NGI Rapport / Report

SP2 – Instrumentation and monitoring strategy for wind energy foundations

Instrumentation and monitoring strategy

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Summary

This document describes monitoring objectives for offshore Wind Turbine Structures including both Monopiles and Jacket/tripods both with piled or caisson foundations.

Monitoring solutions (instrumentation hardware and configuration) are thoroughly described for each monitoring application (parameter).

Advice and guidelines for execution of a monitoring project (from design to offshore installation and operation) are discussed.

Contents

1 Introduction to offshore long term monitoring

1.1 General

A successful instrumentation project is when the monitoring systems provide the data required from the end user. This involves multidisciplinary coordination and understanding, the main disciplines are:

- Sensor and logging technology (instrumentation hardware)
- Marine operation and installation
- End users (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 or the hardware was not adequate for the monitoring application.

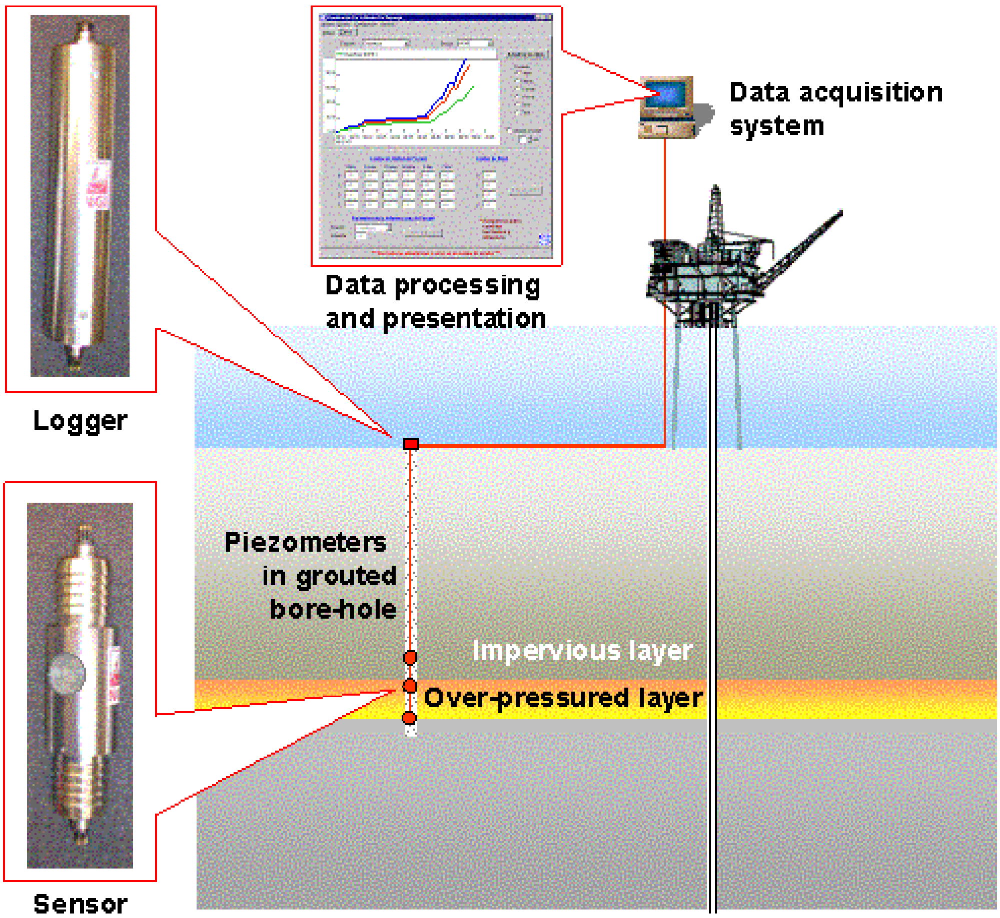


Figure 1.1 Example of a complete subsea monitoring system

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
- Power supply
- Signal transmission (cables or other)
- Logging system
- Operational life (protection, corrosion, biofouling....)
- Installation method
- Data interpretation

The balance between costs, backup and reliability of the monitoring system usually depends on how important the measurements are for the operations 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 usually must be custom made for the application.

For offshore instrumentation, the main factors affecting the design may not always be measurements with highest precision but rather:

- Limited time for design and manufacturing the monitoring system
- Simplified and minimize time for installation in the field at high day rates
- Handling and installation constraints, such as deployment in the water. *Normally operations must be possible to perform in sea states with significant wave height (Hs) of at least 2.5m. Subsea operation may be difficult in strong currents, bad visibility or if the lifting gear not is heave compensated.*
- Access and intervention possible from the surface or by Diver/ROV
- Retrofit to existing structures under water
- Signal transmission (cables, subsea wireless modems or standalone operation)

Offshore operations are costly, as a rule of thumb the costs for operations under water are three orders more costly than on land. Usually the marine operations are much more expensive than the hardware itself. Thus, as much as possible should be prepared or installed on beforehand, subsea intervention should be kept to a minimum. For critical monitoring system, the instrumentation must include a robust strategy for backup and redundancy.

Although a successful installation of a permanent monitoring system many times depends on the “Mood of Mother Nature”, the human factor is still probably the most frequent reason for failures. Skilled and thorough instrument engineers 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 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.

1.2 "Ten Commandments" for subsea instrumentation

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

1.2.1 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 could be saved and where it should **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. "Surviving" the installation of the measuring system and making it work has first priority and many times an optimal setting for the best measurements must be sacrificed. Probably the most demanding application with respect to "survival" is instrumented driven piles.

For under water works the conditions and operations are both difficult and costly, thus ad-hook or retrofit solutions should be avoided if possible.

1.2.2 Harsh conditions and Robustness

The conditions can be rough and usually it is during the launch in or out from the sea were the equipment is exposed to the biggest risk of damage. Deployment on the seabed can be rough if the installation is performed from a floating vessel, especially if the crane or winch is not heave compensated. Normally, the operational limit for the Sea state is related to the significant wave height (Hs) which is a statistical definition. For typical wind farm locations the waves may not be the limited factor 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

Handling on deck and by the ROV/Diver can also be brutal to your equipment. Most ROV manipulator systems only have displacement control without force feedback, thus the pilot may not discover over stressing an element before it breaks. A common design feature is to use elastic or pivoting handles withstanding large deformations before it breaks and becomes useless. A diver usually have better control than a ROV but still cannot be compared with conditions for manual intervention on land.

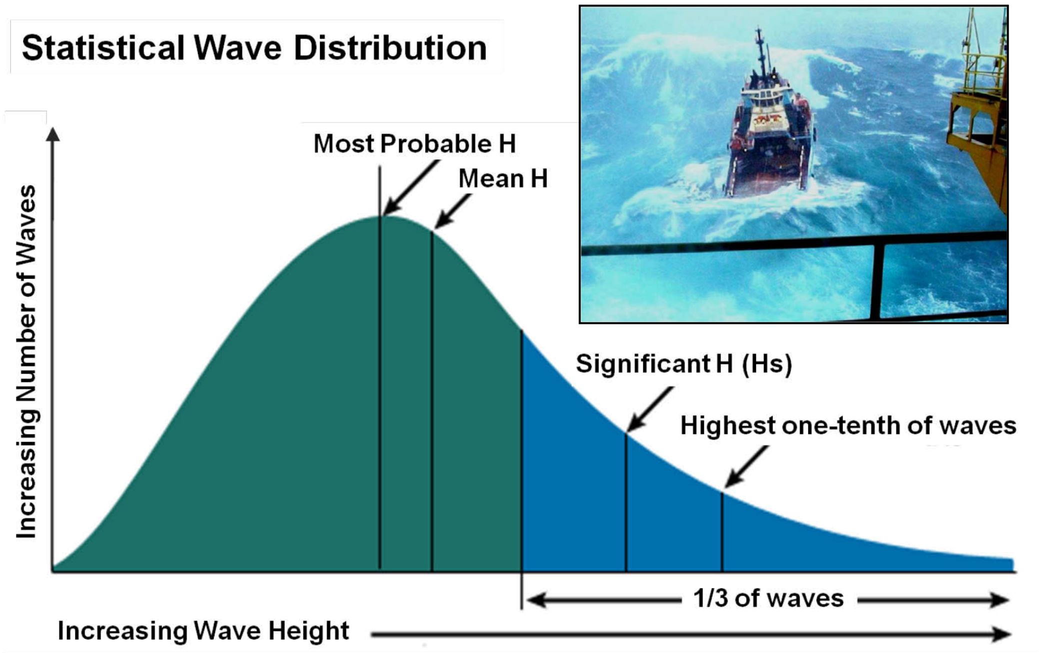


Figure 1.2 Definition of significant wave height (Hs) and rough North Sea conditions

1.2.3 Backup and contingency

Sensor costs are usually small compared to infra structure for the instrumentation (pressure enclosures, cables etc.) and the operational time for replacement is expensive. There for 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, or how much of the system is affected by a ruptured cable. Contingency is a popular word in offshore operation schemes, there must always be a plan for what to do if things do not happen according to the plan.

1.2.4 Pressure integrity and corrosion

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

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

Most failures occurs 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 deep waters.

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 aluminium 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.

Figure 1.3 "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)

1.2.5 Functional Testing and calibration checks

The importance of functional testing can never be exaggerated. Hooking up all components in a representative configuration often saves time for fault seeking and prevents uncertainties during field installation. As many times the obvious is forgotten or wrong, these checks are nicknamed as "idiot tests" 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.

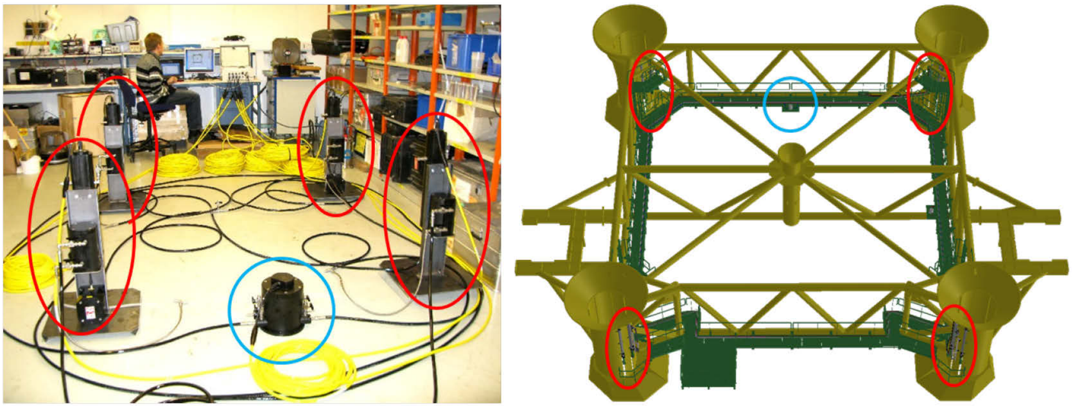


Figure 1.4 Functional testing of a level monitoring system mimicking the configuration and use on a pre-piling template (Geosea)

1.2.6 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 easy replacement of damaged parts.

1.2.7 Interface with offshore contractor

It is important to involve the 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 of the requirements for installing instruments can indeed appear as weird and easily neglected for someone who is not familiar with the “Art of instrumentation”

1.2.8 Delivery time

Installing and use of instrumentation offshore is usually a part of a bigger scheme and the logistics involved must fit a bigger plan. With day, rates of the marine vessel usually higher than the costs for the instrument supply do not expect they will be waiting for you.

1.2.9 Remote operation and data recovery

Data recovery can be challenging in remote places such as the deep sea. Direct hook-up and data transmission using cables is not always possible or associated with high risk in terms of damage. If cables not are used the instrumentation must be self-contained with respect to power for example by means of using high capacity Lithium batteries. For wire-less real-time data recovery acoustic modems can be used for long range (many hundreds of meters) for short range (some meters) also EM modem (under water “radio”) can be used which will work even if there is an obstruction between transmitter and receiver the EM signal will also pass through water and air interface.

1.2.10 The devil is in the details

It is a fact that most problems or malfunctions are caused by small details rather than major faults in design. Therefore ”Paying attention to the details” is necessary for all instrumentation tasks but especially important for monitoring systems that are not accessible after installation and consequently not possible to repair or rectify when in operation.

The following example is taken from the internet and a research program for the monopile Metmast (FINO 3), a project that included extensive monitoring of the embedded pile during both 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.

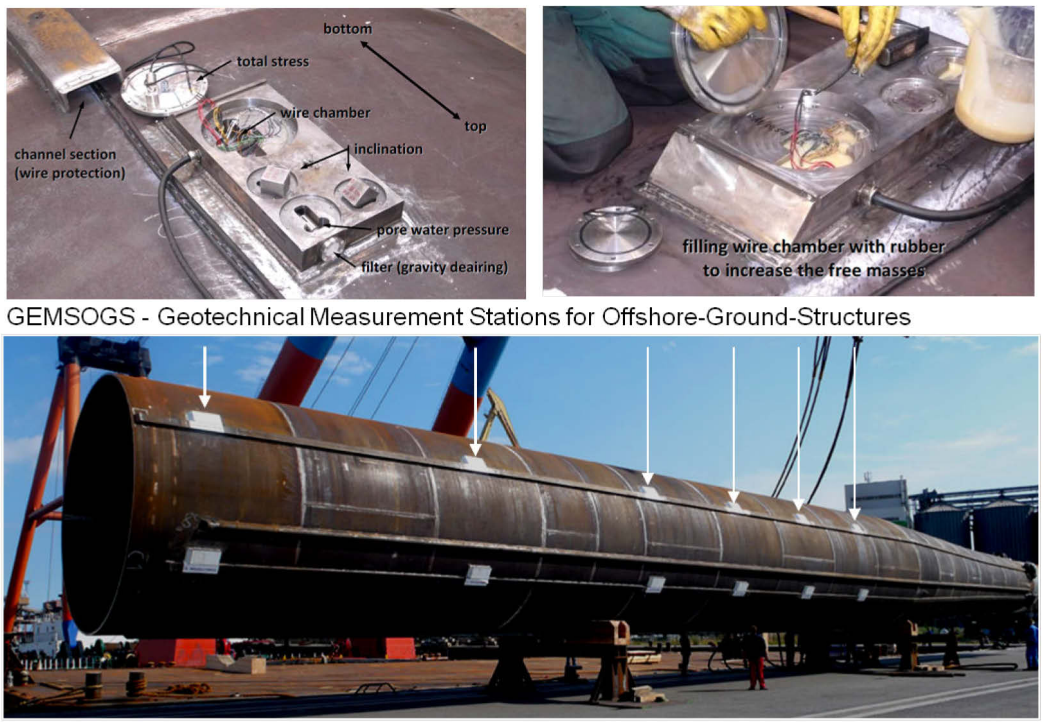


Figure 1.5 FINO 3 Monopile with GEMSOG instrumentation

The instrumentation was nicely done such that it should survive driving as well as long-term immersion under water. However, the readings of total pressure during driving quickly revealed an important detail for successful measurements of radial earth pressures (effective stress) which not was taken into account when designing the monitoring system.

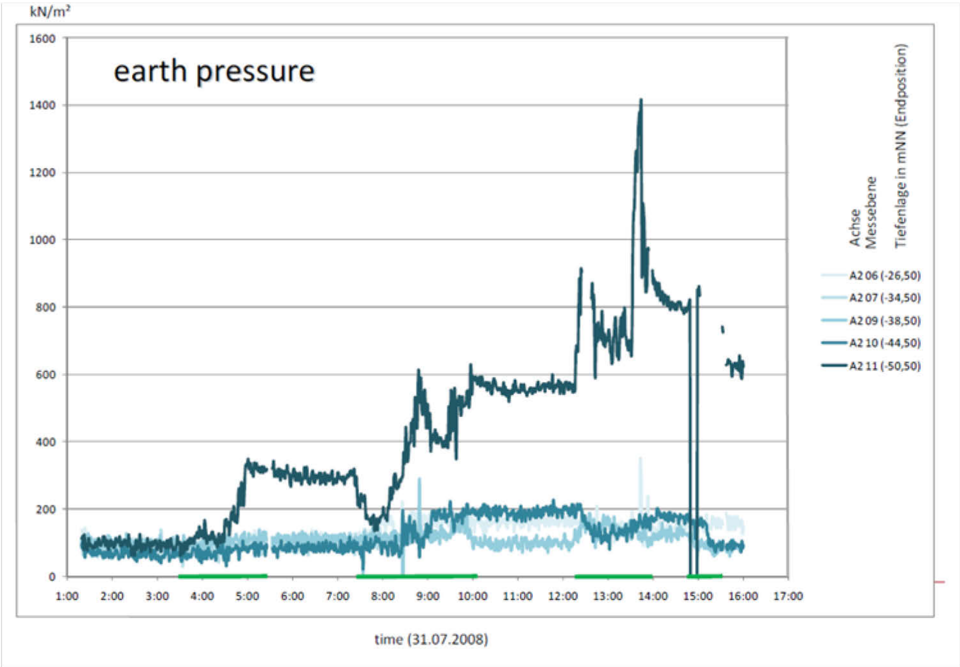


Figure 1.6 Recorded radial earth pressures during driving of FINO 3 monopile

As seen from the plotted earth pressure recordings for one section, only the instrument close to the tip is reading increased earth pressure when the pile is penetrated deeper. All sensors above show more or less a constant value (not representative for the effective radial stresses around the pile).

The explanation is straightforward: the "GEMSOG's" instrument units were fixed and protruded outside the monopile (acting as driving shoes), causing the formation of a slot 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 cut into the soil.

More discussions about lateral earth pressure instrumentations are given in sections 2.2 and 3.9.

1.3 Executing a larger monitoring project

As discussed earlier there are many items to consider executing a monitoring project and the solutions which work are many times based on experience (trial and error). 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 that will provide a solution to the monitoring objectives specified by the client. The system integrator should be able to select the most suitable components for the system from different sub-suppliers.

