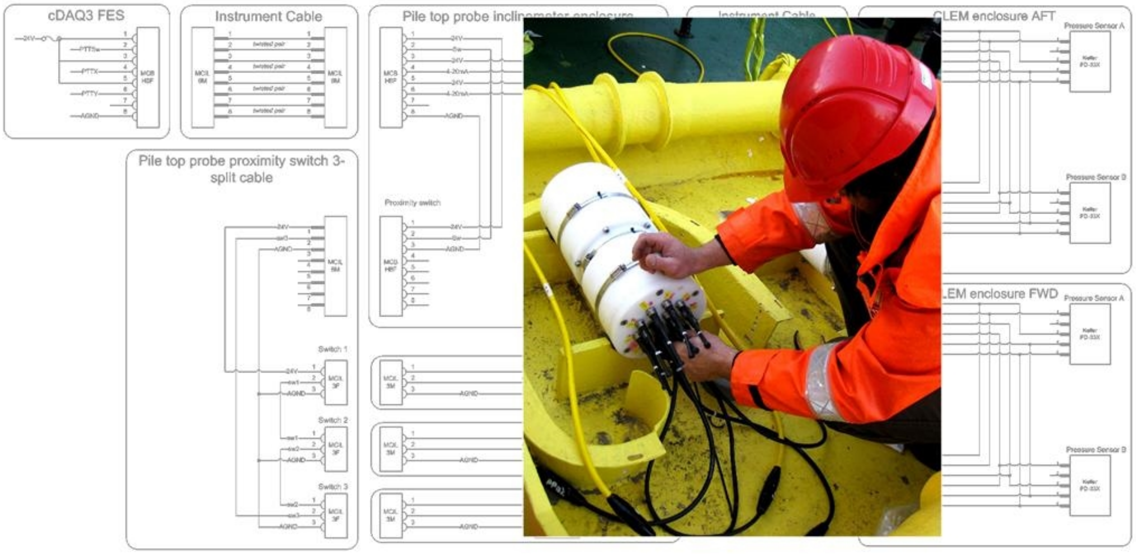


Figure 7-21 Make sure that signal cables and routing is correct during field hook-up! (Photo and hook-up diagram: NGI Archives)

Wrong sensor address, sign convention done or missing offset reading during hook-up unfortunately happens to often and may lead to a lot of confusion or even wrong interpretation of the recorded data. Especially inclinometers are susceptible to such errors as different sign conventions are used (pitch/roll or tilt) from different suppliers.

The example in Figure 7-22 shows recorded pore pressures from a seabed piezometer. The data was difficult to explain by the geotechnical engineers but made sense when a sign error was discovered.

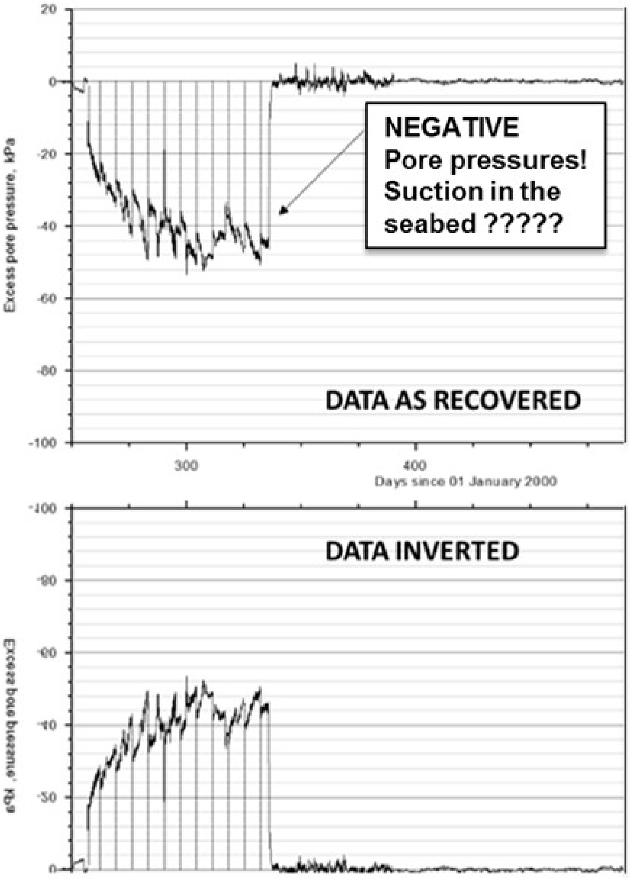


Figure 7-22 Data initially recorded with the wrong sign (Source: NGI archives)

7.6 Instrument corrosion and preservation

Corrosion is important to consider especially for long term deployment. Even if the rules of thumb are followed such as using noble metals in the galvanic series, not mixing metals with different galvanic potential or using cathodic protection, the results may be discouraging. Scratches in the anodized aluminum surface or anodes with oxidized surface may compromise the protection. Mixing of metals or fixture to larger steel structures without galvanic isolation can result in rapid corrosion even if the metals themselves are corrosion resistant. NGI's practice is to keep it simple and only use for example stainless steel in combination with thermoplastic materials such as Delrin. The use of thermoplastic materials is usually OK in shallow waters with limited ambient pressure thus the structural strength of the enclosure is less important. See also section 7.2.4.

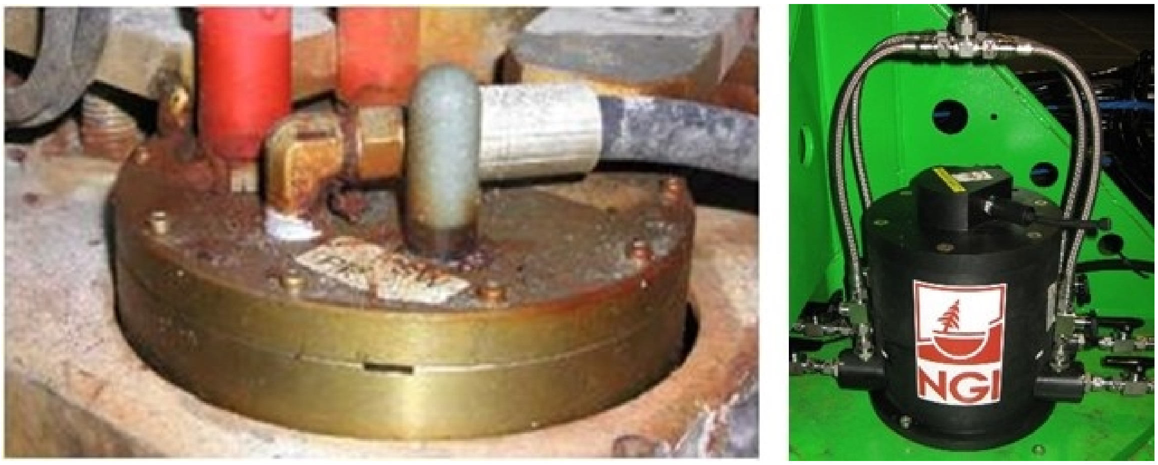


Figure 7-23 Galvanic corrosion on metal enclosure with connectors in different metal grade (left). "Corrosion safe" synthetic enclosure in Delrin for shallow water with connectors/outfitting in stainless steel (right)

As for discussed in section the marine environment at the windfarm is very corrosive this applies for instrumentation under water, in the splash zone and above sea level.

The general recommendations to limit corrosion:

- Don't "mix" metals (except if cathodic protection I used)
- Determine local environmental conditions
- Isolate dissimilar metals

Support items such as brackets, cable trays etc. should either be of similar steel as the structure, coated and protected by the structural CP system or galvanic isolated from the structure.

7.6.1 Suitable materials

Titanium or titanium alloys have both high strength and very good resistance to all types of corrosion in sea water, but expensive and difficult to machine than steel.

Stainless steel alloys, SS 316L or Duplex are recommended with respect to corrosion resistance. Note that it is important that the surface is not treated, e.g. by painting, as the stainless steel must have access to oxygen to oxidize the surface. It is also important to treat the surface after machining to start the oxidization process. More exotic alloys are Inconel 625, Hastelloy C or 254 SMO which are close to Titanium w.r.t. corrosion resistance. Again these materials are expensive and sometimes difficult to machine, some suppliers of pressure sensors offer Hastelloy membranes which are recommended.

Anodized aluminum, has good corrosion resistance in seawater. However, this requires that the anodizing layer is intact and does not become scratched or damaged. Try to avoid if unless weight optimization is required. Pure aluminum should not be used in marine applications.

Non-metallic materials eliminate the risk for corrosion risk, but the application/design must be suitable, e.g. deformation-under-pressure characteristics of pressure vessels. Design of pressure vessels may be different from metal vessels. Synthetic materials which absorb water such as Nylon should be avoided for subsea application due to swelling. Delrin (or POM C) is a cost-efficient choice. Some plastic materials are sensitive to UV exposure and should not be used externally above sea level.

For larger items such as seabed frames etc. ordinary St 52 carbon steel can be used if the surface is coated by two-component epoxy paint and anodes are used, see Figure 7-24.

Figure 7-24 Coated bottom mount for ADCP sensor with zink anodes (Photo Mooring Systems Inc.)

7.6.2 Galvanic isolation

If, for some reason, dissimilar metals have to be used together, they must be galvanic isolated from each other. Figures 7-25 and 7-26 show examples of isolation methods.

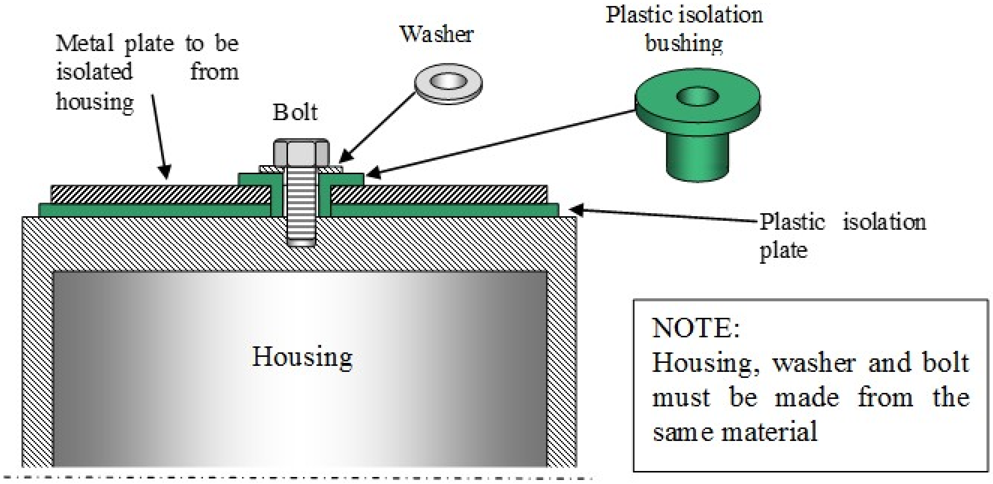


Figure 7-25 Dissimilar metal plate isolated from housing

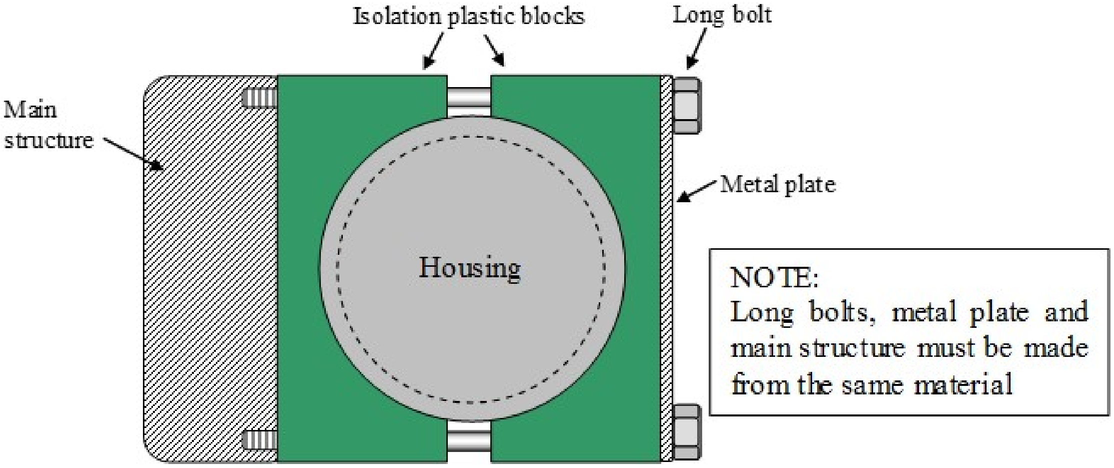


Figure 7-26 Dissimilar metal structure isolated from housing

7.7 Pressure vessels and pressure seals

As an example, for subsea instrumentation, the focus for leakage integrity is on the high loads given to the actual effect of the high-water pressure itself. This is a rather straight forward design issue which can be tested in advance by pressure testing. The truth is that a leak often occurs already at low pressure and usually caused by human errors such as a damaged O-ring. It is therefore recommended to use two independent barriers (O-rings) on seals which must be opened after pressure testing.