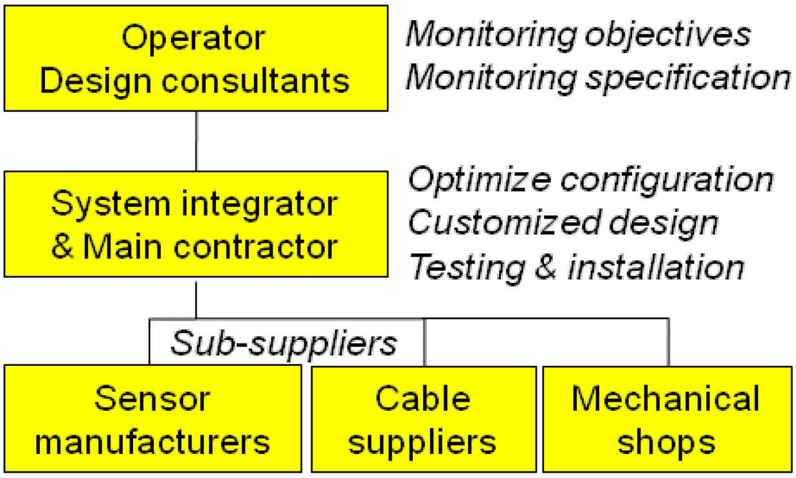


Figure 1.7 Organization and flow chart for execution of a monitoring project

2 Permanent Monitoring for Offshore Wind Turbine Foundations

Figure 2.1 Examples of different Offshore Wind Turbine (OWT) foundations

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

1. Monopiles (or monopods if suction caisson is used) which can be used down to water depths of 30-40m
2. Jackets or tripods, piled, pre-piled or with suction caissons normally used from 25m and deeper
3. Gravity base structures with skirts normally used from 25m and deeper

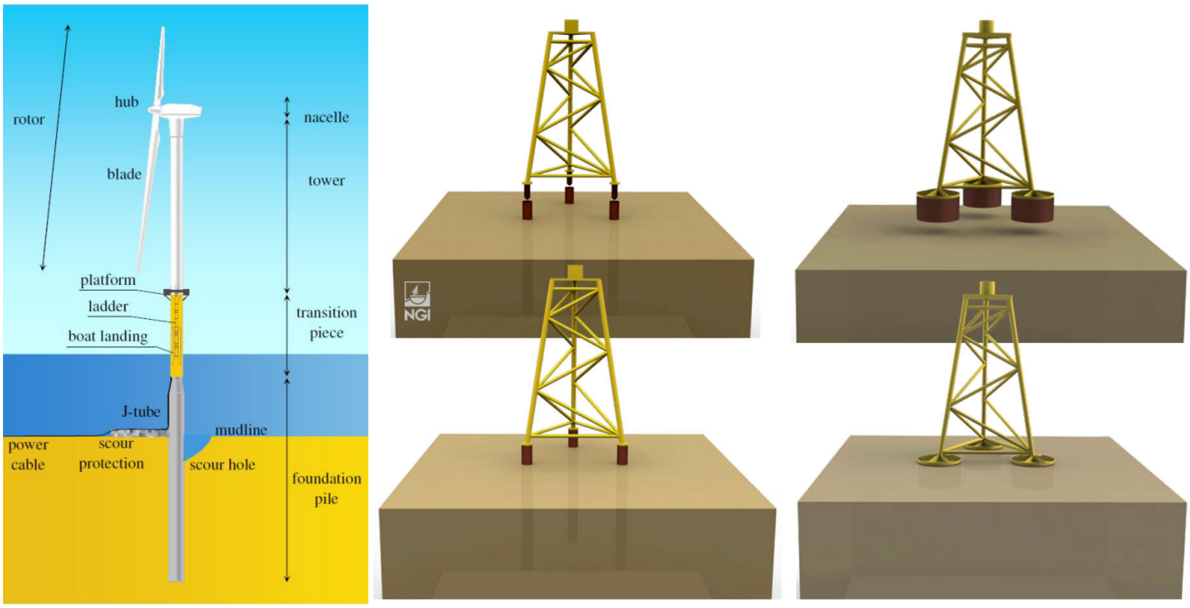


Figure 2.2 Definitions for Monopile foundation (left) and Tripod jackets with pre-driven piles or suction caissons (right)

Please note that in the offshore wind industry the definition for a "Foundation" includes **all** structural elements embedded in the seabed as well as the structure in the water up to the base of the tower.

The described objectives for monitoring and instrumentation systems applies for both monopiles and jacket foundations, we have included both piles (main case) and suction caissons as alternatives. Presently piled foundations are most common OWT's in Europe. The suction caisson concept is not yet fully implemented in the Offshore Wind Industry, but is frequently used by the offshore Oil and Gas industry. Monitoring aspects and solutions for caissons (shallow foundations) also apply for Gravity Base Structures with skirts.

2.1 Objectives for Monitoring of Foundation Response

Although the scope in this report not include geotechnical or structural analyses some aspects which may apply for OWT foundations in Korean waters are discussed as objectives for possible monitoring applications.

For monopiles, horizontal loads and moment must be transferred directly to horizontal soil reactions, as shown in the left-hand side of the figure below. As the pile is not fixed at the top, it is free to rotate and translate. For monopile OWT's, this horizontal load transfer usually dictates the pile length, the pile must be drive long enough to mobilize enough soil over its length to transfer all loads and prevent "toe-kick": displacement of the tip of the pile.

For overturning moment on multi-legged structures, the piles are fixed to the structure and deforms in an S-shape, mobilizing at the same time horizontal soil resistance. The overturning moment is then transferred as axial loads (compression and tension) to opposing foundation piles as shown in the figure below.

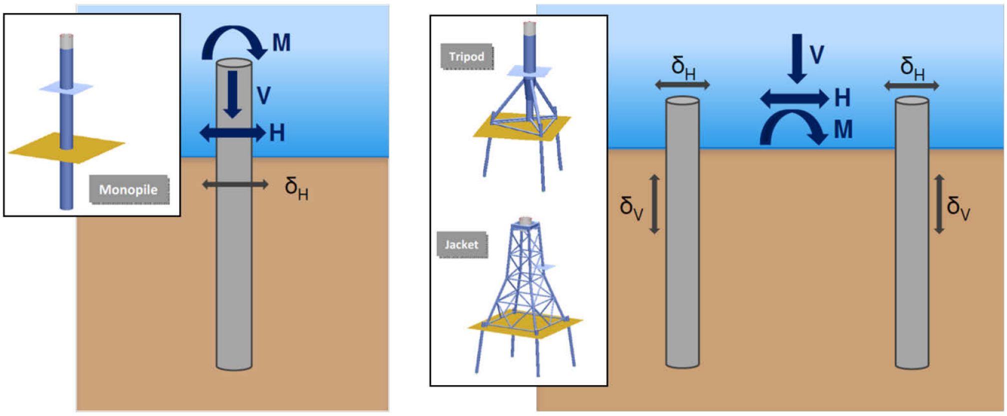


Figure 2.3 Load transfer to the soil for monopile (left) and tripod/jacket (right) foundations

Independent on foundation type, an Offshore Wind Turbine is a tall and slender structure, possible accumulated cyclic deformations or bending of the foundation will result in a tilt of the tower and the verticality of the tower is 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.

Figure 2.4 Failed foundation resulting in a tilted wind turbine tower

Monitoring of the environmental conditions (source for loads) also applies for all types of OWT foundations:

- 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 wind exceeding the cut-out speed (typical 25m/sec) shutting down the turbine but may for example occur for big waves just before cut-out wind speeds occur combined with an emergency stop of the turbine.

Figure 2.5 OWT in operation during stormy weather

2.2 *Specific monitoring aspects for Monopiles*

The dominating and critical loading condition for a monopile 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. A natural frequency close to the rotor frequency will cause the turbine to shut down.

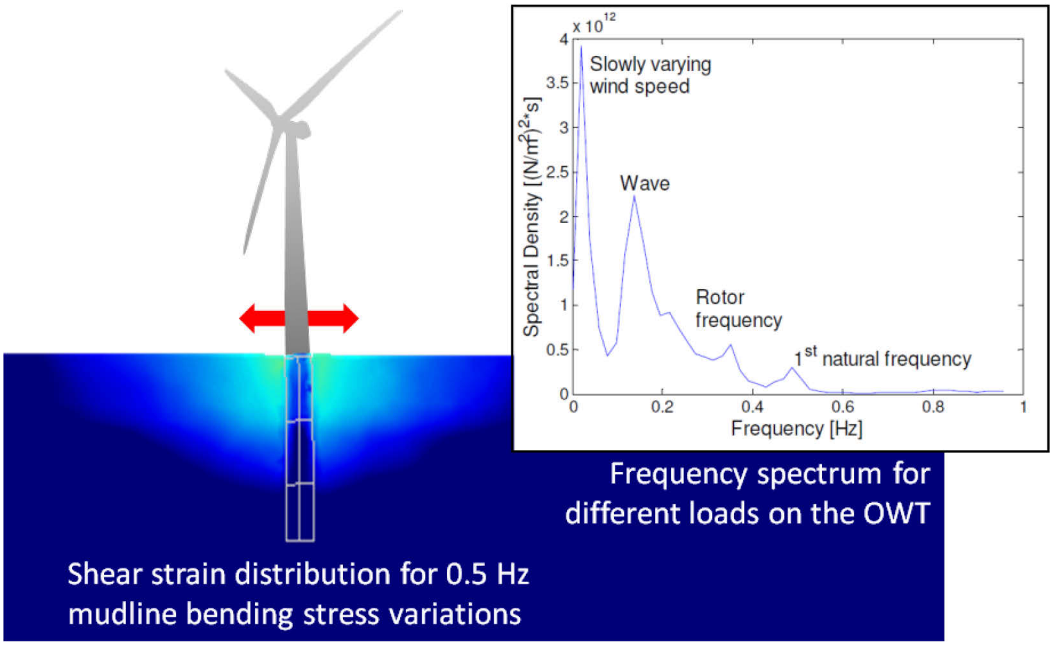


Figure 2.6 Load frequencies for a typical monopile OWT and simulation of dynamic radial dampening in the soil

The traditional approach to derive soil stiffens for a monopile is based on P-Y approach. There are many indications (from various monitoring programs and model testing) that this approach may be conservative, i.e. the foundation is stiffer than calculated according to API design. A stiffer foundation is will increase the operation life of the monopile foundation (fatigue life) and (maybe more important) to keep the resonant frequency well above the rotor frequency when the water depth and turbine size are increased.

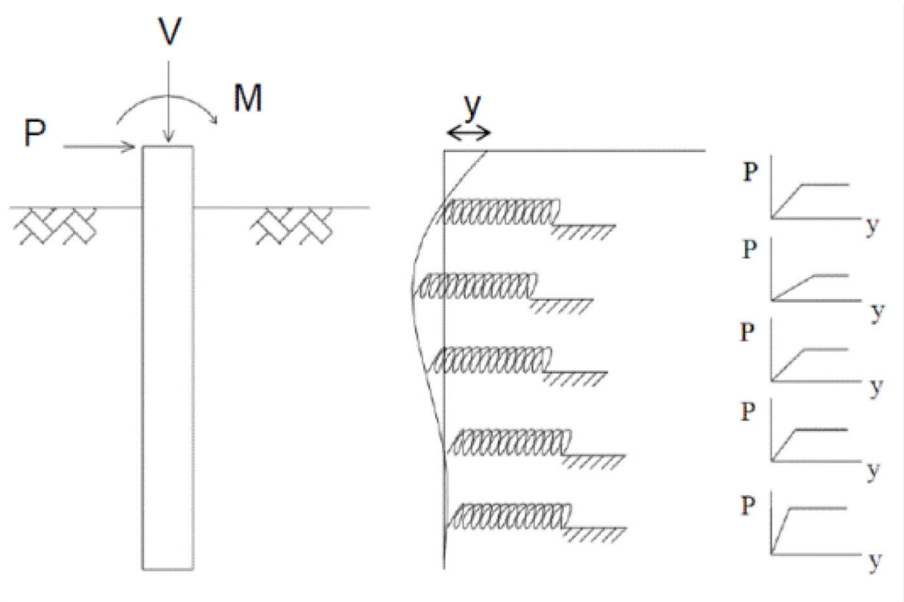


Figure 2.7 P-Y stiffness approach from API

Based on this discussion a paramount monitoring objective for a monopile foundation may be to evaluate the lateral loading stiffness or P-Y behaviour of the pile, after installation and with time.

Relevant instrumentation may include:

- Dynamic motion (accelerometers) along the structure (above seabed)
- Stress in the pile from mud-line and down wards
- Cyclic pore pressure build up (affecting the soil stiffness) with piezometers along the pile

Scour is another feature that will affect the stiffness (and resonant frequency) of the monopile foundation, usually the lowered natural frequency caused by scour is more critical 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 may be relevant (also depends if seabed and current conditions can be critical for scour). For shallow foundations scour may introduce a bearing capacity problem.

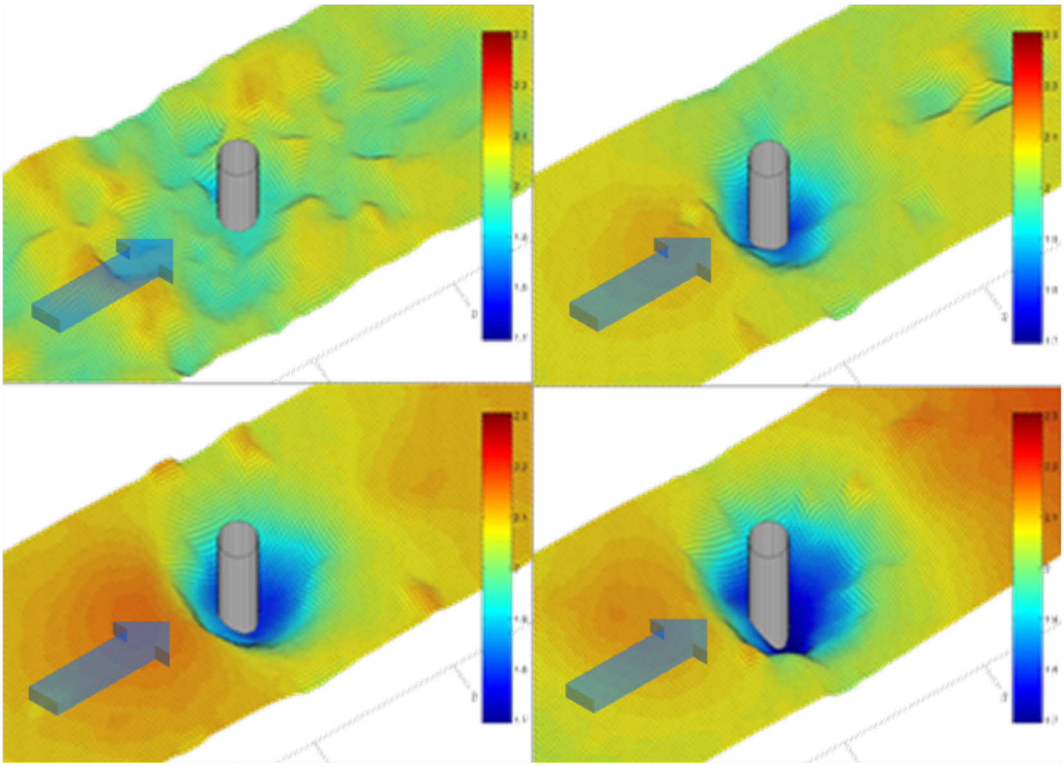
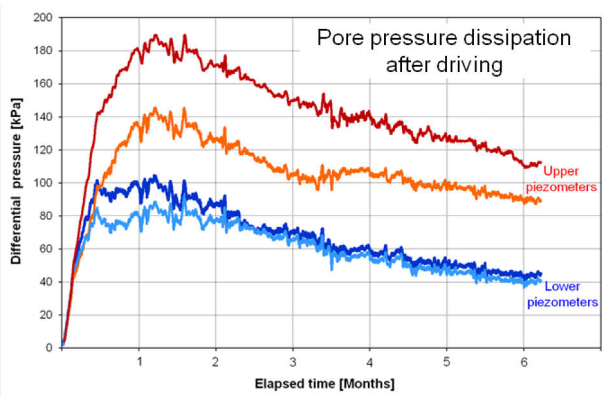


Figure 2.8 Measured scour development around a monopile during large scale model testing (from www.fzk.uni-hannover.de)

Figure 2.9 Scour pattern after basin testing of a mono caisson foundation (HR Wallingford)

The ultimate bearing capacity of a monopile is normally not a critical issue for design as the lateral stiffness usually is a governing factor.

However, cyclic degradation and pore pressure build may be an issue for impermeable soil conditions. In addition, the pore pressure build up during pile driving (or vibro piling) may be an issue for design, such as dissipation and reconsolidation time after installation.



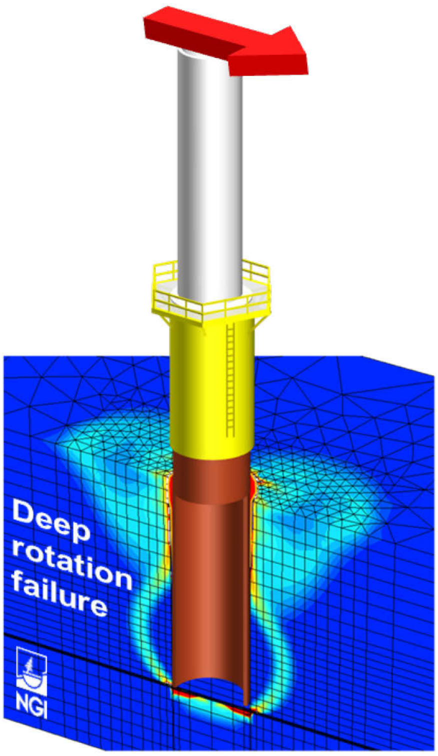


Figure 2.10 Excess pore pressures generated during driving and dissipation 6 months after installation of a steel pile in seabed consisting of clay in conjunction with the Femern Large Scale field tests (left). Modelled deep rotation failure for a monopile in clay (right).

The radial effective stresses (earth pressures) may for some soil conditions be an important parameter with respect to both 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 measured pore pressure at the same location in order to obtain the effective stress. 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.

The stiffness of the cell is also important, to prevent arching effects it should not be significantly lower than the medium it is embedded in (in this case steel). Radial stresses measured on a steel pile after driving has a tendency to be less than expected probably due to arching effect around the membrane.

Other important monitoring issues not directly related to the seabed foundation are:

2.2.1 Grouted connection of the transition piece

A grouted connection is used to connect the transition piece to the monopile as shown in the A transition piece is placed on top of the monopile, resting on temporary supports. During installation, the temporary supports are jacked up to correct the verticality of the transition piece before the grouting is carried out. After curing, the jacks are removed, leaving a gap of a few centimetres between the temporary supports and the top of the pile.

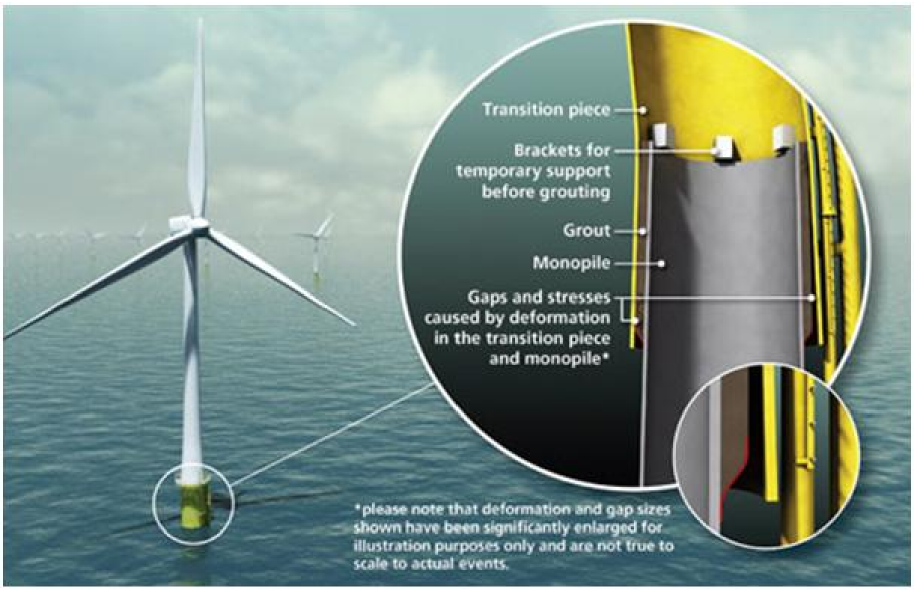


Figure 2.11 Transition piece connection with temporary supports and straight grouted section

Settlement down to the temporary supports may result in a different force distribution between the structural elements than that intended at the design stage. An unintended force transfer through the temporary supports (not design for permanent loading) has led to concern about fatigue cracking in the transition piece structure. This fundamental shortcoming in design was discovered in April 2010 when it was discovered that the transition piece for some monopile foundations had slipped down by up to 25mm.

An extensive monitoring programme was initiated in order to alert wind farm operators if the strain in temporary support brackets should exceed acceptable limits. A Joint Industry Project was also executed by DNV in order to analyse the slippage problem and to improve on the design practise. 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.

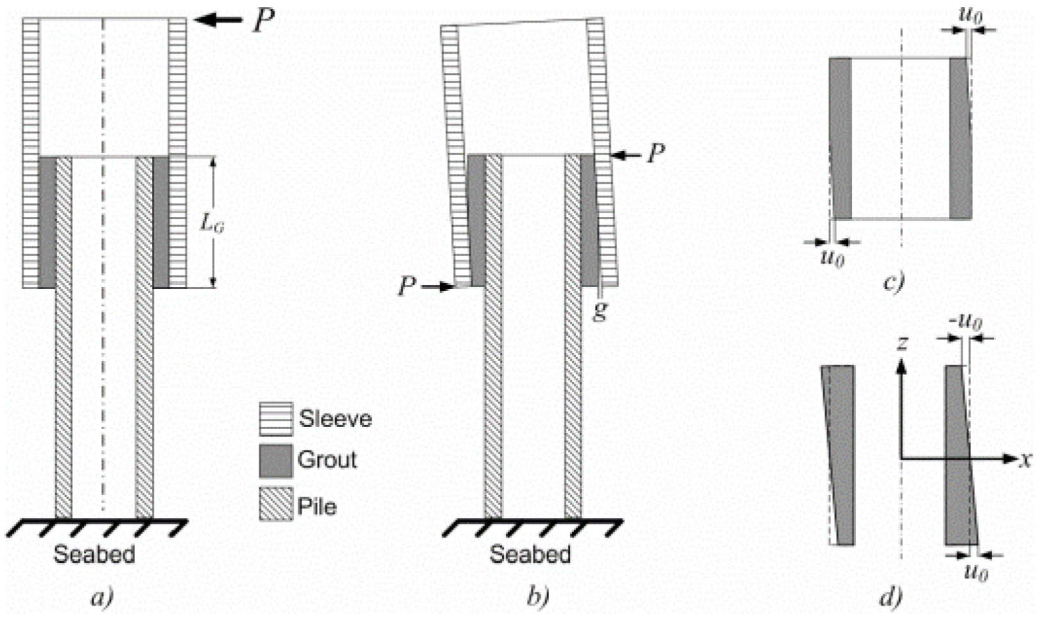


Figure 2.12 Structural behaviour of the grout due to horizontal load transfer from the transition piece to the pile (temporary supports not shown)

Accounting for the large dynamic bending moments on monopiles, 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. The coned connection will expose the grout to compression loads, rather than shear forces as on traditional designs. In addition, 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 *DNV-OS-J101 Design of Offshore Wind Turbine Structures standard* will be revised including the new recommendation for the fixture of the transition piece using conical shaped connections.

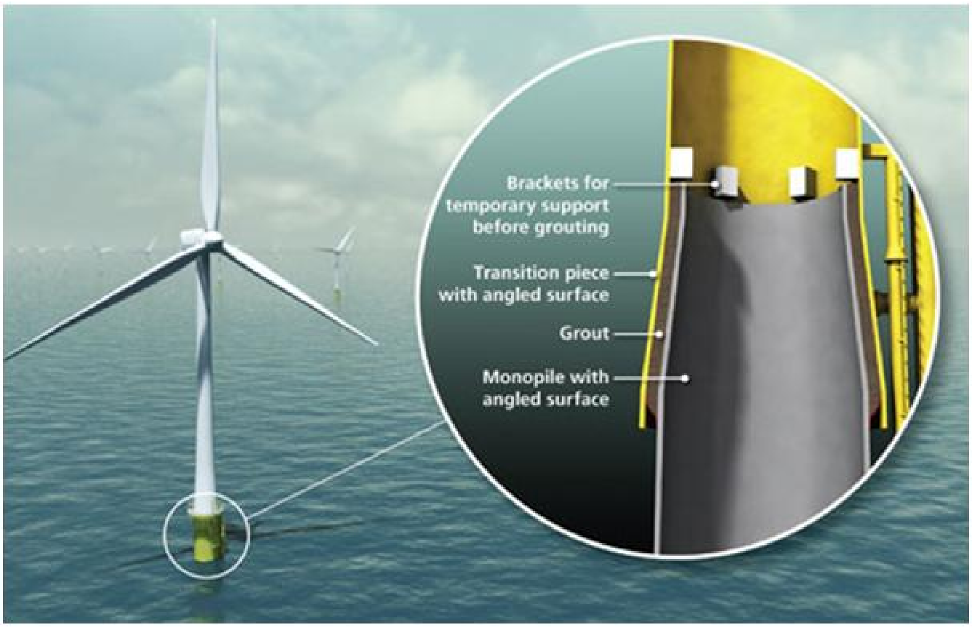


Figure 2.13 Recommended transition piece connection with conical grouted section (DNV)

The rigidity of the grouted connection may be an application for long term monitoring using crack/joint meters (miniature extensometers) or strain gauges bolted/welded between the top of the monopile and the inner wall of the transition piece or across the vertical gap between the temporary supports and the pile top. The stress in the grout may also be monitored by embedded load cells.

2.2.2 Corrosion

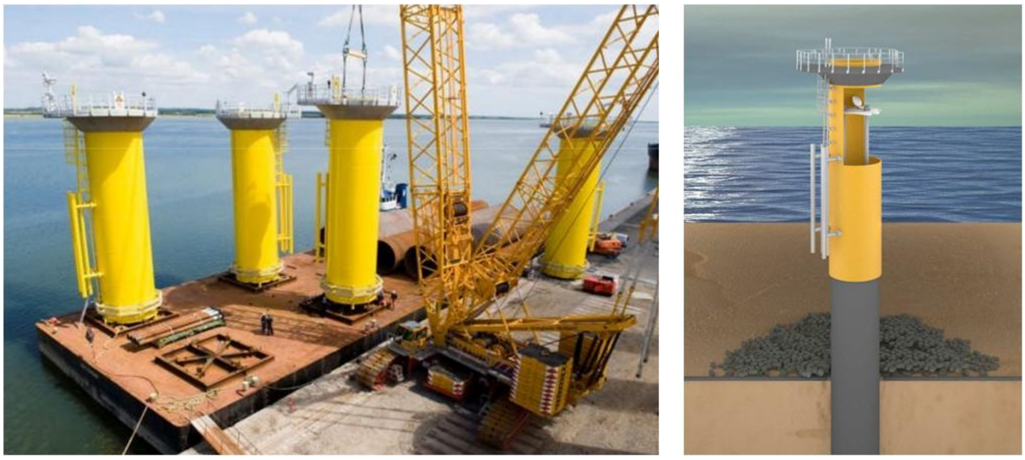


Figure 2.14 Transition pieces with corrosion resistant concrete work deck

Corrosion is a major failure mechanism for offshore wind structures and may cause expensive repair if progressing without control. For a monopile, 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, seawater and thus oxygen ingress in the closed compartment below the airtight deck have been detected for 2-10 year old monopile foundations, with observed increased corrosion rates and concentrations. Inspections are therefore 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 de-signs, thus simple corrosion monitoring arrangement should be installed at the time of construction.

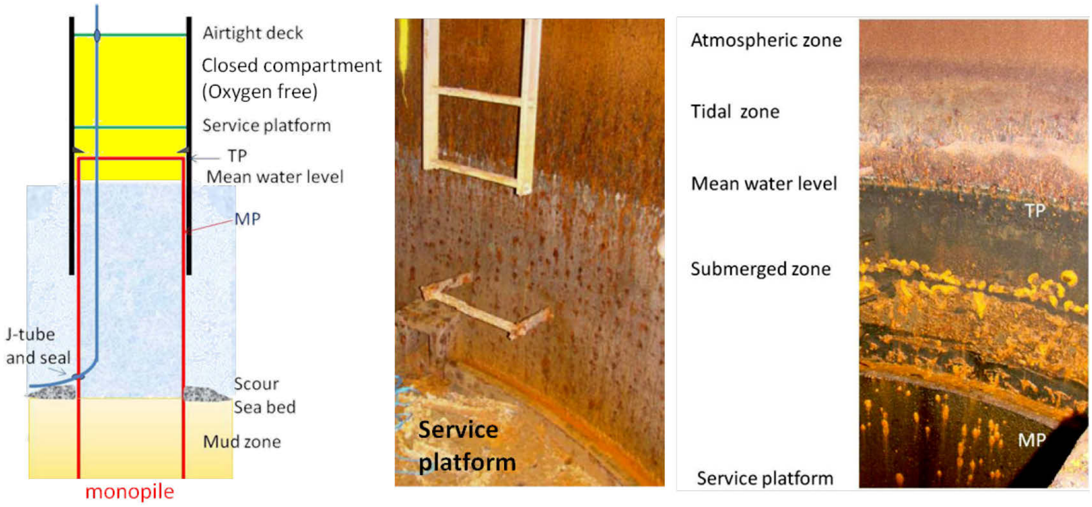


Figure 2.15 Closed compartment at Monopile (MP) and Transition Piece (TP) joint (left) Observed internal corrosion on Transition Piece and top of Mono Pile (right)

2.3 Specific monitoring aspects for Mono caissons

The stiffness of the foundation is critical for a mono caisson structure (may also be a GBS type of footing with skirts). However, for this type of shallow foundation the rotational stiffness critical for the behaviour of the tower.

The general recommendations for monitoring are similar as for a monopile with the following exceptions:

- Strain in the caisson walls is not important, as lateral bending of a shallow foundation is not an issue. From a structural point of view, the fixture between the caisson and the tower is subjected to large stresses and may be relevant to monitor.

- In combination with cyclic moment loads, a monopod caisson will probably be subjected to settlements in conjunction with a progressing rotational failure. Thus in addition the monitoring the dynamic **rotational** motion for the foundation, accumulated settlements are relevant to monitor.
- Load distribution at the base (not only the skirts) is important for the overturning capacity of a mono caisson foundation, therefore under base grouting is normally used. If other solutions are implemented monitoring vertical soil contact and effective stresses along the base are relevant.
- Pore pressures should also be monitored inside the caisson

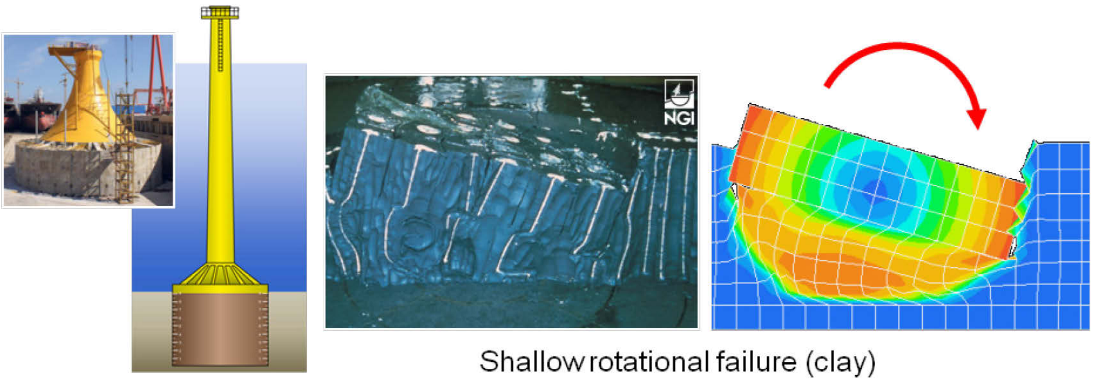


Figure 2.16 Mono caisson OWT foundations and critical failure mechanism in clay

2.4 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 exploited in several design methods and the axial soil/pile stiffness is usually not a critical design issue. As these structures normally are placed in deeper water (from 30m), the structural stiffness may be more important to monitor.

Pore pressure build up during cyclic loading may be an issue that could be considered for monitoring (dependent on soil conditions).

Thus, the relevant monitoring parameters may include pore pressure along the piles and structural health/fatigue life including dynamic motion and possible strain in critical members/connections.

For pre-piled foundations the grouted stab connections between the piles and the structure may be a weak link and dependent on the quality of the grouting operations (*see also section 2.2.1 Grouted connection of the transition piece*).

Grouted stab connections has been used widely in the offshore industry, the legs of the structure to connected to the piles are either outfitted with a male stab which is fitted into or a sleeves inserted 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.

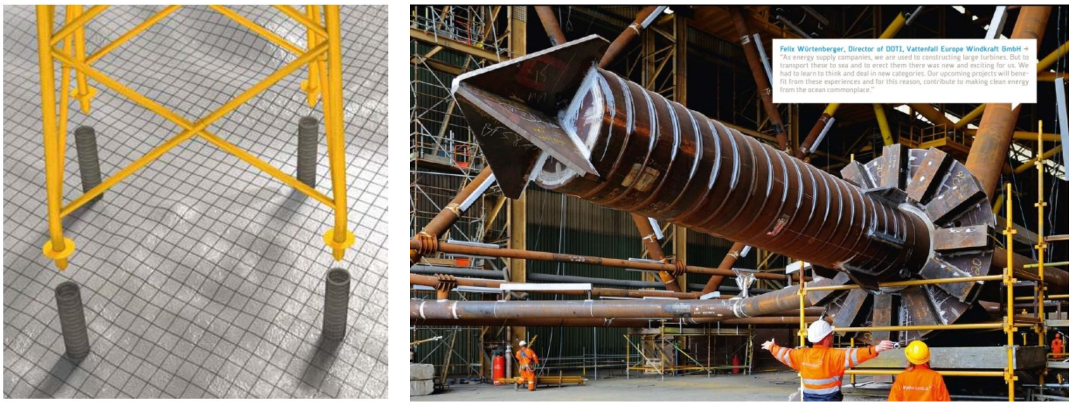


Figure 2.17 Example of grouted male stab connections to pre-driven piles (OWEC tower)

The connections can be monitored using subsea crack/joint meters, which must be retrofitted by diver. It may also be possible to use inductive contacts sensors that would detect any spacing developing between the pile top and the flange of the stab. If the structure is designed with adequate coating and cathodic protection system there is no special concern and requirements for corrosion monitoring.

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 compensated for possible deviations. The required accuracy in these measurements is normally within +/-10mm.

Scour is less important to monitor as increased pile stick-up will have limited effect on the Eigen frequencies of the structure and little impact on the axial bearing capacity of the piles (which should be designed with ample margins against scour)

2.5 Specific monitoring aspects for caisson foundations

Similar needs as for mono caisson foundations, however the load transfer to the caissons is mainly axial compression and tension (rotation is prevented by the stiff connection to the legs). In terms of structural health, the leg connections to the caissons are subjected to large stresses and may be subjected to strain monitoring.

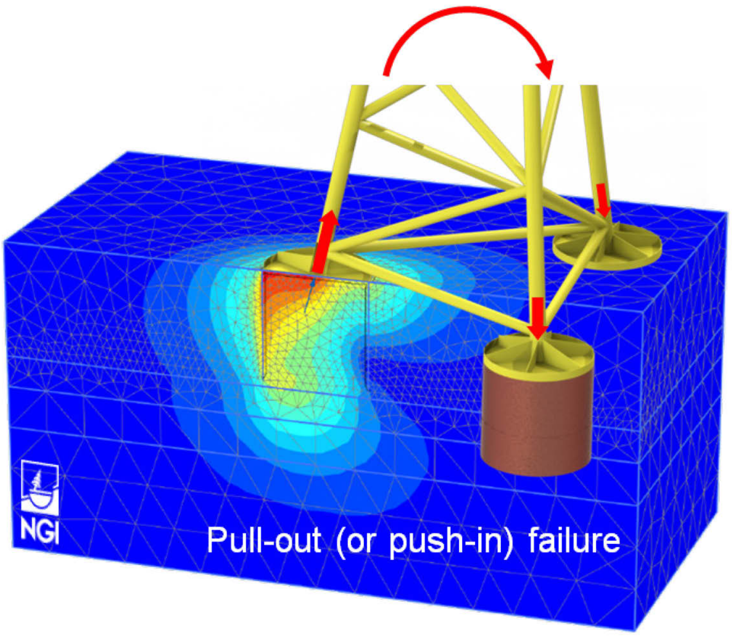


Figure 2.18 Tripod caisson foundation and critical failure mechanism in clay

For a four-legged structure it is important that the foundation caissons are penetrated with the same rate or that the corners are kept in a straight plane. For large caissons the driving forces generated during suction penetration can be significant and possible distort or bend the jacket inducing large stresses in the structural members. Thus, it is important to monitor the elevation of each caisson during installation as the jacket may remain vertical also with a distorted base.

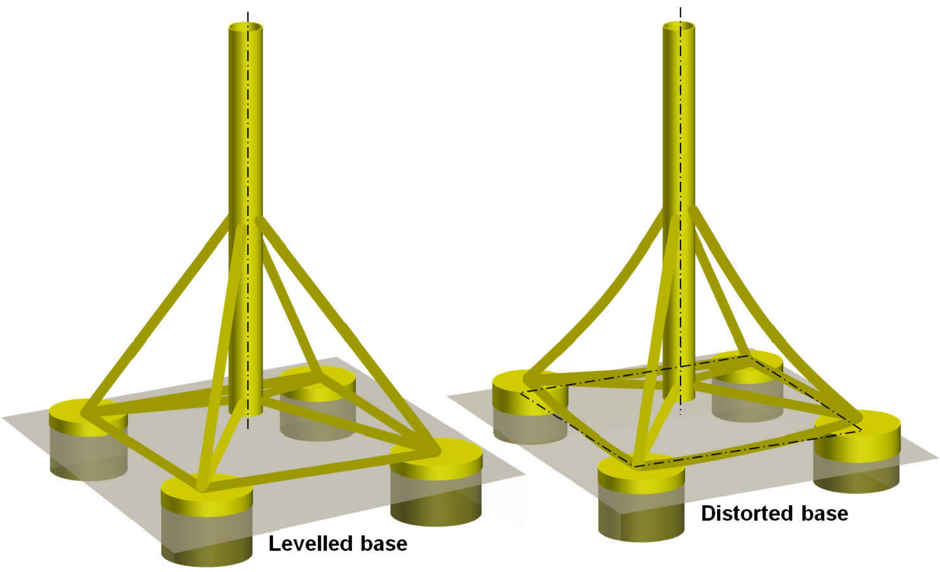


Figure 2.19 Vertical four legged caisson foundation with levelled or distorted base

2.6 Summary of recommended monitoring parameters

The following parameters may be relevant for long term monitoring programme.

All types of foundations:

- Wind
- Wave height

Driven Monopile foundations:

- Scour and currents (if the seabed is prone for sediment transport)
- Axial strain along the pile (P-Y behaviour)
- Lateral dynamic motion of the structure at different levels
- Cyclic pore pressure along the pile
- Lateral earth pressure along the pile (difficult)
- Tilt of tower
- Internal corrosion transition piece-pile top
- Deformations/strain grouted connection transition piece

Mono caisson foundation:

- Scour and currents (if the seabed is prone for sediment transport)
- Strain in connection tower to caisson.
- Dynamic rotation motion of the foundation and Lateral motion of the structure at different levels
- Cyclic pore pressure along the skirts and inside caisson
- Load distribution, vertical earth pressure along the base of the caisson (if not grouted)
- Settlement (shake down)
- Tilt of tower

Piled jackets/tripods:

- Lateral Dynamic motion of structure
- Strain in critical members (fatigue)
- Cyclic pore pressures along the piles
- Integrity/deformation in grouted connections (pre-piling)
- Tilt of tower

Jackets/tripods with caisson foundations:

- Scour and currents (if the seabed is prone for sediment transport)
- Strain in connection legs to caissons and critical members
- Dynamic linear motion of the caisson and lateral motion of the structure at different levels
- Cyclic pore pressure along the skirts and inside caissons

- Load distribution, vertical earth pressure along the base of the caissons
- Settlement (shake down)
- Tilt of tower

3 Specific monitoring solutions for OWT structures

An offshore wind farm includes numerous of structures, for monitoring it is probably only possible to apply extensive monitoring to a few selected OWT's or the first being installed (possible in advance). Usually Metmasts are installed some year prior to full development of a wind park, therefore these structures also may be outfitted with instruments for monitoring structural and geotechnical behaviour. It should however be noted that the loads on a Metmast are significantly less than 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 maximise the utilisation and data obtain 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.

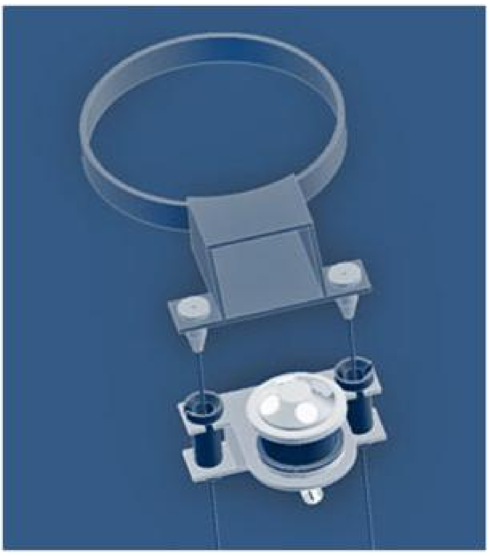


Figure 3.1 Hoisting system for Acoustic Doppler instrument (AWAC) from Abyssus A/S

3.1 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 instrument and sea. It is also possible to range the water surface from below (instrument mounted below sea level) using acoustic Dopplers. The most commonly used down-looking wave radars are for example 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.