The basic considerations for water ingress integrity and pressure testing are described in section 7.2.4. Creeping leaks are difficult to detect during pressure testing and for permanently immersed system prolonged testing period is recommended (at least a couple of days). It is also a good practice to avoid sensitive electronics in the bottom of the enclosure and have an "umbrella" on top such that droplets of seawater do not fall directly into the electronics, see Figure 7-27. The bulkhead connector may be a weak point with respect to leakage. Such simple arrangement may prolong the operational life of the instrument unit with several months if a creeping leak is present.

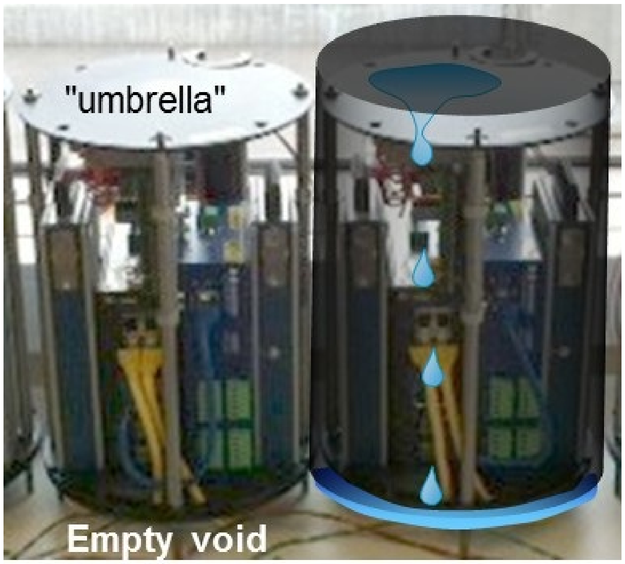


Figure 7-27 Instrument enclosure with internal umbrella and sensitive electronics elevated from the bottom (photo NGI archives)

A water ingress detector (two electrodes in the bottom of the enclosure sensing the difference in conductivity when immersed in salt water) can be used for early warning of leakage. However, leakage detection is only useful if the instrument enclosure can be recovered from the sea within short time and not relevant for permanent equipment.

7.7.1 Pressure sealing approaches

Insert lids with O-ring grooves is the most common and recommended type of seal for external pressures enclosures. The cylinder housing contracts evenly around O-ring grooves, and lid will have very little tendency for geometric deformation when external pressure is applied. Use two O-rings for redundancy, see Figure 7-28.

NOTE: include a means to grip the lid so it can be lifted off. The O-rings and generated suction pressure difference may make the lid difficult to pull out. Screws passing through the edge of the lid and acting on the edge of the container can be used (turning the screws lifts off the lid). Another approach is to machine small slots in the lid to allow several screwdrivers to be used to pry off the lid.

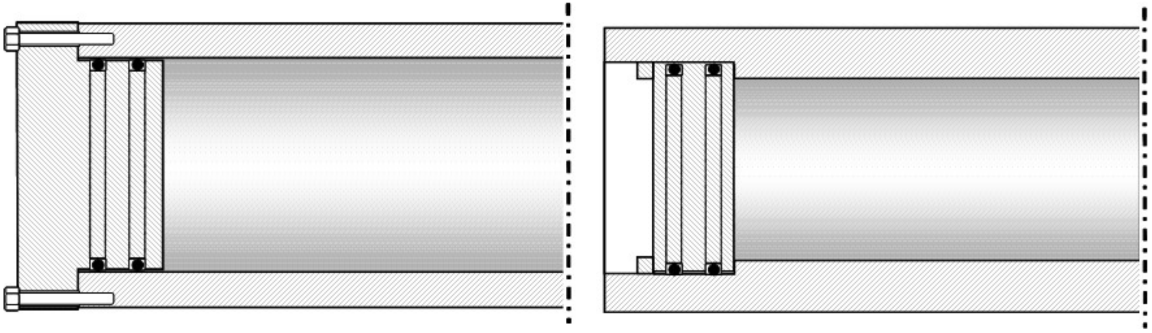


Figure 7-28 Insert lid container: Held in place by bolts (left) or by locking ring (right)

From mechanical strength a cylinder enclosure is preferred, for larger diameters the wall thickness must be increased. Mechanical strength is however normally not an issue at the shallow depths relevant for offshore wind farms. To simplify opening and closure of the container, the inside electronics can be attached to the lid which is equipped with the external bulkhead connectors. Thus, all cabling and electronics are hooked-up and attached to only one part of the instrument enclosure. Care should be taken when closing the lid, pinched cable leads is probably one of the most common reasons for failure.