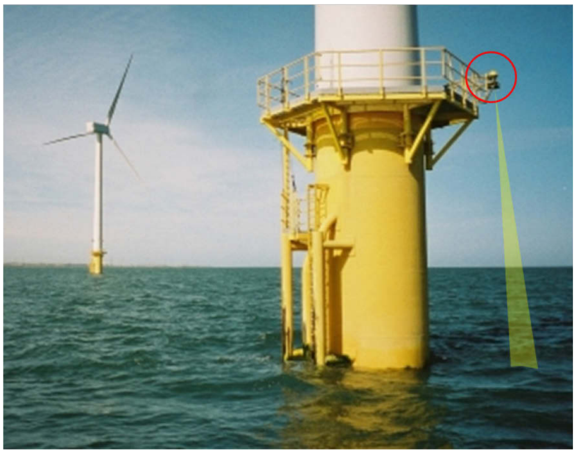


Figure 3.2 Mounting of a Rosemount wave radar on a monopile OWT

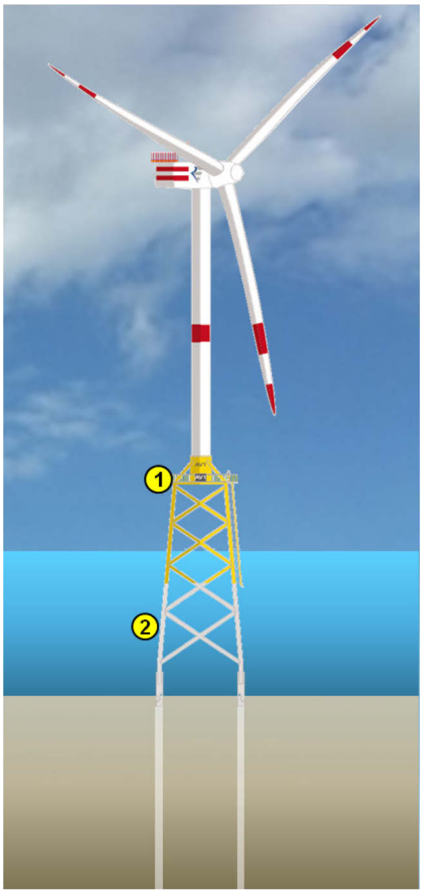


Figure 3.3 Position of down looking microwave radar (1) and up looking acoustic Doppler (2)

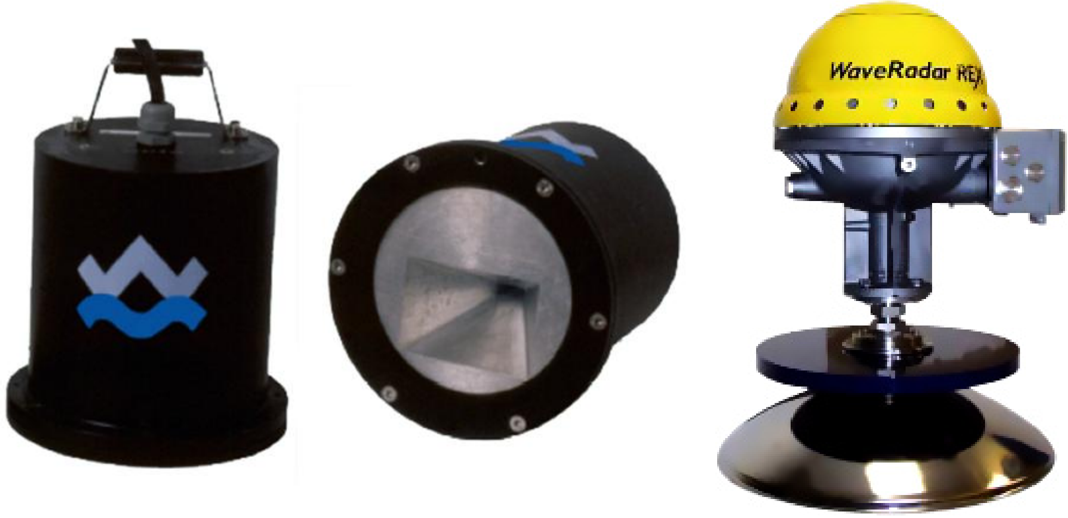


Figure 3.4 *Down looking micro wave radars from Miros (left) and Rosemount (right)*

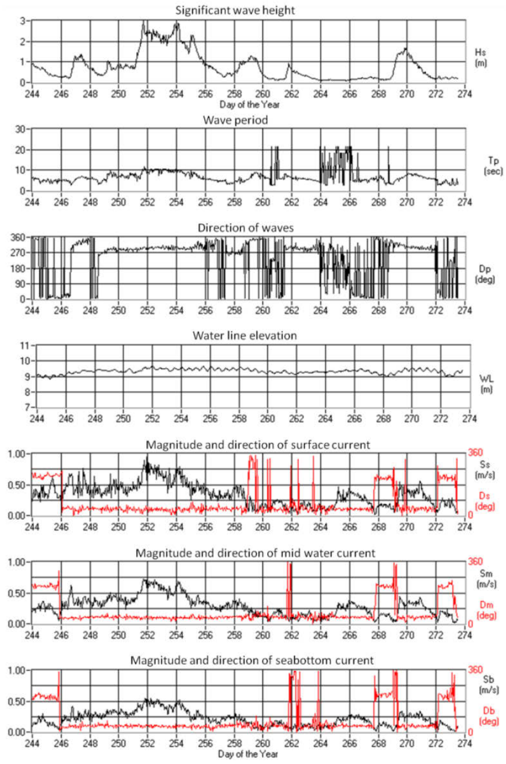
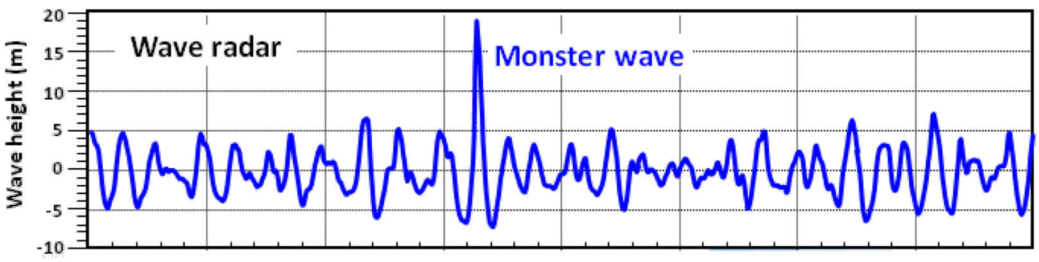


Figure 3.5 *ADCP from TeledyneRDI (left) and typical wave and current data (right). Time history showing heights of individual waves (below)*



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)

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.

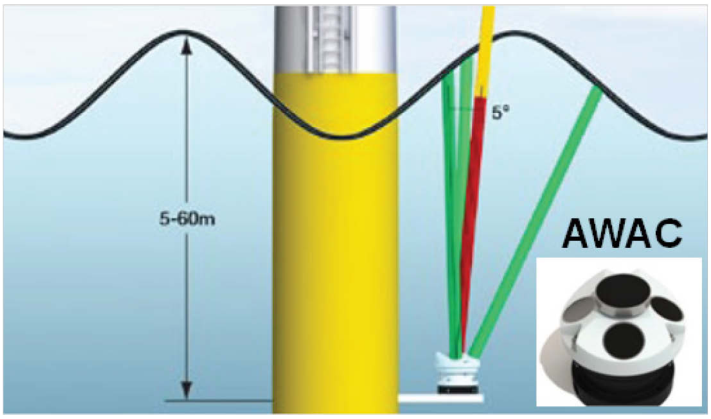


Figure 3.6 AWAC from Nortek mounted on a monopile foundation

3.2 Current

Dedicated current measuring instruments are divided into current meters and current profilers (ADCP).

Single point current meters can be based on mechanical (impeller) or electromagnetic sensing principles

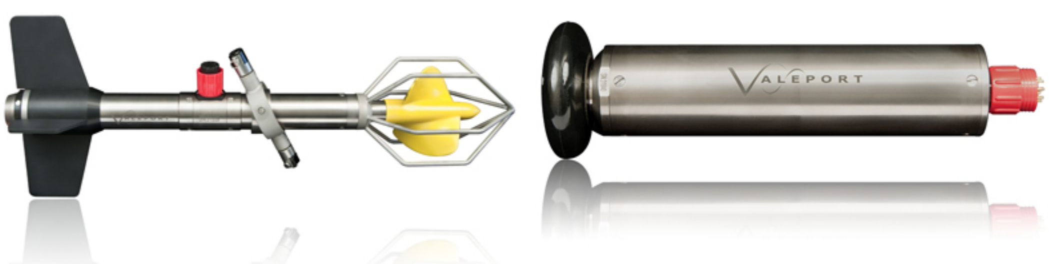


Figure 3.7 Mechanical (impeller) and electromagnetic current meters from Valeport

The most versatile current monitoring instruments are based on acoustic doppler principles, these instrument are delivered as 3D current meters or current profilers (ADCPs) to monitor currents at different levels in the water column.

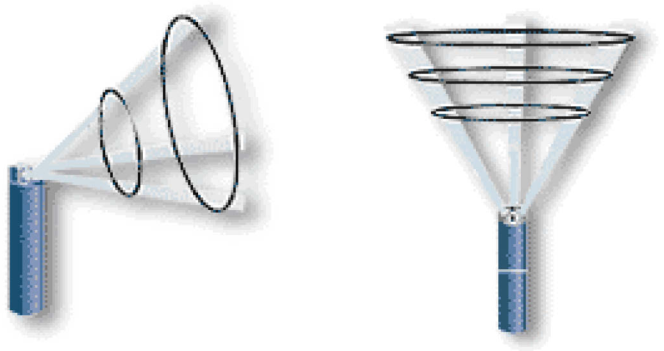


Figure 3.8 Acoustic Doppler 3D current meter (left) and current profiler (right)

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 to 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).

Figure 3.9 Nortek's Aquadopp 3D current meter

3.3 Scour

Scour development around an OWT foundation is monitored by echo sounders or sonar scanning the seabed. The instruments (3) are fixed to the structure well below the water line. Echo sounders or sonars are ranging the distance to the seabed by measuring the travel time from 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. For all acoustic sensor the sonar beam should not be obstructed by structural elements as they may cause false reflections (noise)

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

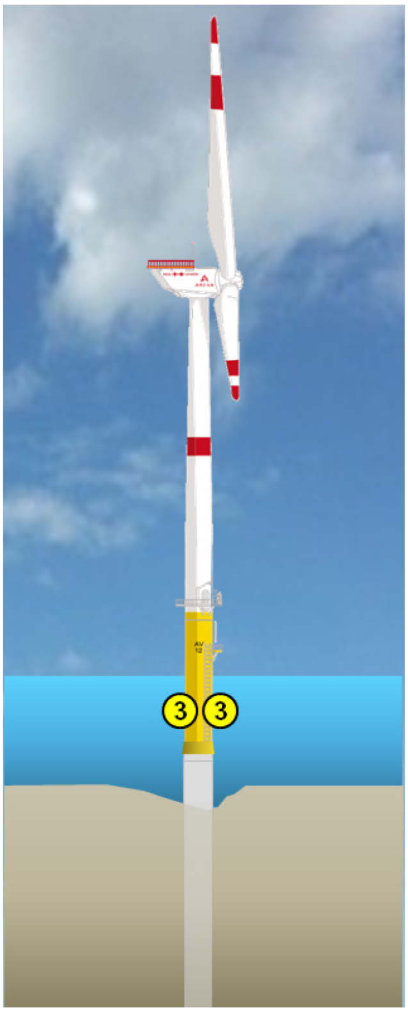


Figure 3.10 Positions of scour sonars on a monopile foundation

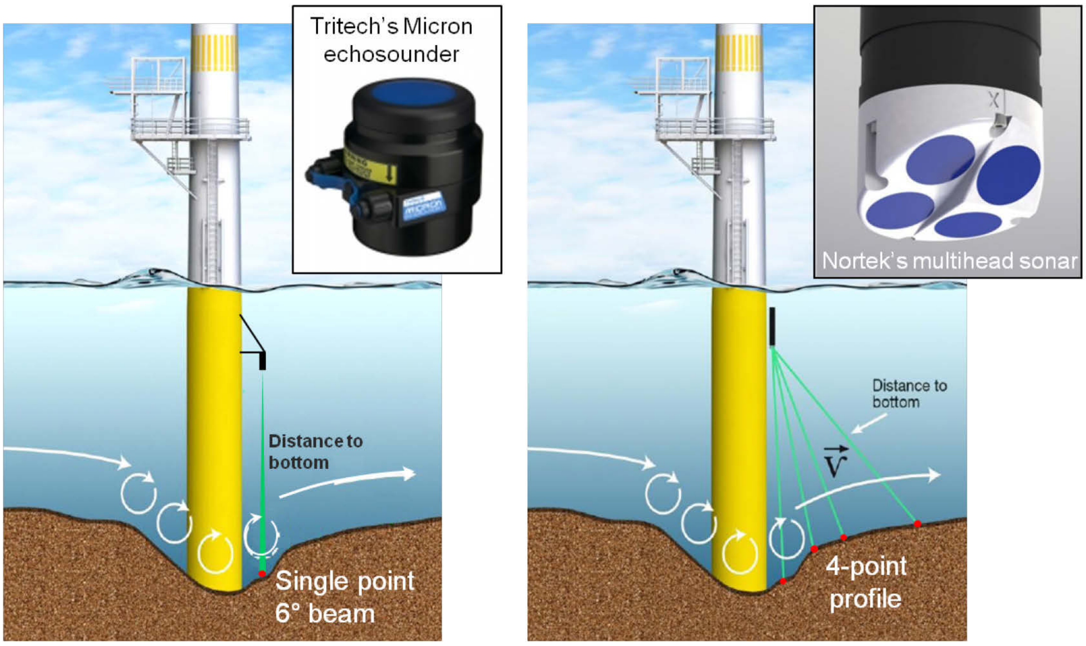


Figure 3.11 Single point and multihead sonars for scour monitoring

For even more information about the seabed topography scanning 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.

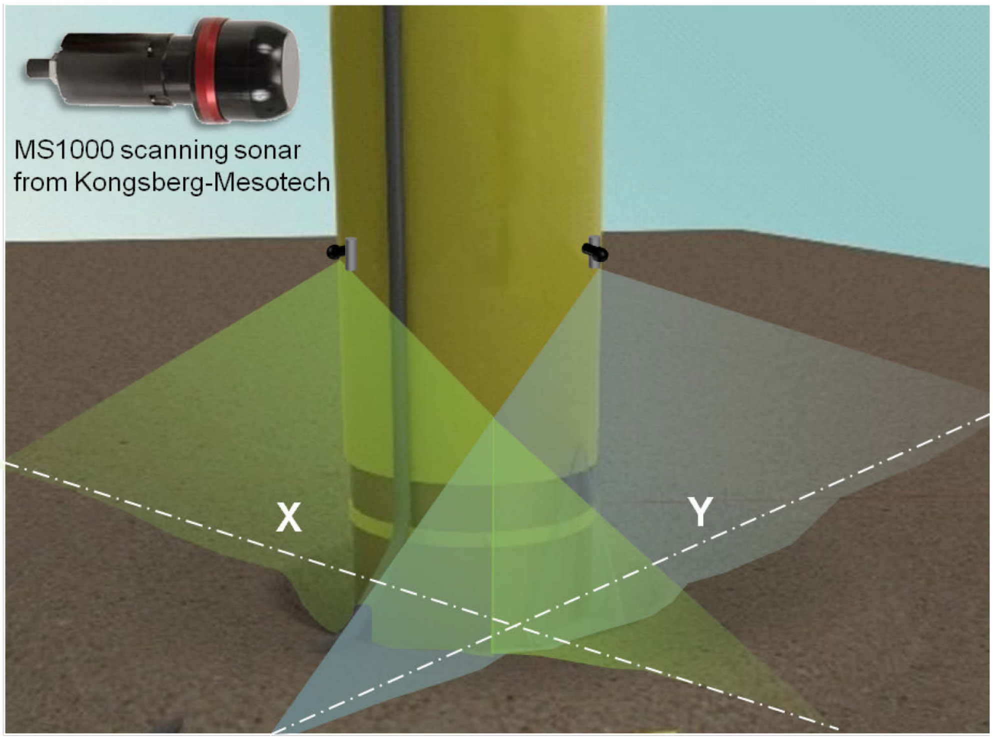


Figure 3.12 Two scanning sonars used for Monopile scour imaging along two baselines

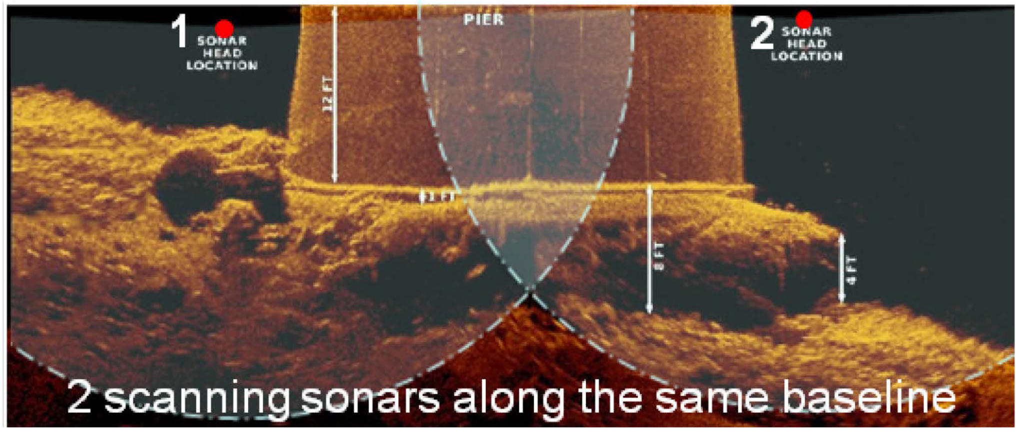


Figure 3.13 Sonar image of scour/seabed profile across a bridge pier using MS1000 scanning sonars placed at either side of the pier

For a full 3-D image of the scour development the scanning sonars can be mounted on rotators and the scanned profiles are merged in a 3D image during post processing using dedicated software.

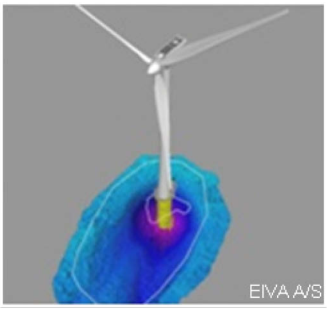


Figure 3.14 Post processed 3D image from rotated sonar profiles

3.4 Dynamic motion

Understanding the dynamic response of the structure and configuration of the accelerometers is perhaps the most important aspect when monitoring dynamic motion. For an OWT dynamic motion is usually monitored at three different levels (4), namely Foundation, Tower base and Turbine elevations. Although the turbine usually is equipped with accelerometers integrated in the control system, a dedicated system should be used for monitoring of the dynamic behaviour of the complete structure. For later analysis it is important that identical sensors are used at all locations and that the data from the sensors is synchronized.

Angular rate gyros to monitor rotation are usually less sensitive and more expensive compared to linear accelerometers. Two linear accelerometers located at either side of a baseline are a better solution to detect rotation.