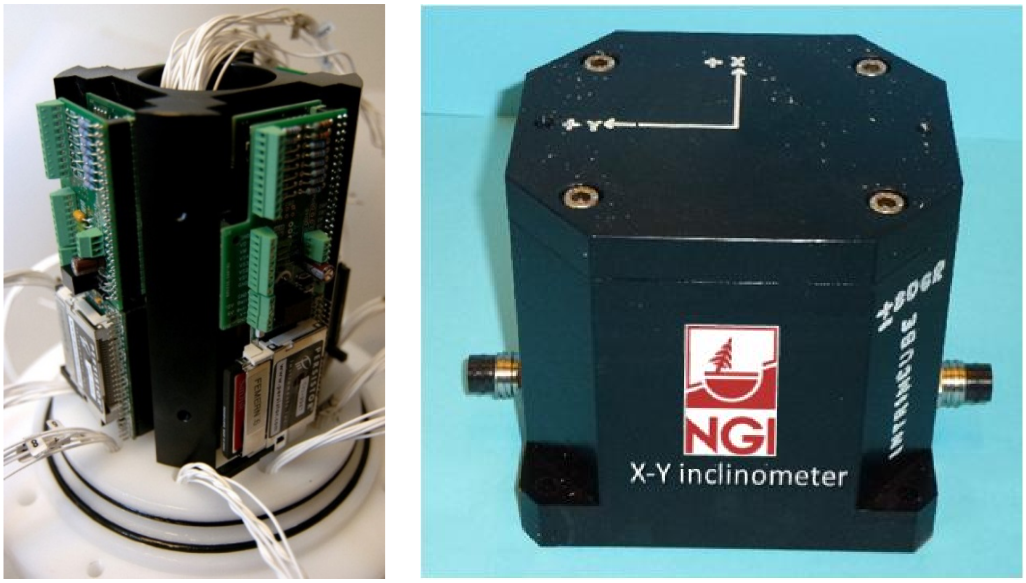


Figure 7-29 (Left) Electronics fixed to lid and hooked up to bulkhead connectors on the lid. (Right) Inclinometer housing with connectors on the body and no outfitting attached to the lid (photo: NGI archives)

Other alternatives for securing the enclosure lid(s) are shown in Figure 7-30.

Figure 7-30 From left to right, Lid flange plates with through bolts, external stress rods and enclosure with threaded locking ring/collars

Note that a leaking subsea container may be pressurized with the hydrostatic pressure at the installed depth. This can be a potential hazard, however for shallow water application the possible over pressure will be limited and it is sufficient to open the containers with care.

7.7.2 General types of seals

Various types of container seals are available:

- Flat gaskets for no pressure differential (Pressure compensated vessels or 'Splash-proof' rating only).
- O-rings for applications with pressure differential

Incorporate 'double barrier' philosophy when possible, e.g. use two O-rings to make the seal. Recommendations and check list for O-ring seals:

- Always use on metal or thermoplastic containers for pressure sealing applications
- Many O-ring types & different materials:
    - ✓ Hardness to suit pressure range – check!
    - ✓ Material to suit medium (sea water, oil, etc.) – check!
- O-ring dimensions (thickness) influence sensitivity to small particle impurities; "fat" O-rings are less sensitive to small particles.
- O-ring groove dimensions vs. O-ring dimensions. Specific rules apply for O-ring vs. groove dimensions. Check manufacturers/suppliers specifications

- O-rings should be moderately greased with appropriate silicone grease, Aqualube, Molycote 111 or 44. Avoid Vaseline in colder temperatures (temperature sensitive and hardens when cold).

7.8 Connectors and cables

Leakage integrity check of subsea connectors and cables is also very important in order to ensure long term functioning of the subsea instrumentation system, see Figure 7-31.

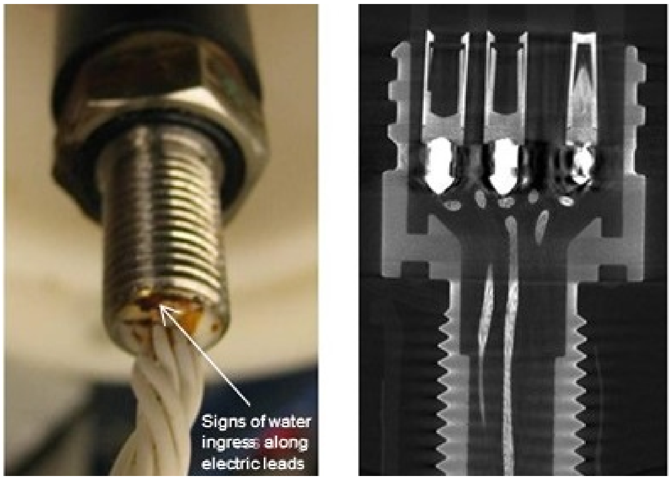


Figure 7-31 Creeping leakage along one lead in a subsea connector due to improper priming and bonding of neoprene pin seals (source: NGI archives)

7.8.1 Connectors

The most common (and less costly) subsea connectors are neoprene connectors with over molded pin seals, see Figure 7-32. There is wide range of this type of connectors with different layout and configuration available in the market. Some of the biggest suppliers are Seacon (Wetcon), Subcon, Impulse, Burton., etc. All brands are more or less of similar design. The connection should be secured with locking sleeves. The sealing is increasing with the hydrostatic pressure and the over molded pins seals must be treated as O-rings (greased and protected from dust). Unplugged connectors should always be protected by blind plug or caps.

Figure 7-32 Neoprene bulkhead and inline connectors with over molded pin seals. Locking sleeve arrangement shown to the right. These types of connectors are not water blocked.

Metal shell connectors are robust and normally water blocked, see Figure 7-33. They must be dry mated, available both for electric and fiber optic connections. Suitable for long term operation and for larger number of pins than the over-molded connector (also more expensive)

Figure 7-33 Metal shell connectors from Seacon and Burton

Penetrators provide continuous connection and are normally used for pressure tight routing of fiber optic lines through a bulkhead. PG cable glands are not recommended for permanent subsea operation.

Figure 7-34 Fiber optic penetrator (left) and typical PG cable gland (right)

External connectors above sea level must as a minimum have IP67 ingress protection, MIL type of connectors are commonly used, see Figure 7-35. Subsea connectors should be used in the splash zone.

Figure 7-35 MIL type connectors (common field connector based on US Military specifications)

7.8.2 Offshore instrumentation cables

Polyurethane (PUR) jacket is recommended for all cables routed externally (both subsea and topside). PUR cable are easy to handle, robust against abrasion, both saltwater and UV resistant. Kevlar reinforcement is recommend, if the cable is subjected to tension during installation and/or operation. The PUR jacket is also suitable for over molding of neoprene inline connectors or splices, see Figures 7-36 and 7-37.