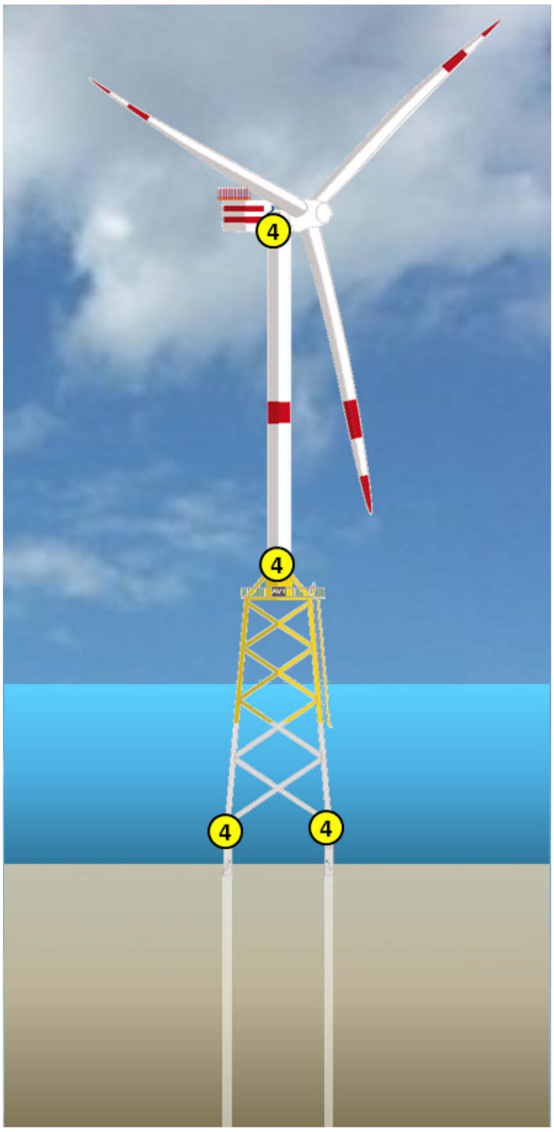


Figure 3.15 Key dynamic motion monitoring elevations for an OWT structure

The accelerometers should be suitable for low frequencies (down to DC). Force balanced linear servo accelerometers (such as the Q-flex series from Honeywell) have been used for monitoring dynamic response of offshore structures. MEMS (Micro Electro Mechanical Systems) based are more often replacing the servo accelerometers as this type of sensor is produced as a chip and requires less space (3D accelerometers are easily integrated in one unit). State of the art MEMS accelerometers suitable for structural monitoring is the Siflex 1500 sensors from Colibrys.

Figure 3.16 Q-flex servo accelerometer (top) and SF1500 MEMS 3D assembly (below)

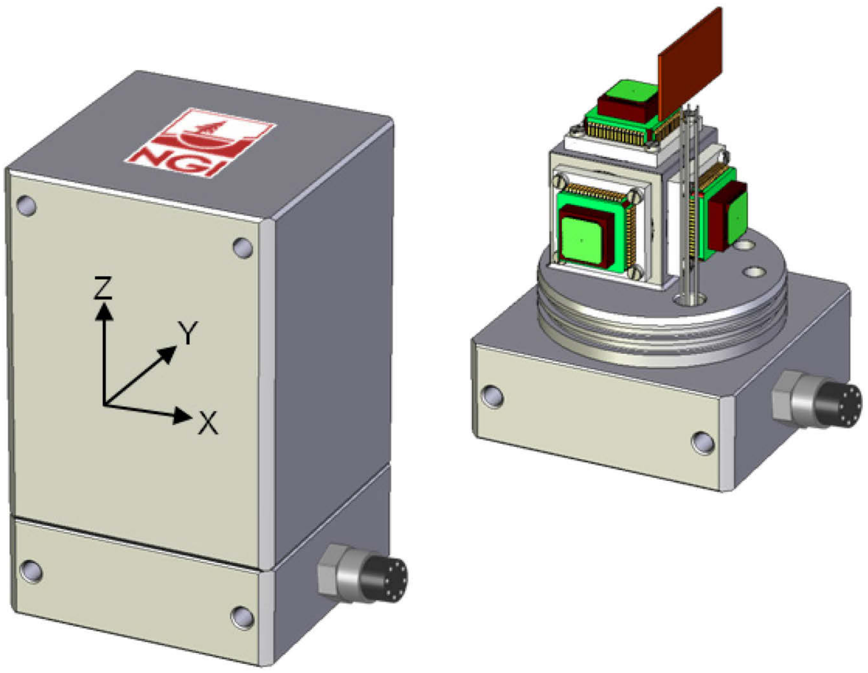


Figure 3.17 NGI's 3D linear accelerometer (SF1500) assembly in subsea enclosure

There are many suppliers of both servo and MEMS type accelerometers in the market for offshore dynamic response the low frequent wave response motion is critical for selection of sensors (high sensitivity at low frequencies). Long-period high swell waves reaching the Korean east coast have a dominating frequency of about 0.1 Hz, slowly varying wind speed will have even longer periods (down to almost DC).

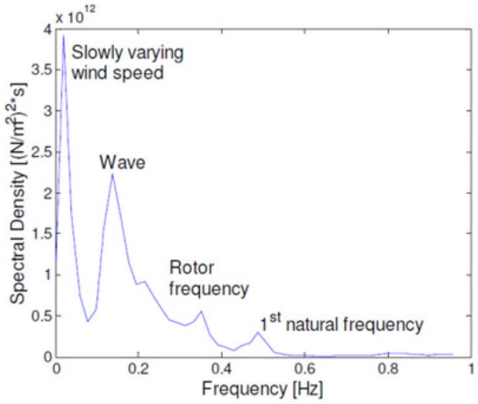


Figure 3.18 Typical frequency ranges for different loads on a monopile OWT foundation (local turbine vibrations not included)

Both Q-flex and the SF1500 accelerometers are sensing g and consequently the inclination of the instrument. Therefore, a constant offset depending on the mounting angle will be recorded this offset should be subtracted from the dynamic motion data. Although the accelerometers will have an offset proportional to the angle relative earth's gravitation, they are not suitable to monitor stationary tilt at high precision (see section 3.5 Tilt).

3.5 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 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.

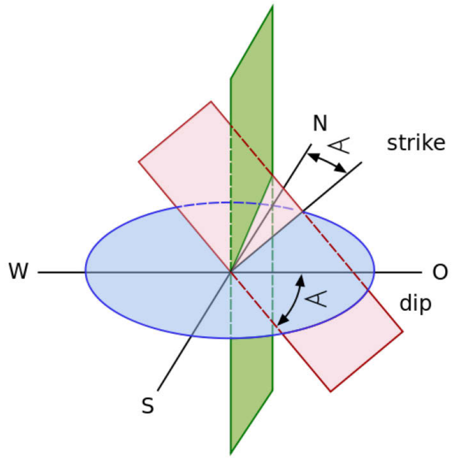


Figure 3.19 Definitions Dip angle = Maximum tilt and Strike = Heading of maximum tilt

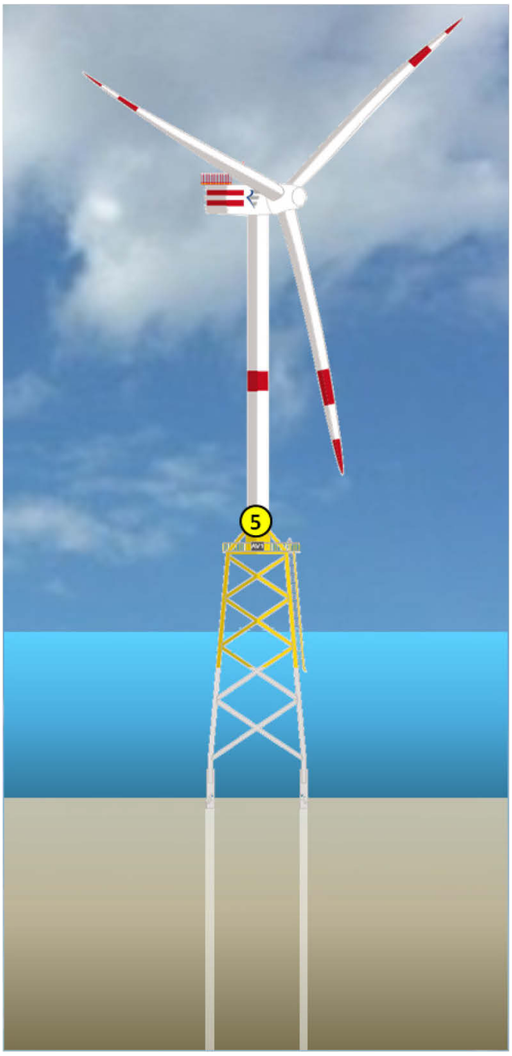


Figure 3.20 The biaxial inclinometer is preferable located at the base of the tower (5)

Many high precision inclinometers are available in the market for this purpose an overall accuracy better than 0.01° should be used normally a range within ±10° is sufficient. There are many types of inclinometers; however servo and capacitive inclinometers are some of the most common types used for structural monitoring. Negligible drift of the inclinometer is the most important parameter for accuracy.

The common errors 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 gradient direct sunlight) may give false readings. Solid mounting and use of materials not subjected to temperature deformations is important. These aspects are in most cases more important for the overall measuring accuracy than the sensors itself. For large structures it can be challenging to determine the mounting alignment deviation compared to the baseline of the overall structure thus a reference baseline must be used (for example the mounting flange to the tower).

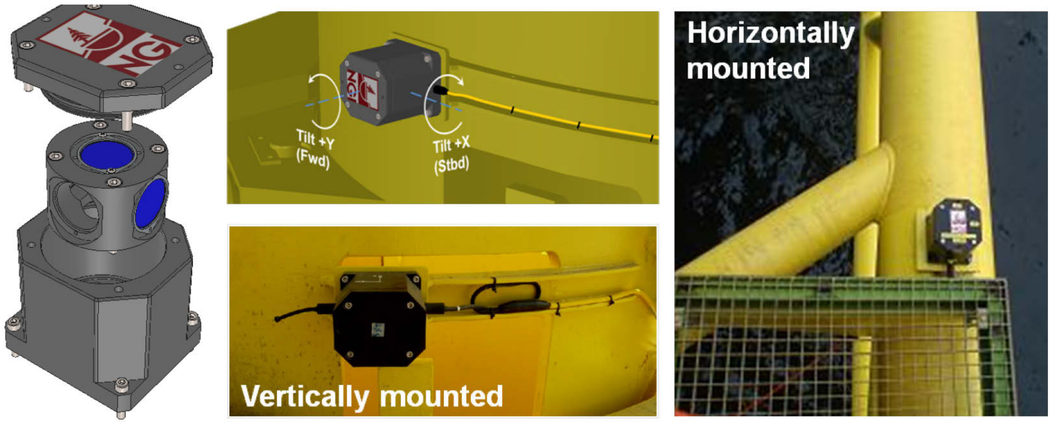


Figure 3.21 NGI biaxial inclinometer assembly with capacitive inclinometers (blue), the unit can be mounted horizontally or vertically by changing the internal position of the two inclinometers

3.6 Structural strain and fatigue

Structural strain can be measured in order to assess distribution of forces but also locally to assess structural health at critical locations (joint etc.) this includes stress magnitude with respect to yield and stress history with respect to fatigue.

The most common approach is to use electrical resistance strain gauges (glued foils or spot-welded). These strain gauges are applied for point measurements and must be pre-installed on the structure.

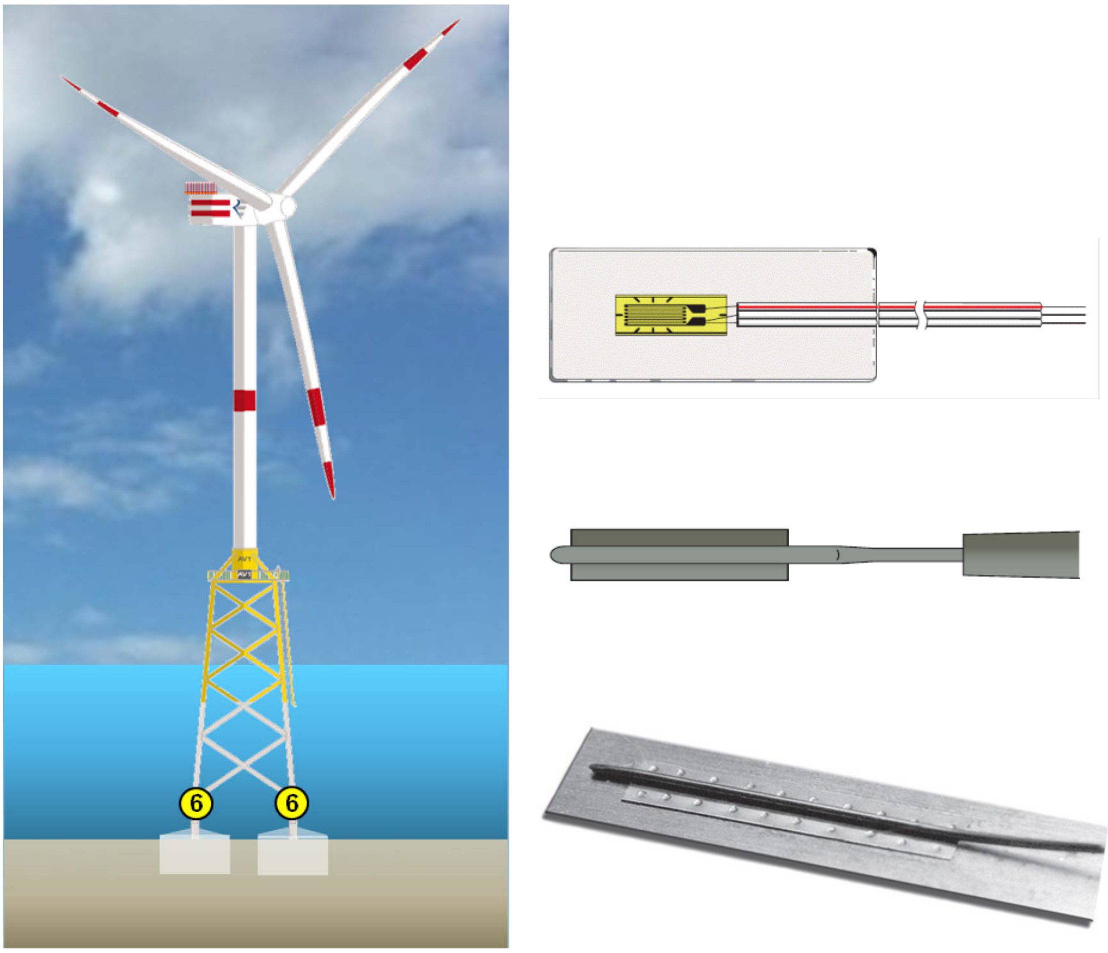
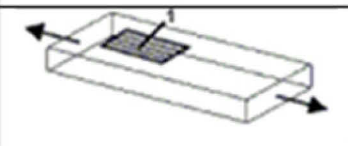
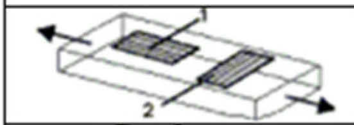
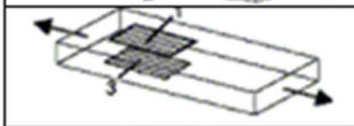
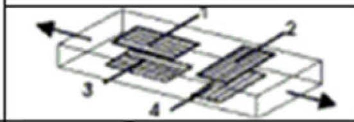
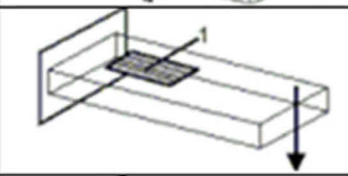
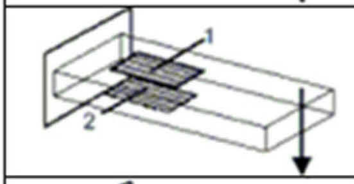
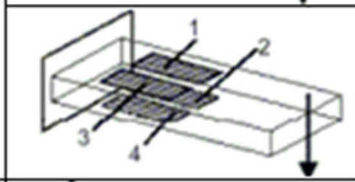
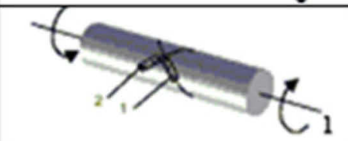
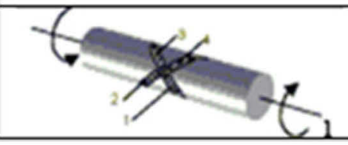


Figure 3.22 *Position of strain gauged sections (6) to monitor foundation loads. Foil (top right) and spot weldable (bottom right) strain gauges from Kyowa both types are hermetic encapsulated and can withstand immersion in water down to 1000 m depth*

Integrity against water ingress, proper preparation and bonding to the surface as well as adequate strain gauge configuration are essential factors for successful strain monitoring, the instructions from the supplier should closely be followed.

The electrical resistance strain gauges are connected in Wheatstone bridge configuration (1, 2 or 4/full gage systems) which depends on application and required accuracy. The table below summarizes some of the most common applications and strain gauge configurations.

Strain	Gage Setup	Bridge Type	Sensitivity MV/V @100 uE	Details
Axial		¼	0.5	Good: Simplest to implement, but must use a dummy gage if compensating for temperature. Also responds to bending strain.
		½	0.65	Better: Temperature compensated, but it is sensitive to bending strain.
		½	1.0	Better: Rejects bending strain, but not temperature. Must use dummy gages if compensating for temperature.
		Full	1.3	Best: More sensitive and compensates for both temperature and bending strain.
Bending		¼	0.5	Good: Simplest to implement, but must use a dummy gage if compensating for temperature. Responds equally to axial strain.
		½	1.0	Better: Rejects axial strain and is temperature compensated.
		Full	2.0	Best: Rejects axial strain and is temperature compensated. Most sensitive to bending strain.
Torsional and Shear		½	1.0	Good: Gages must be mounted at 45 degrees from centerline.
		Full	2.0	Best: Most sensitive full-bridge version of previous setup. Rejects both axial and bending strains.

Other types of strain gauges are based on vibrating wire principle or use of LVDT extensometers. These instruments are less sensitive in order to compensate for this the strain is measured over a longer distance between the anchor points. These instruments can be bolted or clamped to the structural elements and can be retrofitted to pre-installed mounting brackets.

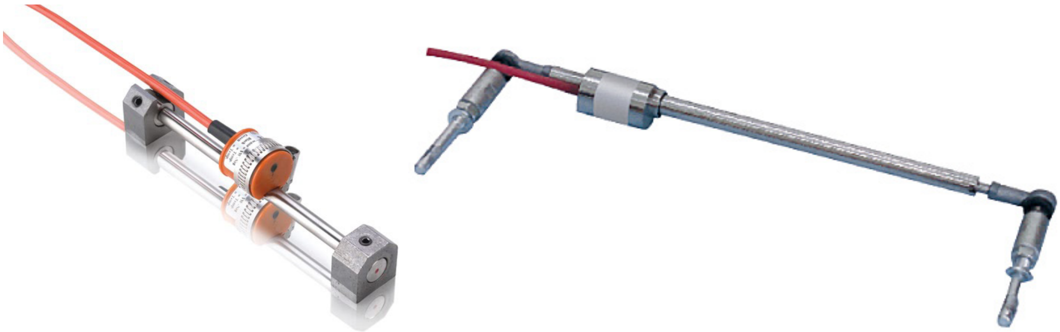


Figure 3.23 Vibrating wire strain gauge (left) and LVDT type strain gauge (right) often used as crack or joint meter (large deformations)

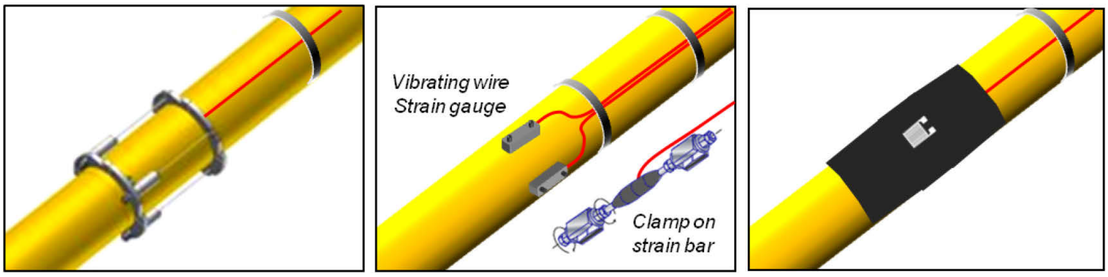


Figure 3.24 From left to right, clamped on strain collar with 4 LVDT's, bolted or clamped VW strain gauges and glued or welded strain gauges inside potted seal

Usually the strain gauge offset will change during mounting, thus the readings may not directly correspond to the absolute strain in the structure. 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. If only dynamic strain variations are of interest the offset does not matter.

3.7 Strain in piles

Axial strain monitoring is relevant for monopoles in order to understand the P-Y response and the lateral stiffness (moment distribution) with depth. In order to monitor this response, strings of strain gauges can be mounted at different elevations along the pile with 90° spacing.

The measured strain is used to calculate the remaining moment at each instrumented elevation of the pile. The measured moment distribution can be compared with predicted using different design methods.

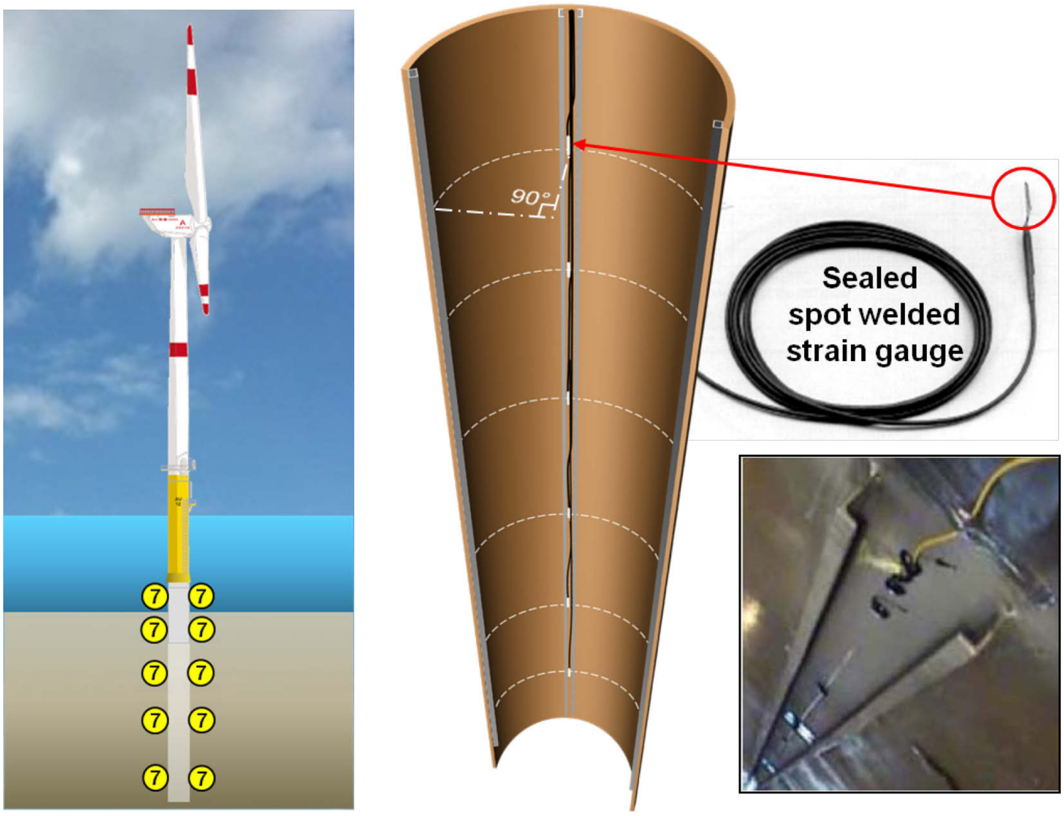


Figure 3.25 *Axial strain gauges (6) mounted at different elevations along the pile. The strain gauges are mounted inside channel protection elements with a driving shoe in the bottom. After mounting the channel are filled with for example grease and sealed with a lid.*

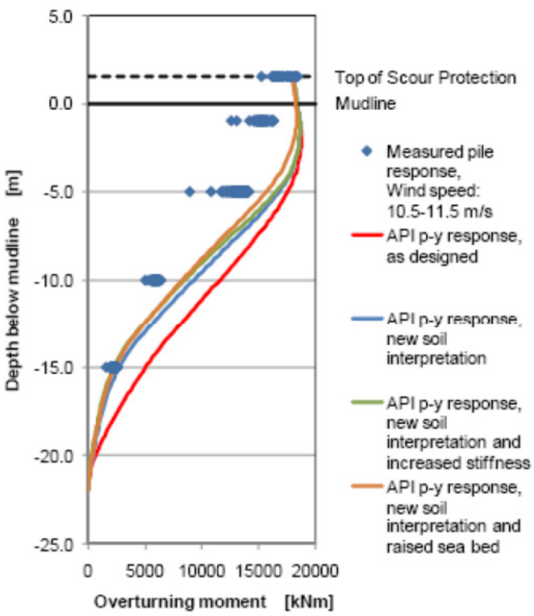


Figure 3.26 Graph showing results from DONG's full scale measurements at Horns Rev, T. Hald et al., EOW 2009

For strain measurements along piles, a distributed optical sensor may provide an optimal monitoring solution. Such a sensor can measure temperature, strain and vibration information from any point along an optical fibre through light scattering. When an electromagnetic wave is launched into an optical fibre, the light will be redistributed by various mechanisms in the form of Rayleigh, Brillouin or Raman scattering. If the local temperature, strain, vibration and acoustic wave changes are relayed to (mostly via direct contact with some types of specialty glue) the optical fibres, the scattered signal in the fibre will be modulated by these physical parameters, and by measuring the changes of modulated signal, one can realize distributed fibre optic sensors.

The most common distributed sensor systems are based on Brillouin scattering, the strain resolution is a few micrometers over one meter (micro-strain) and the measuring fibre length can be several kilometres.

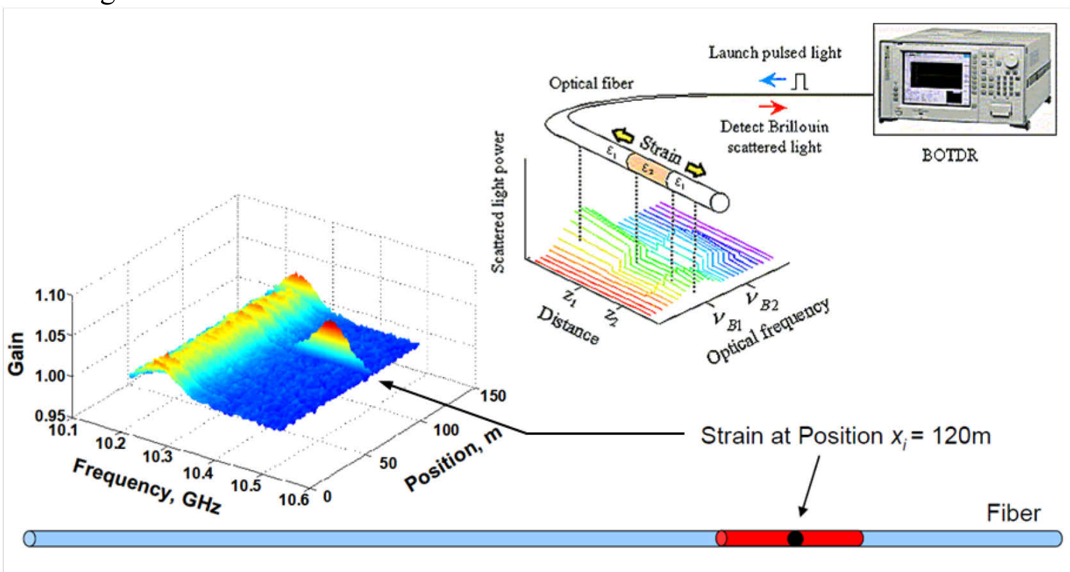


Figure 3.27 Principles for a distributed fibre optic sensor system based on Brillouin scattering

A continuous fibre can easily be bonded to the pile wall and protected due to the minimal stick-up. Strain readings can be obtained for e very meter along the pile without any extensive cabling except for the fibre itself which is less prone to damage during driving.

Although the technology is advanced, it has matured over the last 10 years and is provided by several specialist companies worldwide.

3.8 *Pore pressure monitoring*

The pore pressure is defined as the pressure differential between entrapped water in the seabed and hydrostatic (ambient) pressure at the same depth.

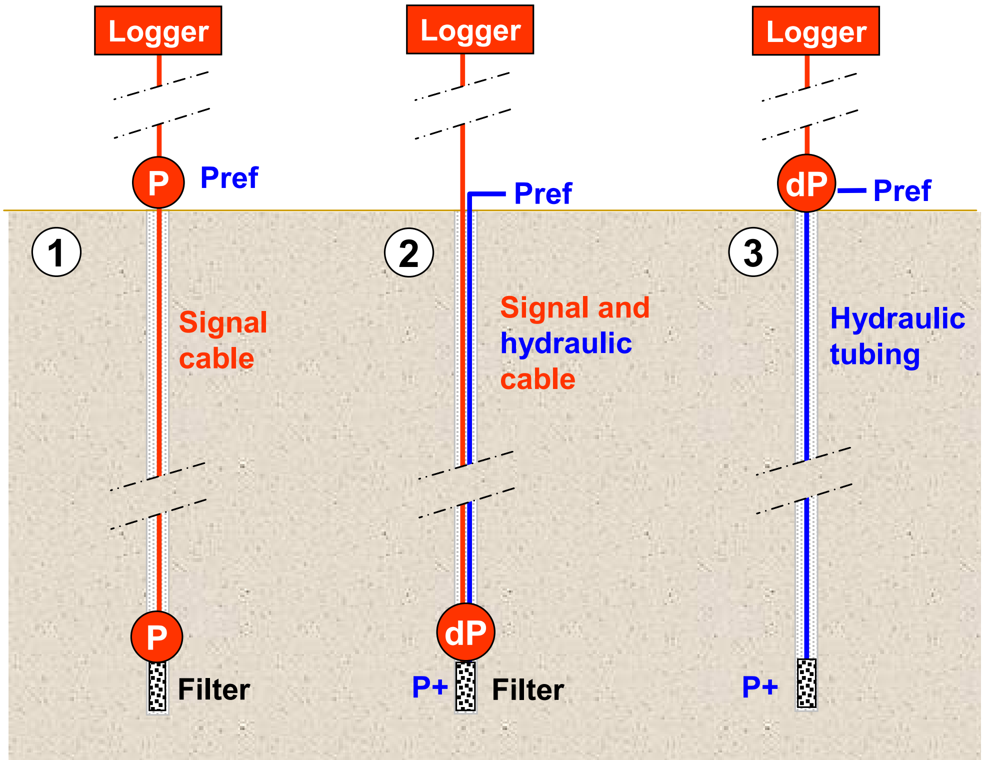


Figure 3.28 Sensor configurations that can be used for pore pressure monitoring in the seabed (P refers to total Pressure and dP to differential Pressure sensors)

For subsea pore pressure monitoring NGI recommends to use the third set-up with only a filter inlet embedded in the soil with an hydraulic tube or standpipe routed up to the pressure port of a differential pressure sensor located in a monitoring head near the seabed, the reference port is routed directly to sea. Only one sensor that is accessible for replacement by divers is required, the embedded parts do not include any electronics.

The filter and standpipe should be open to sea during installation of the foundation and will be flooded by seawater by means of the open drainage. The system self saturates if the hydraulic lines have sufficient inner diameter and are routed such that entrapped air can escape. The pore pressure is directly measured after the pressure port to the differential pressure sensor has been connected. By means of a 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. 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

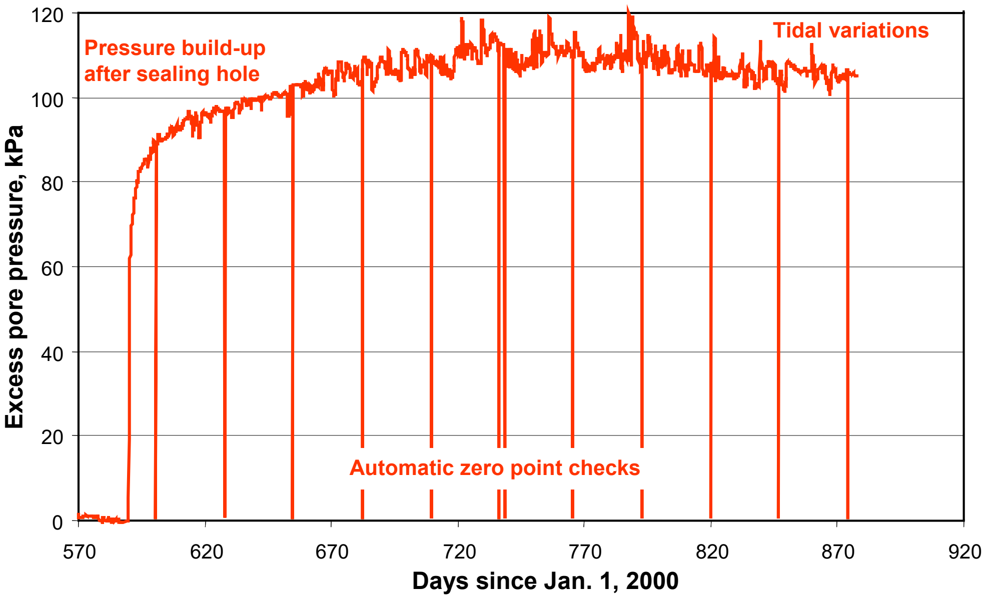


Figure 3.29 Example of down-hole pore pressure measurements (200m below the seabed) done by NGI using up-hole differential pressure sensor with automatic zero point check every month (using a solenoid operated bypass valve)

Figure 3.30 Trial fit of seabed sensor head containing two differential pressure sensors serving to hydraulic piezometer lines which are hooked op by the (white) flexible jumper hoses. This unit is equipped with manual operated bypass valves to sea (yellow handle).

3.8.1 NGI Pile piezometers

The system is based on sensor set up (3) with filters and stand pipes mounted along the pile, the sensor head containing differential pressure sensors is hooked up by divers after pile driving using flexible hydraulic jumpers with quick connectors. The piezometer configuration depends on soil conditions (critical layers for pore pressure accumulation and capacity/stiffness of the soil). A minimum configuration may be piezometer filter at two levels and at diametric opposite sides of the pile in the dominating load direction.

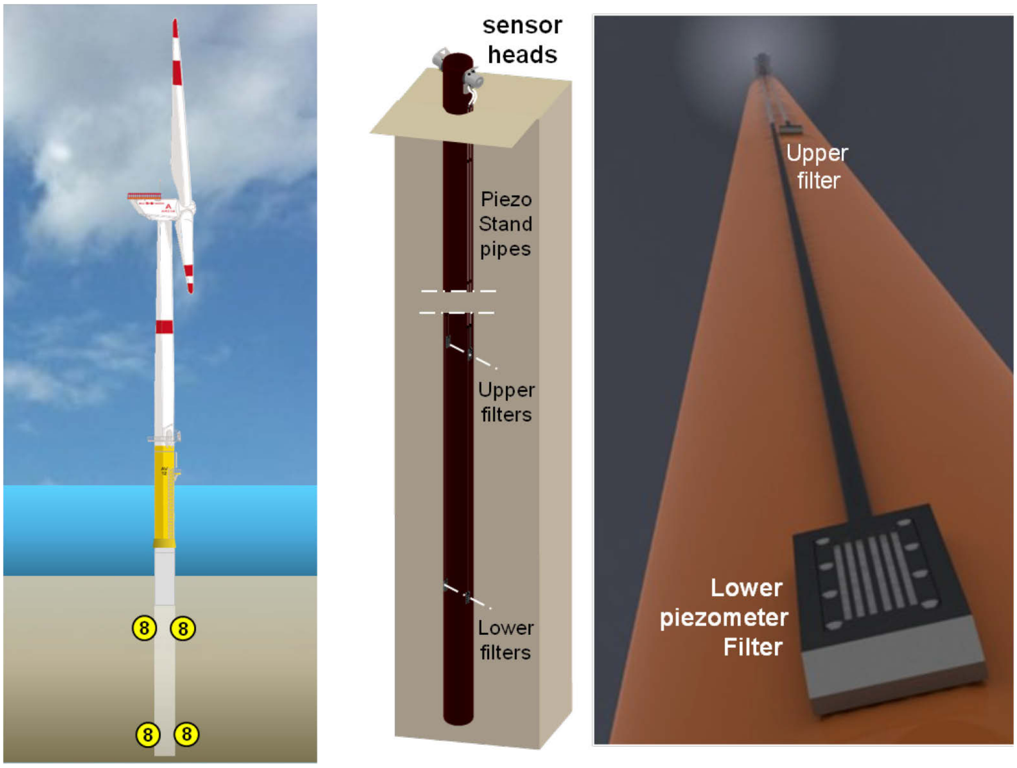


Figure 3.31 Pile piezometers (8) at two elevations along a monopile and outlines of the NGI pile piezometer system with external standpipes and filter boxes

The filter boxes are heavy duty and designed as driving shoes, a 50-micron Polypropylene filter insert is mounted into the box after it is welded to the pile wall. Filter materials subjected to corrosion should be avoided as gas affecting the measurements may develop during oxidation. For some soils the routing of the standpipes along the outside of the pile can be of concern with respect to leakage and hydraulic communication between piezometers and sea. If it is allowed to drill holes in the pile the lines can be routed along the inside of the pile to avoid possible leakage paths.

As the differential pressure sensors are connected after driving the high pressure chocks during driving are avoided and less range can be selected. NGI use high precision temperature compensated differential pressure sensor such as the Keller PD-33X.

3.8.2 NGI Caisson piezometers

The caisson piezometers are based on a similar set up as for the pile piezometers the configuration may however be slightly different. For skirted foundations it is usually the pore pressure at either sides of the skirt tip (0.5-1m from the tip) and the caisson pressure at the base which are of primary interest for monitoring (both direct response to transient overturning loads and possible cyclic pore pressure accumulation.