Figure 7-36 Typical cross section and examples Kevlar reinforced PUR cables for offshore and subsea use

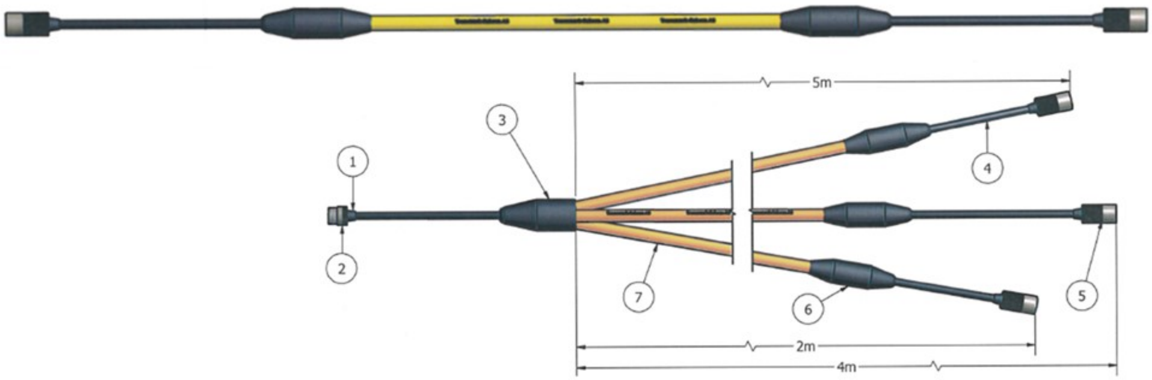


Figure 7-37 Example of inline connectors molded directly to PUR cable and molded cable split which many times is more cost efficient than using subsea junction boxes.

For short jumpers (not exposed to any loads neoprene cables may be used). The cables should be properly routed and secured to the structure. Especially the connectors must not be subjected to strain, see Figure 7-38. Cables traversing the splash zone will be subjected to significant slamming forces and should be protected inside steel conduits (pipes).

Figure 7-38 Example of proper cable routing (Photo from NGI archives)

7.9 Electric system design

An offshore wind turbine is a power generator, thus considered as noisy with respect to electro-magnetic (EM) conditions. The noise conditions (especially EM) are significantly attenuated below the sea surface. Some general electric system design aspects are discussed in the following sections:

7.9.1 Signal and cable routing

See also section 6.2 Signal transmission.
For hook-up of sensor arrays the sensor signal can be:

- Analog voltage (0-10 V) or Current loop (4-20 mA) 2 or 3 wire system
- Vibrating wire (frequency)
- Digital for example RS232, RS485, Ethernet, CAN/ProfiBus (RS232 is usually not suited for data transmission through long lines, without extender Ethernet signals also have a limitation of about 100m cable transmission)

In general, a cable does three important things to the signal:
(1) it attenuates the signal,
(2) it contributes its own inductive (L) and capacitive (C) reactance, which can alter different parts of the signal differently--of particular importance, attenuating some frequencies, such as high audio notes, more than it attenuates others, and
(3) it exposes the signal to electromagnetic energy from other sources which can enter the cable and pollute the signal with noise.

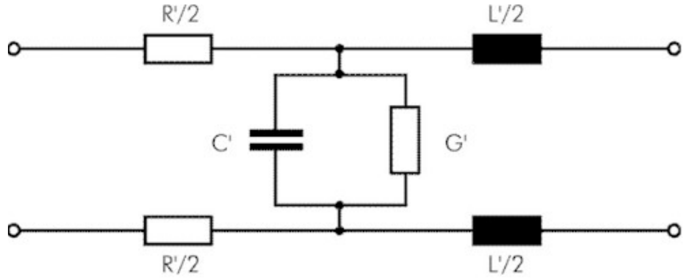


Figure 7-39 The cable in theory

For most signals, twisted pair wiring is a good solution and provides the best shielding against EM noise. It is usually no problem to mix power and signal leads in one cable. For ethernet signals the reactance must be considered.

With respect to power it is important to check the voltage drop in long cables (dependent on cross section on power conductors). In some cases (if the cable cross section should be optimized) it may be necessary to feed the instruments with a higher voltage through the cable and transform it to the specified input voltage using a local DC-DC converter in the sensor enclosure.

7.9.2 Grounding

One of the basic electronic laws tells us that each current flowing from a power supply has to come back to the source. This “back wire” is often called the ground and one of the most common failures is to mix the ground path of different electric equipment liker power consuming motors, low power analog signal and high frequency digital signals. If all different signals share the same ground path, there will for sure be some influence between the signals which most often result in noise on the analog lines. To overcome this problem, star grounding with different ground loops for different needs are recommended.

Star grounding means at there are different electric connections to each device from one central ground point. For a balanced system, the connector from the power supply to the electric instrument should be equal to the return path from the instrument to the power supply.

Other grounding problems can arise when metallic under water enclosures are used. There are several sensor types where the ground pin from the connector is connected to the sensor housing. If the sensor housing is in contact with sea water an additional ground loop is introduced. This may result in additional noise and corrosion problems. For subsea instrumentation, the ground should not be connected to sea.

7.9.3 Mains power supplies

There are two types of power supplies on the market: Linear power supplies and switch power supplies.

Category	Linear	Switch mode	Comment
Size	☹	☺	Switch typical 80% smaller
Weight	☹	☺	Switched typical 80% lighter
Input voltage range	☹	☺	Linear 10% versus 300% switched
Efficiency	☹	☺	Power save over long term
Reliability	☺	☺	Probably equal
Ripple / noise	☺	☹	Switched needs extra filter
Transient response	☺	☹	Linear up to 1000 times better
Leakage current	☺	☹	Linear has low leakage current

In most applications one power supply serves several units like data logger, sensors, communication devices and more. When designing the power distribution care has to be taken to the possibility of a failure on one of the connected units. A short circuit on one unit should not influence the functions of the other connected units. A simple possibility is to use a fuse for each unit such as the faulty devices in case of a short circuit is disconnected from the power line. An example is shown in Figure 7-40.