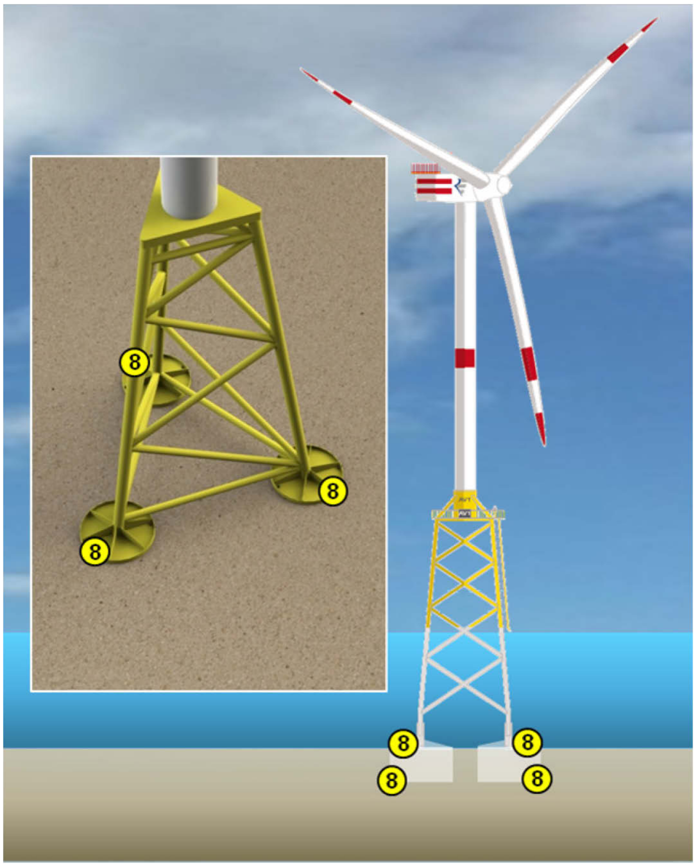


Figure 3.32 Caisson piezometers (8) on a tripod jacket with caisson foundations

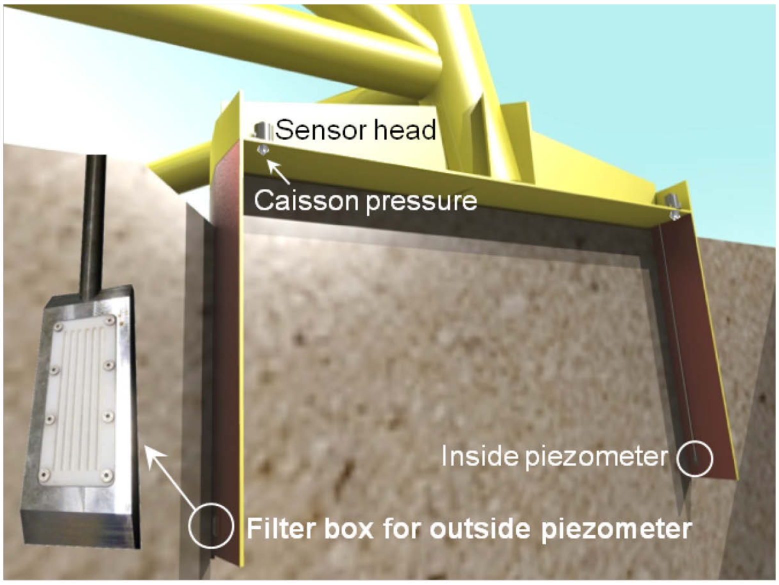


Figure 3.33 Position of piezometer filters on the caisson and routing of hydraulic lines to the sensor heads

For connection to multiple piezometer ports, NGI use a sensor head with a hydraulic stab on top of the caisson this solution allows for easy hook-up by both ROV or divers. The electrical connection to the topside cable is done using a jumper with a wet stab allowing for under water hook-up.

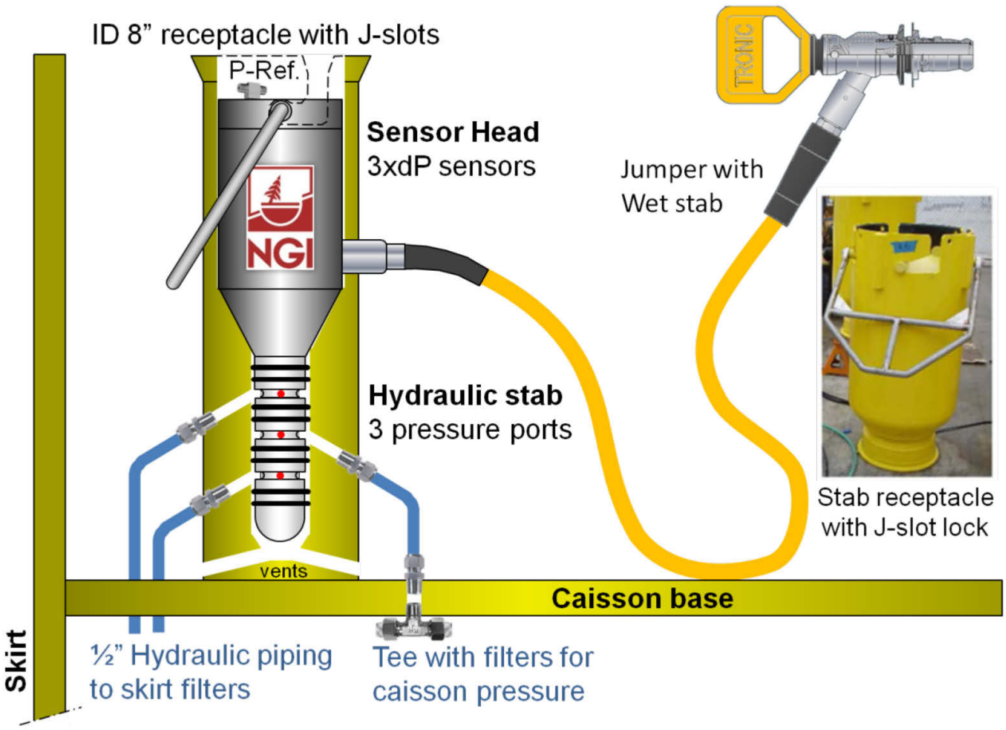


Figure 3.34 Sensor head and stab receptacle with multiple hydraulic ports for hook-up of caisson piezometers. The sensor head can also be outfitted with other instruments such as accelerometers.

3.9 Lateral earth pressure

As describe in section 2.2 great care must be taken for successful monitoring of lateral earth pressure and the total pressure cells must survive the driving. In order to derive effective stresses also pore pressures must be monitored in the vicinity.

Most of the “stiff” earth pressure cells available in the market are based on membranes with vibrating wire-sensing mechanism. In order to fit flush with the pile the assembly must be modified dependent on pile radius and wall thickness

Figure 3.35 Geonor P100 Vibrating Wire Earth pressure cell

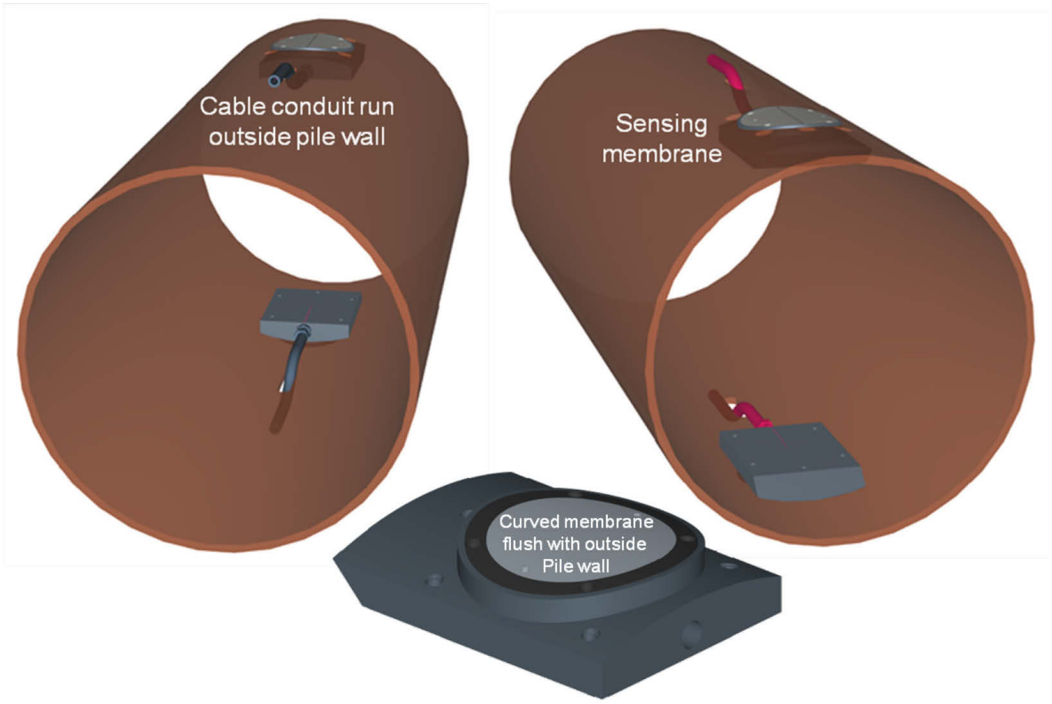


Figure 3.36 NGI Earth pressure cell for piles modified for flush fit to pile wall and designed as a an internal driving shoe

3.10 Static displacement and settlement

In general, the use of satellite positioning systems like GNSS offers best flexibility. The position precision which can be obtained is however a critical issue especially for offshore applications.

A commonly used technique for improving GNSS performance is differential GNSS, which is illustrated in the figure. Using differential GNSS, the position of a land based GNSS receiver, referred to as a “Reference station,” is determined to a high accuracy or is assumed to be fixed (no displacements). The Reference station determines ranges to GNSS satellites and compares these ranges. Differences between the ranges can be attributed to satellite ephemeris and clock errors, but mostly to errors associated with atmospheric delay. The Reference stations process and send corrections of these errors to the OWT’s with GNSS antennas for displacement monitoring, which incorporate the corrections into their position calculations.

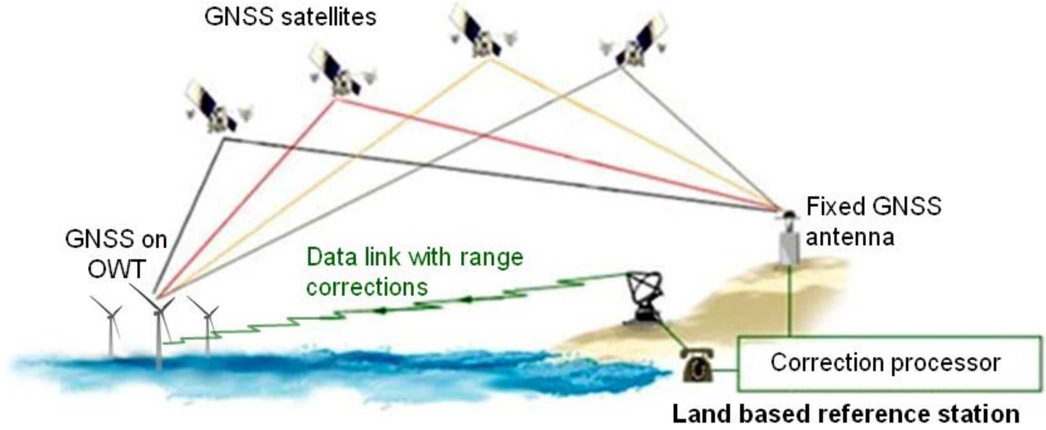


Figure 3.37 Principles of differential GNSS for offshore application

There are also other methods to enhance the GNSS positioning accuracy. The precision that can be obtained depends on the satellite within range in Korean waters as well, distance to the Reference station as well as local conditions. The GNSS antenna should not be placed up on the turbine were the dynamic motions are large creating “noise” for GNSS displacement measurements.

Figure 3.38 Recommended position (left) and outlines of GNSS antenna (right)

According to NGI's experience based on offshore GNSS measurements done in Europe the accuracy using differential GNSS can be better than 10 cm maybe better using averaging data over longer periods. Usually the precision is better for horizontal positions than for vertical displacement.

Thus, satellite positioning is still probably not good enough for monitoring settlement of offshore structures. For 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 isolating the system from seawater and using compensating lines to make sure that the back (gas) pressure is equal at all point of the system an overall accuracy better than 10mm can be obtained. The system can be configured in many ways provided the reservoir with the liquid gas reference is always at the highest point.

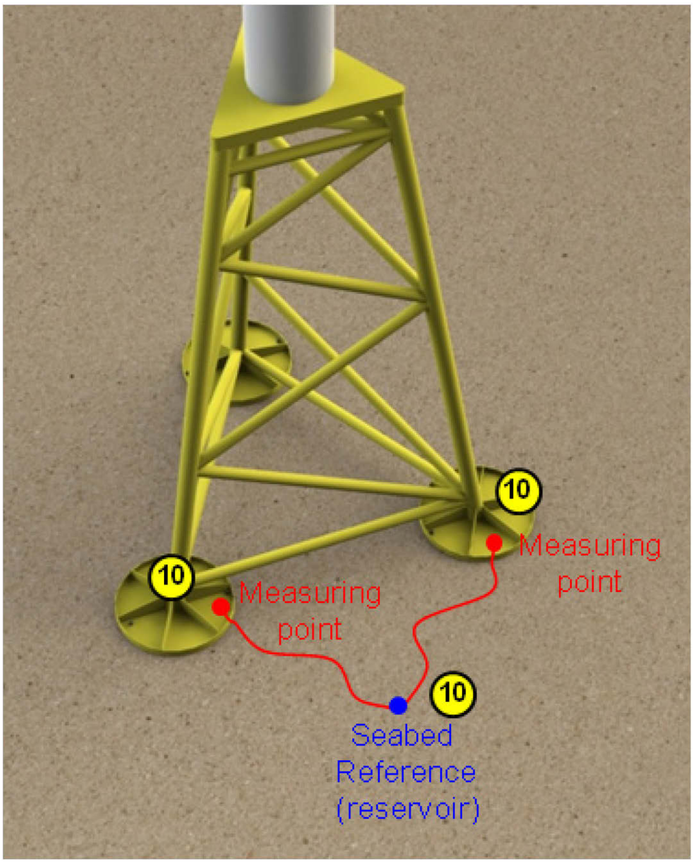


Figure 3.39 NGI's Liquid level system for settlement monitoring, measuring unit with differential pressure sensors (above) and Reservoir reference (below)

3.11 Deformation/cracks in connections and joints

Deformations or cracks in joints are normally larger (millimeter scale) than strain deformations (micrometer scale). Thus, extensometers are normally used to monitor this type of deformations. These instruments are referred to as *Crack- or Joint-meters*. The instruments are usually based on the potentiometer or vibrating wire sensing principles and are bolted/welded/glued across the gap to be measured.

Figure 3.40 Crack or Joint meter with anchors pins epoxy glued in drilled holes

The stroke is possible to adjust and lock after mounting and the instruments have flexible ball joints to allow for practical mounting tolerances.

If the directions of deformation are unknown, 3D joint meters may be used.

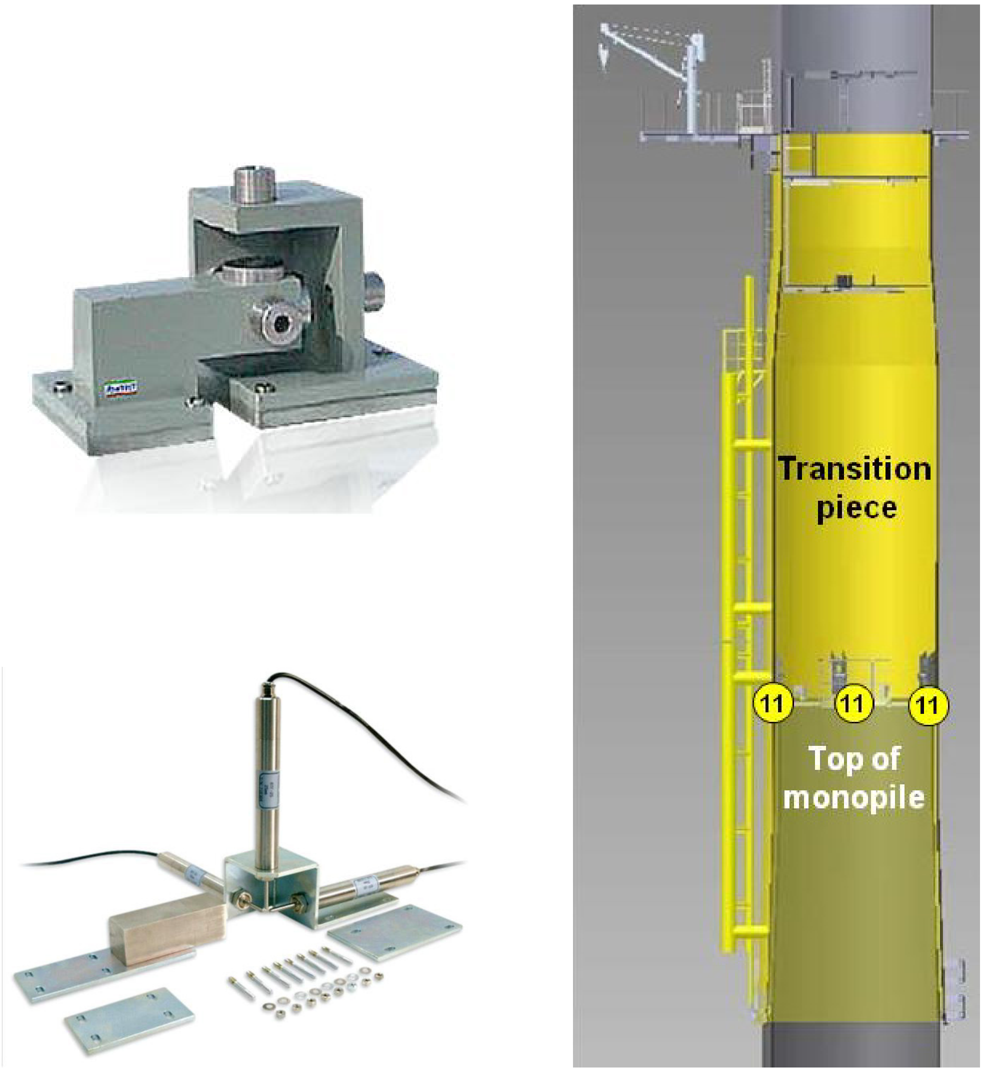


Figure 3.41 *3D joint meter for manual readings (left) and with displacement gauges (below). (Right) Positions of 1D Joint meters to monitor possible settlement of transition piece (a minimum of three positions are required around the gap to the pile top)*

The 3D jointmeters are avialable with different design for various applications and also for immersion in shallow water.

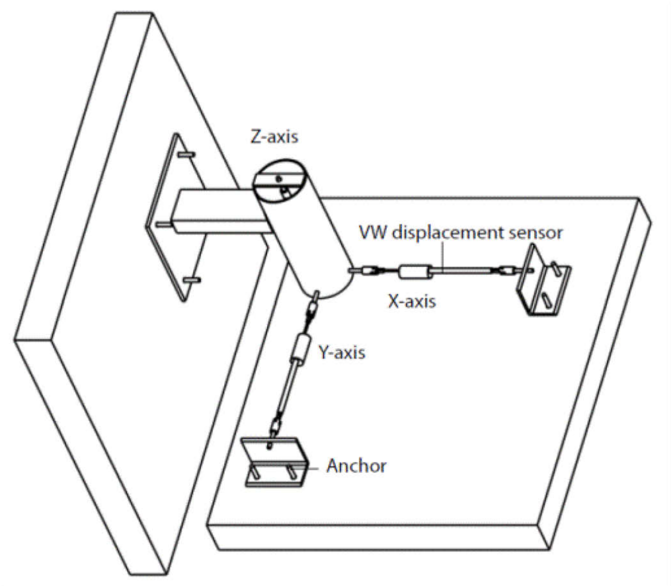


Figure 3.42 Set up of 3D joint meter from Slope Indicator

3.12 Corrosion

Based on experience from installed OWT's in Europe the corrosion inside a monopile is the most relevant application for remote monitoring (reducing the need for visual inspection).

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.

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. A galvanic probe 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 oxy-gen 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.

An alternative approach is to apply 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 either caused by active corrosion and/or fatigue cracks can propagate 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 piezo-electric type and low cost.

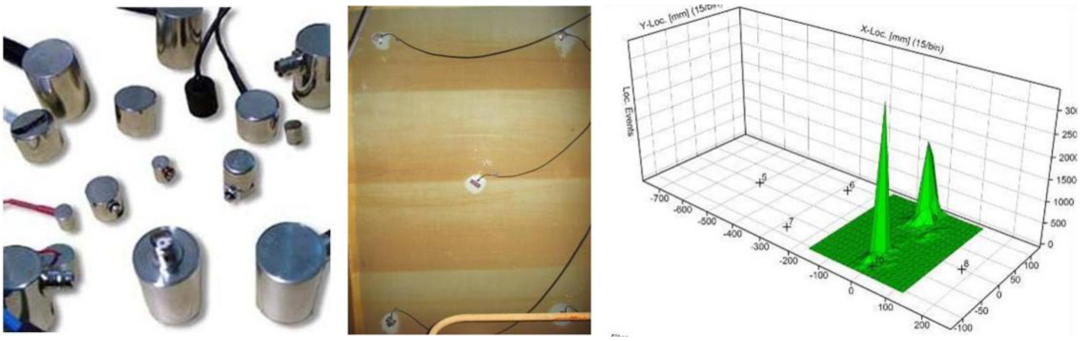


Figure 3.43 Piezo-electric AEM transducers (left), array of transducers mounted on a tank wall and 3D plot showing intensity and location of recorded acoustic emissions

4 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 or transferred to shore by available links installed for operation the wind turbine.