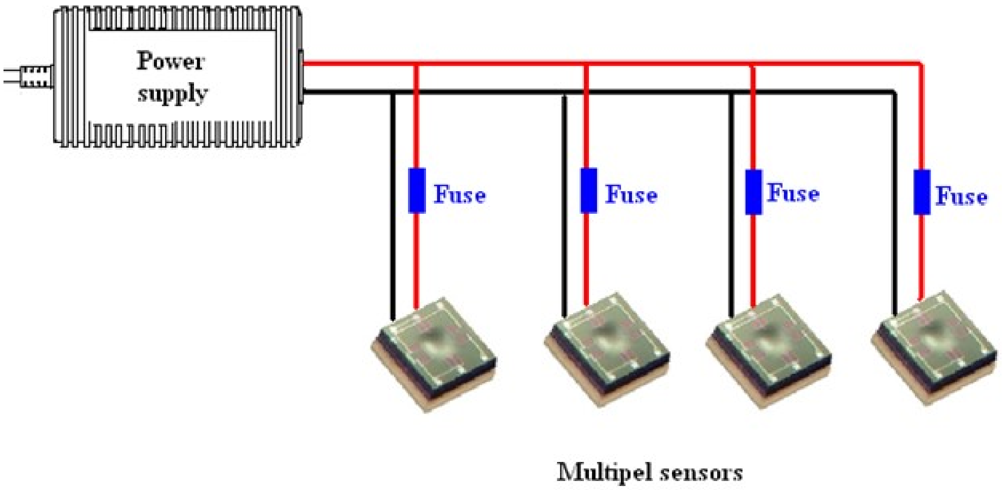


Figure 7-40 Main power supply with individual fuses for each unit

Isolating power supplies should be used for safety. Most linear and switched power supplies are isolating power supplies, means at there is no electrical connection between the input voltage and the output voltage.

With respect to current loops under water it may not be sufficient to only use fuses at one side of the loop. There may be situations where a damaged cable could cause a short circuit to the sea allowing stray currents in the water to form another loop.

The current may not be sufficient to trigger any fuses but could cause rapid corrosion at unexpected locations, see Figure 7-41. Thus, it is recommended to use fuses on both sensors sides of a current loop.

Figure 7-41 Burned batteries and galvanic corroded connector caused by stray currents in the water probably originating from broken cable isolation and fuses with insufficient sensitivity (Photo NGI archives)

7.10 Quality control and documentation

Performing tests or checks along the way to completion can usually prevent costly mistakes and longer delays for installation.

IMPORTANT: A test which is not documented in written form has no value with respect to the QA/QC system. The documentation does not need to be extensive. It can be as simple as a handwritten note describing what is tested, how the testing is done, what the results are, and signed + dated by the person doing the tests.

In general, the following milestones checks should be included:

7.10.1 Technical design stage

- Concept design. What is to be measured? What are the specifications and the design constraints? Involve project QA responsible as well as appropriate technical experts/specialists at NGI. Verify with the client that we are designing equipment to meet their needs.
- Multi-disciplinary check. Have others reviewed the design concept?
- Final design drawings. Pre-production control.

7.10.2 Procurement and Manufacturing stage

- Orders of components (Send written orders; get quotes from several suppliers if possible)
- Make sure the that the supplier has understood the order correctly (order confirmation)
- Follow up on delivery times, special cables are often long lead items and only produced in batches. Sometimes this can lead to delays.
- Control of externally manufactured hardware. Include visit to factory if applicable.
- Receiving of components (including initial function testing)
- Calibrations of sensors
- Software or firmware to run the data loggers
- Testing of assembled sub systems (if appropriate)
- Leakage testing of pressure containers
- Assembly checks: Visually check system that everything looks correct and not damaged (particularly after transporting of equipment). Check all subsea connectors
- Electrical test: Perform instrument loop test and test isolation against earth. Check power consumption against available battery power
- Overall system testing (functional testing) before FAT

7.10.3 Delivery stage: FAT and SAT/SIT

Executing FAT (Factory Acceptance Test) and SAT/SIT (Site Acceptance Test/System Integration Test) is in interest for both the SHM contractor (instrumentation supplier) and the Operator (end user). As the instrumentation system may be subjected to conditions outside the suppliers control, given warrantees must be limited. Witnessed testing of the equipment (FAT and SAT) constitute important milestones in an instrumentation project and demonstrates that the delivery is compliant with the specifications. From the clients perspective these tests are important verification of the purchased system. Usually the ownership of the equipment and payment is linked to those tests.

FAT testing may include:

- Submittal of test documented tests performed during the manufacturing stage
- Inspection of mechanical completion of the system
- Functional and calibration testing of the system, usually limited to spot checks

During FAT the hardware and software is tested and functionality verified in accordance with the procedures and acceptance criteria. The Client's acceptance of the FAT is usually also the acceptance of the delivery in accordance with the contract. FAT testing is usually performed at the supplier's premises. If the FAT not is accepted and punch list is compiled describing the rectifications required for acceptance.

SAT/SIT is normally performed at the yard or/and in the field and is limited to demonstration proper rigging/installation and normal operation of the system after installation. As for the FAT test procedures to be agreed on in advance. System integration testing is relevant if the SHM supply consists of sub systems which not have been tested together at an earlier stage. This may for example be communication with turbine SCADA system.

7.11 Offshore and Subsea installation considerations

As described earlier it is advised that parts of the instrumentation system are pre-rigged (mechanical components, cables and some sensor systems) to save offshore installation time. However, for retrofit and maintenance offshore/subsea installation operations are expected.

7.11.1 Weight of equipment

In general one should try to keep weight of equipment as small as possible to make yard and offshore handling easier. Consider the following factors which may limit the total weight:

- Manual lifting on deck
- Crane handling
- ROV/Diver handling

In some cases extra dead weight of the equipment may be necessary for stability purposes, e.g. subsea templates. In other cases buoyancy may be added to simplify subsea handling by ROV/Diver

NOTE: Equipment that has to be lifted by crane should have offshore certified lifting points, or must be able to be lifted in a certified basket.

7.11.2 Safety and access

Offshore work is demanding and safety must be taken serious with highest priority. Access and safety for offshore installation work must therefore be taken into account when designing the system solution. This also includes safe access for later inspection and calibration checks.

Figure 7-42 Difficult access for instrument mounting (left). Mounting instruments inside installed offshore pile is not a comfortable or safe work place (picture from internet)

Figure 7-43 No longer a safe workplace!

7.11.3 System rigging and hook-up plans

Points to consider when designing the layout of the instrumentation system:

- Compact layout for handling onboard/lifting through water column. Split into manageable sections if possible
- How is it installed - requirements for lifting, work at heights or ROV/Diver intervention
- Hook-up. Some jacket/tripods are assembled as building blocks, when can instruments be installed (accessible), when can cables be routed…etc. Is subsea hook-up required by ROV/Diver?
- Protection and securing equipment for rough handling bot at the yard and offshore

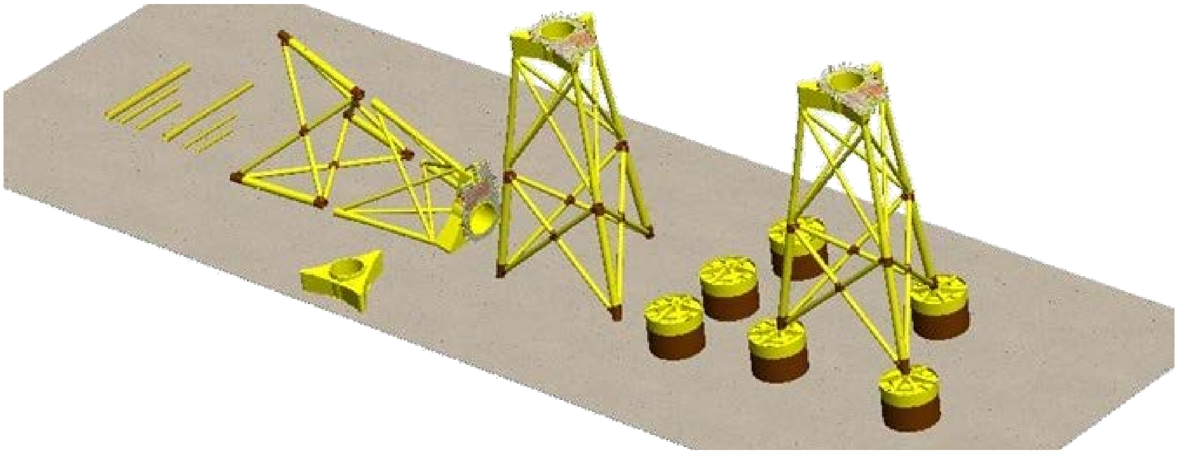


Figure 7-44 Dong Energy's SBJ foundation assembled as building blocks. How and when to install strain gauges required thorough planning and cooperation with the Yard (Source NGI archives)

7.11.4 ”As installed” protection

Instruments and especially cables installed on the structure should if possible be protected against falling objects and environmental forces. External cables run through the splash zone are exposed to very rough conditions (breaking waves) and recommended to be fully protected inside conduits or channels. The splash zone can also by highly exposed to severe corrosion and marine growth, see Figure 7-45.

Figure 7-45 Examples of the severe conditions which can expected at the splash zone

7.11.5 Summary of factors affecting the Long term durability

The ability of the installation to withstand the duration of the deployment must be evaluated. Several factors should be addressed in the concept and detail design phases:

- **Corrosion:** Integrity of the instruments, protection enclosures, brackets and fixture and if relevant, the ability to operate moving parts (extensometers). Corrosion of lifting slings/eyes can be a problem for later recovery.
- **Biofouling:** Marine growth covering the instruments can affect the measurements (especially for chemical sensors, see Figure 7-46). May also overload the equipment and make access difficult.
- **Leakage** (water migration) through synthetic materials: Neoprene plugs may leak over extended deployments (many years) due to water creeping along inside of the over molded pins if not water blocked. Some materials absorb water (swelling).
- **Degradation:** Some materials become brittle over long term exposure to salt water, or in shallow water/splash zones. Especially important for cables.
- **Mechanical protection:** External instruments are subjected to significant forces both from waves and wind. The risk of human interference is also a factor which cannot be neglected (dropped objects, removal of components, sandblasting, paintwork, welding, etc.). The requirements for mechanical protection and proper marking of the installation depends on the location at the structure.
- **Electrical**, Lighting, mains power failures and human interference (cables and junction boxes).
- **Long term processes:** Sensor out of range may be caused by drift or measured parameter larger than expected.

Figure 7-46 Biofouling on a chemical sensor immersed one year in tropical waters

Although NGI have kept SHM systems on offshore platform alive for more than 27 years it is unrealistic to expect that the initial SHM installation will have the same operational life as the OWT foundation itself, sensors or cables being damaged or failing with time must be expected. Much shorter operational life must be expected for some types of instruments like strain gauges under water or instruments embedded in the seabed, 5 years operational life is then a realistic goal. If life time monitoring is the aim, future replacement monitoring solutions must be planned for. Future technology may also allow for better and simpler monitoring.

In order to keep the system in operation some maintenance must be expected, this is limited to accessible instrumentation and DAQ system. Many times financing and lack of interest for continued operation of the SHM system also limits the operational life of the system.

Figure 7-47 The cassette tapes and recorders more or less disappeared 20 years ago and was replaced by other technology. What about SHM monitoring solutions 20 years in the future?

8 Standards and guidelines

Presently the only known wind power specific standard for Structural Health Monitoring is the new German VDI Guideline 4551 “Structure Monitoring and Evaluation of Wind Turbines and Platforms”. All other standards are mainly related to the drive train and wind turbine itself (machinery).

9 References

A significant share of the information and examples presented in this study is based on NGI in-house experience and knowledge. Other examples are based on articles and presentations at homepages from cited suppliers and academic institutions.

Other published references are listed below:

Design of monopiles for offshore wind turbines in 10 steps
Laszlo Aranya, S. Bhattacharyab, John Macdonalda,, S.J. Hogan
Soil Dynamics and Earthquake Engineering
Volume 92, January 2017, Pages 126–152

Condition monitoring of wind turbines: State of the art, user experience and recommendations - Project report 2015
Diego Alejandro Coronado and Katharina Fischer,
Fraunhofer Institute for Wind Energy and Energy Systems IWES.

Guideline for the Certification of Offshore Wind Turbines (2012).
Germanischer Lloyd Industrial Services GmbH. Hamburg, Germany.

Revisiting mono pile design using p-y curves - Results from full scale measurements on Horns Rev
T. Hald, C. LeBlanc, C. Mørch, L. Jensen, K. Ahle, EOW 2009
Proceedings Frontiers in Offshore Geotechnics III, Oslo 2015

Structural Health Monitoring Systems in Difficult Environments—Offshore Wind Turbines
P. Faulkner, P. Cutter and A. Owens
6th European Workshop on Structural Health Monitoring - Fr.2.A.3

Structural health monitoring of a monopile foundation structure of an offshore wind turbine
Michael Link, Matthias Weiland
Department of Civil and Environmental Engineering, Kassel, Germany
Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014
Porto, Portugal, 30 June - 2 July 2014

Inspection and monitoring of corrosion inside monopile foundations for offshore wind turbines
L. R. Hilbert, A. R. Black, F. Andersen, T. Mathiesen, FORCE Technology,
Paper no. 4730 EUROCORR 2011 Conference Stockholm September 4th-8th 2011

Monitoring resonant frequencies and damping values of an offshore wind turbine in parked conditions
Christof Devriendt, Wout Weijtjens, Mahmoud El-Kafafy, Gert De Sitter
Offshore Wind Infrastructure Lab, Brussels, Belgium
Published in IET Renewable Power Generation 2014

Foundation Monitoring Systems: Analysis of 2 Years of Monitoring at the North Sea
Gert De Sitter, Wout Weijtjens, Yves Van Ingelgem, Daan De Wilde, Kristof Verlinden, Stefan Millis, Christof Devriendt
Vrije Universiteit Brussel, Parkwind NV, Sirris, Offshore Wind Infrastructure Lab, Zensor
Poster EWEA 2014, Barcelona, Spain

Long-gauge fibre optic sensors: Performance comparison and application
Carlos Rodrigues ,Daniele Inaudi, Branko Glisic
International Journal Lifecycle Performance Engineering Vol X, xxx

Structural health monitoring of offshore wind turbines: A review through the Statistical Pattern Recognition Paradigm
Maria Martinez-Luengo, Athanasios Kolios n, Lin Wang
Cranfield Energy,Cranfield University,BedfordMK430AL,UK
Journal article Renewable and Sustainable Energy Reviews 64(2016) 91–105

Kontroll- og referanseside/ Review and reference page

Dokumentinformasjon/*Document information*		
Dokumenttittel/*Document title* Guidelines for Structural Health Monitoring for Offshore Wind Turbine Towers & Foundations		**Dokumentnr./*Document no.*** 16-1036
Dokumenttype/*Type of document* Rapport / Report	**Oppdragsgiver/*Client*** BSEE Environmental Enforcement Division	**Dato/*Date*** 2017-05-15
Rettigheter til dokumentet iht kontrakt/ *Proprietary rights to the document according to contract* Oppdragsgiver / Client		**Rev.nr.&dato/*Rev.no.&date*** 3 / 2017-06-15
Distribusjon/*Distribution* BEGRENSET: Distribueres til oppdragsgiver og er tilgjengelig for NGIs ansatte / LIMITED: Distributed to client and available for NGI employees		
Emneord/*Keywords* Offshore wind turbine, foundation, towers, Structural health monitoring, instrumentation, guidelines		

Stedfesting/***Geographical information***	
Land, fylke/*Country USA* USA	**Havområde/*Offshore area***
Kommune/*Municipality*	**Feltnavn/*Field name***
Sted/*Location*	**Sted/*Location***
Kartblad/*Map*	**Felt, blokknr./*Field, Block No.***
UTM-koordinater/*UTM-coordinates* **Zone:** *Type here* **East:** *Type here* **North:** *Type here*	**Koordinater/*Coordinates*** **Projection, datum:** *Type here* **East:** *Type here* **North:** *Type here*

Dokumentkontroll/*Document control*

Kvalitetssikring i henhold til/*Quality assurance according to NS-EN ISO9001*

Rev/ *Rev.*	**Revisjonsgrunnlag/*Reason for revision***	**Egenkontroll av/ *Self review by:***	**Sidemanns-kontroll av/ *Colleague review by:***	**Uavhengig kontroll av/ *Independent review by:***	**Tverrfaglig kontroll av/ *Interdisciplinary review by:***
0	Original document DRAFT (Working document)	2016-10-25 Per Sparrevik			
1	Finalized DRAFT report for BSEE comments	2017-05-15 Per Sparrevik			
2	Internal QC (grammar and language corrections)	2017-06-09 Per Sparrevik	2017-06-09 Amir Rahim	2017-06-09 Amir Rahim	2017-06-09 Amir Rahim
3	Final report with BSEE comments implemented	2017-06-15 Per Sparrevik	2017-06-27 Amir Rahim	2017-06-27 Amir Rahim	2017-06-27 Amir Rahim

Dokument godkjent for utsendelse/ *Document approved for release*	**Dato/*Date***	**Prosjektleder/*Project Manager***
	29 June 2017	Per Magnus Sparrevik

NGI (Norwegian Geotechnical Institute) is a leading international center for research and consulting within 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 following sectors: Offshore energy – Building, Construction and Transportation – Natural Hazards – Environmental Engineering.

NGI is a private foundation with office and laboratories in Oslo, a branch office in Trondheim and daughter companies in Houston, Texas, USA and in Perth, Western Australia

www.ngi.no

NGI (Norges Geotekniske Institutt) er et internasjonalt ledende senter for forskning og rådgivning innen ingeniørrelaterte geofag. Vi tilbyr ekspertise om jord, berg og snø og deres påvirkning på miljøet, konstruksjoner og anlegg, og hvordan jord og berg kan benyttes som byggegrunn og byggemateriale.

Vi arbeider i følgende markeder: Offshore energi – Bygg, anlegg og samferdsel – Naturfare – Miljøteknologi.

NGI er en privat næringsdrivende stiftelse med kontor og laboratorier i Oslo, avdelingskontor i Trondheim og datterselskaper i Houston, Texas, USA og i Perth, Western Australia.

www.ngi.no

OSLO
TRONDHEIM
HOUSTON
PERTH

NGI Inc.
WWW.NGI.NO/HOUSTON

T +1 281 752 4667
ngi@ngi-inc.com

NGI Inc
2000 S. Dairy Ashford, Ste 322
Houston, TX 77077, U.S.A

NGI Oslo
PO Box 3930 Ullevaal Stadion
NO-0806 Oslo, Norway