Sensors with analogue output must be interfaced with AD's and multiplexed a monitoring system usually contains 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 efficient to use subsea AD/MUX in order to reduce the extent of cabling to the surface.

Filtering, processing of statistical data and re-sampling is performed in the topside acquisition PC in order to condition and reduce the amount of data transferred to shore. A local data storage and battery UPS should be included in the offshore Data acquisition system in case power or data link failures. Sensor configuration including setting of conversion factors such as sensitivity and offset is performed from the data acquisition PC. Other logic functions may be time synchronization or controlling the rate of re-sampled sensor data and data reduction, for example more frequent logging of data samples in stormy weather and storage of complete time series.

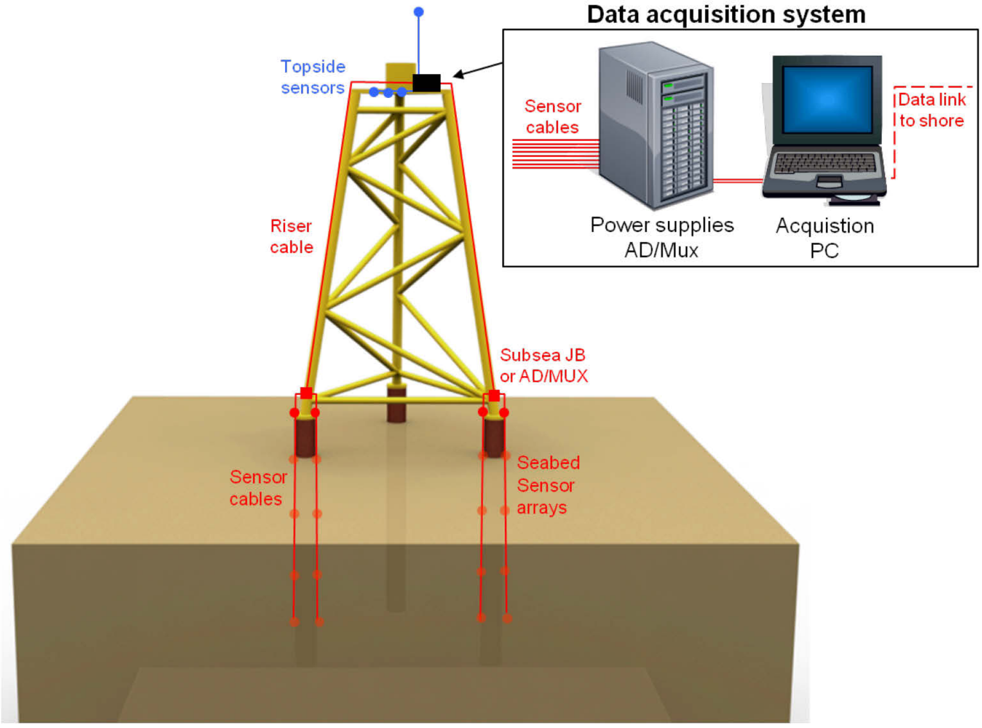


Figure 4.1 Components and hierarki for an OWT data acquistion system

For smaller monitoring systems with standard sensors the acquistion system can be based on for example National Instruments acqutions systems using Compact DAQ (AD/Mux system) and Labview or Labwindows software aquisition platforms.

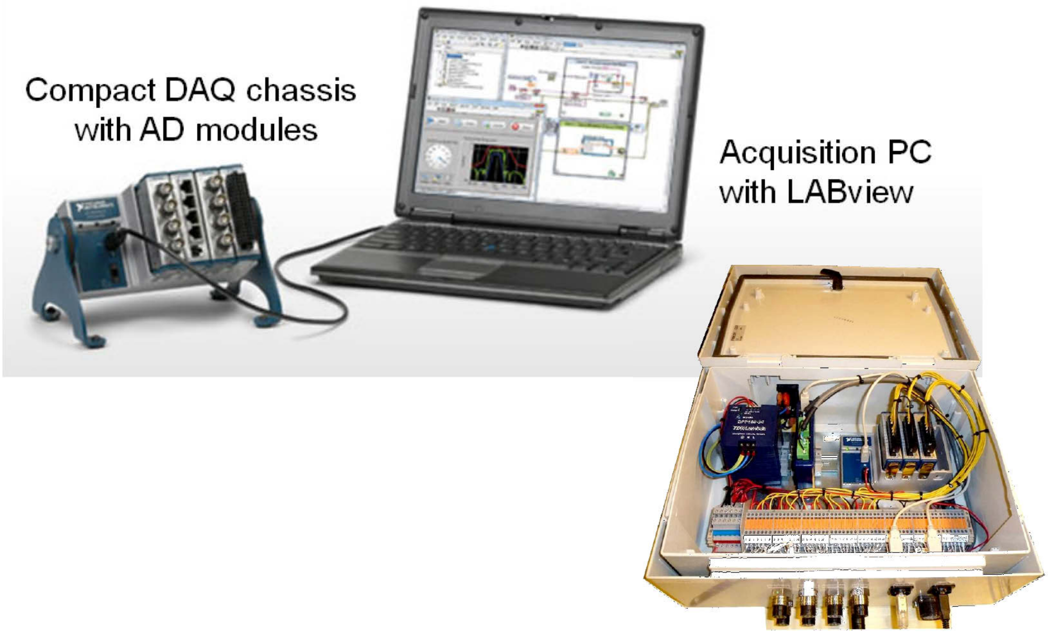


Figure 4.2 Simple Data acquisition set up based on National Instruments CompactDAQ and LABview system. (Left) Topside Interface box with cable terminations, power supplies and CompactDAQ modules

Larger systems may require dedicated software for more advanced processing such as NGI's VISMON/AMANDA platform for data storage, processing and display of parameters from all sub systems into customized user interface for both installation monitoring control and long-term performance monitoring of the foundations.

Some instruments may require dedicated interface units, the complete acquisition system is then usually rack mounted.

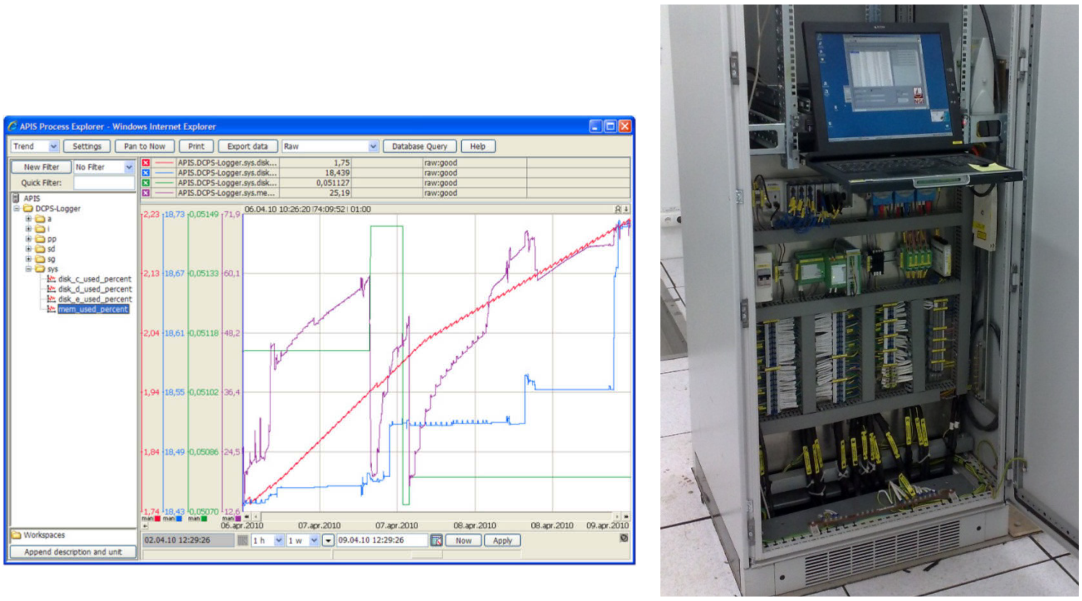


Figure 4.3 Example of processed data trends (VISMON) and a data acquistion cabinet delivered by NGI for placement on an offshore platform

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
- Resolution, e.g. 8, 10, 12, 16 bits logger and number of channels
- Interface type / communication
- Storage capacity
- Logging speed
- Size
- Programming interface
- Costs

The Analog-Digital converter is playing a virtual rule when connecting analogue sensors to a data logger. There are several analogue 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. Please use high quality resistors with low thermal drift and good long-term stability.

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 gives no answer on the sensors accuracy. A good rule may be to choose an A/D converter giving a resolution 10 times better than the sensors accuracy.

In some applications, the analogue signal has to be amplified or reduced before logging. The main reason may be to adjust the sensors output to the A/D input. A 10 volt signal applied to an analogue input designed for maximal 5 Volt may destroy the input pin and gives for sure an out of range error.

Some sensors may have serial I/O. and communicate by using a special protocol. The most common are RS232 (only for short) or RS485 line, however more intelligent protocols and HW interfaces like HARD, PROFIBUS, CAN-BUS and other field bus system are also used. In such cases, the data logger must have a digital interface fitting the used protocol as implementing the software needed for the protocol is time consuming.

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. For a monopile, 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.

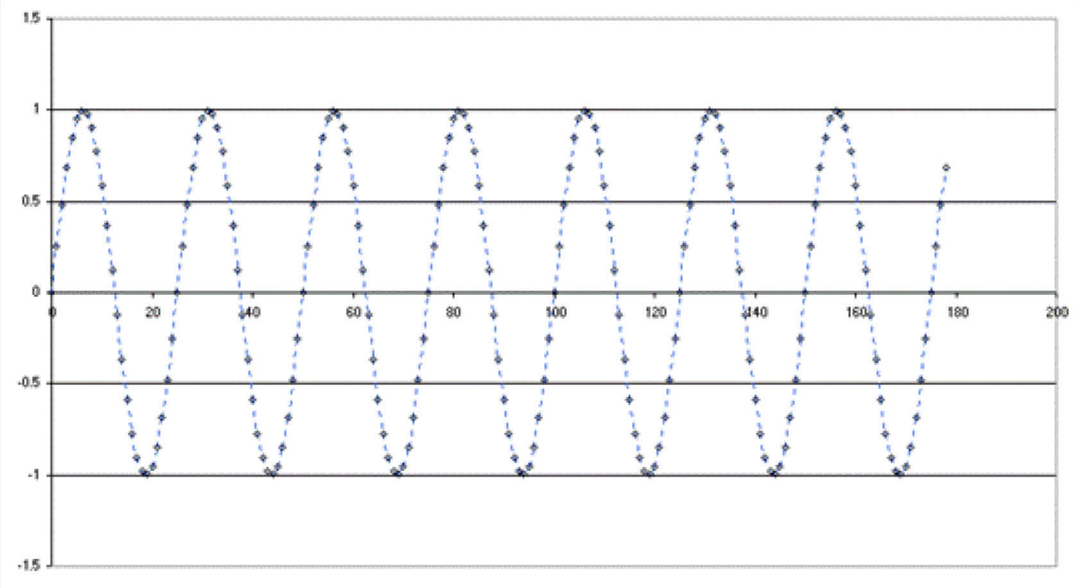


Figure 4.4 Real-time trace of a cyclic signal based on a logging rate corresponding to 25 samples per period

5 General guidelines for selection of sensors

5.1 Basic considerations

Parameter to be measured: Determine the best method to obtain the required parameter(s) including how to get the desired accuracy.

Priority: Which priority do you give to this particular measurement? This may govern the type of equipment you choose w.r.t. price and sophistication.

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.

Environmental: The environmental conditions must be taken into account when choosing materials, ruggedness of enclosures and mounts etc.

Signal type: Which signal type (Frequency, voltage, current, optical etc.) is best suited for this particular application? This has implications also for choice of cabling, data acquisition etc.

Specifications: Range, precision and accuracy required. Cost is a function of the specifications - choose the specifications appropriate for the design and not simply the very best sensor on the market.

Sensor materials: Requirements regarding corrosion, pressure, size, electrical effects etc.

Sensor manufacturer: Previous experience with supplier.

5.2 Sensor accuracy

Sensor accuracy is often specified as the sum of the following errors, see also the figure below.

- Non-Linearity
- Hysteresis
- Drift

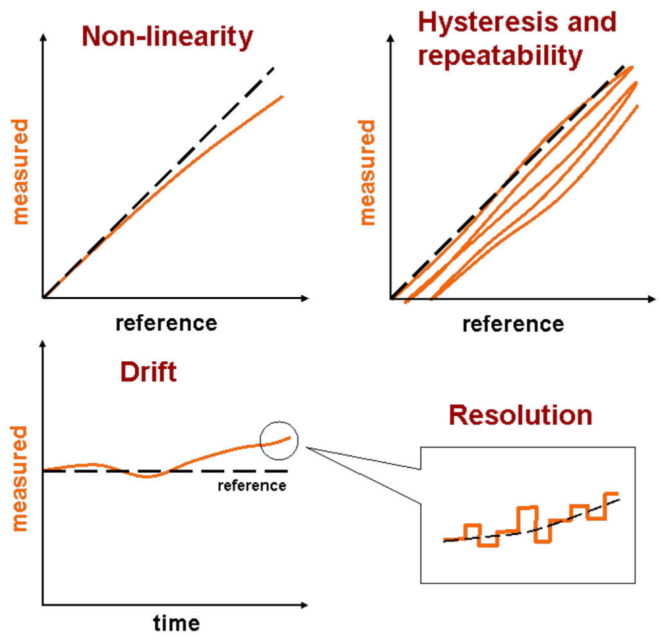


Figure 5.1 Definitions of sensor specifications affecting the overall accuracy

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 be re-calibration for the utilized range or taking reference or offset readings.

It should be noted that sensor resolution is not sensor accuracy. It should also be noted that it is the overall system accuracy which is important for the end user. In conjunction with deformation 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, seabed elevation is often measured using ultra precision pressure sensors. However, the biggest source of error is normally the unstable condition (density) of the sea water which is used as reference.

5.3 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 that 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
- Logging cabinet on platform: Does not need redundancy.

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 neglected. If two different sensors show the same trend it is more or less certain that the response is real.

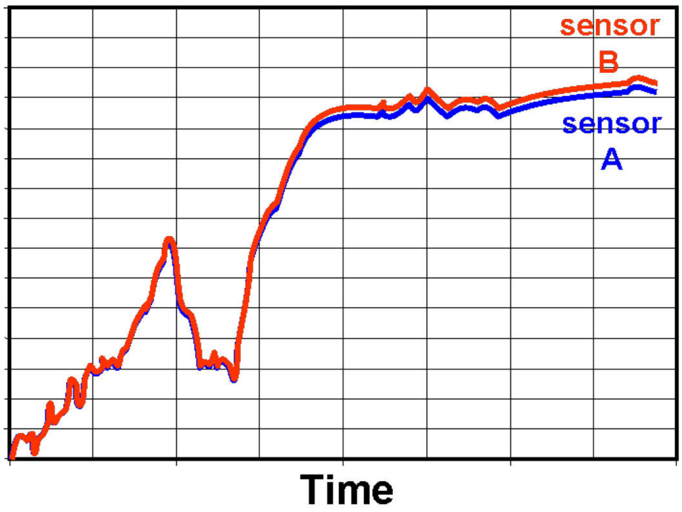


Figure 5.2 Redundant sensors (A and B) - increased data reliability

6 Guidelines for purchase and calibration of sensor systems

6.1 Receipt of sensors

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

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

- Visual signs of damage
- Power up sensor and check signal
- Document this is done and put into project files (can be a simple handwritten note stating what was checked, dated and initials.)

Calibration checks:

- Calibrate 1-2 steps within range, check signs and zero point
- Verify this is in accordance with specifications from manufacturer
- Document this and put into project files (can be simple handwritten note stating what was done and results, with date and initials.

6.2 Special 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 new calibration of the sensor within that limited range to obtain a better and more accurate calibration. This may also be advisable when operating for example at low temperatures.

6.3 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 has been mounted on the structure.

If possible, the sensors should be live during installation and data recorded. The sensor response should be carefully logged and as observed values may be used directly as new offsets in the configuration files for the data acquisition software.

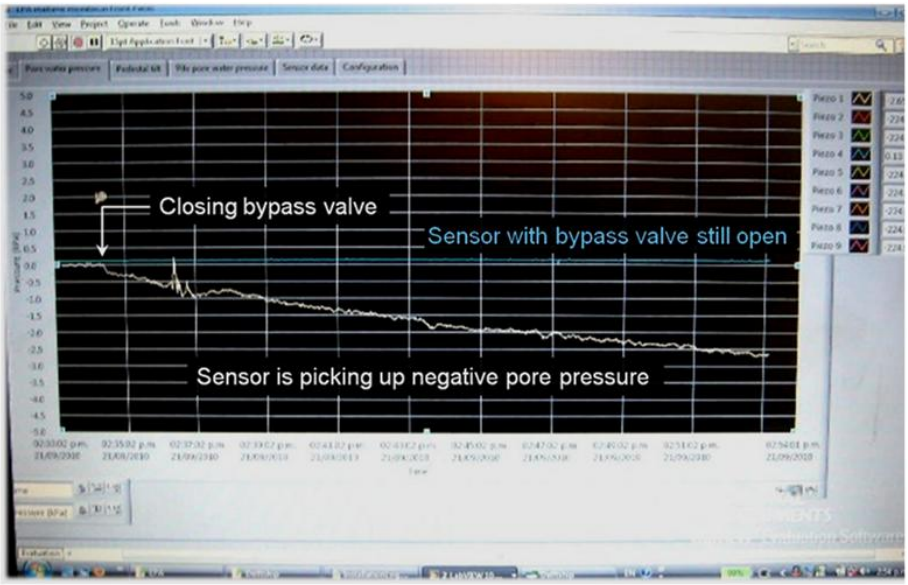


Figure 6.1 Real-time display showing the piezometer response after seabed installation and closure of the bypass valve (in this case negative pore pressures were expected as the instrument was installed in swelling clays)

For larger systems, it is absolutely essential that the sensor IDs and line/cable routing is properly described in hook-up diagrams with sensor, cable and channel IDs. A master list showing all IDs, as well as conversion factors is useful 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.

Still 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 is correct....this may save a lot of questions receiving and interpreting data during later operation.

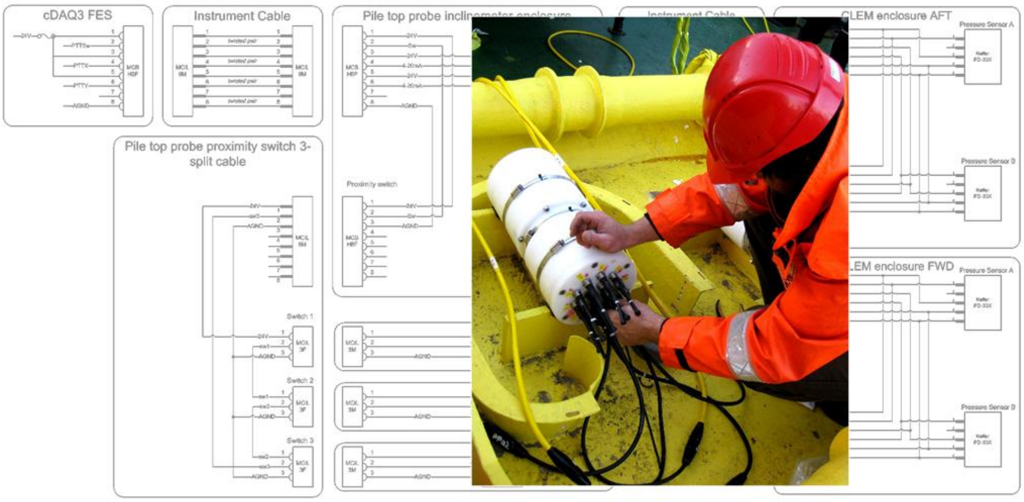


Figure 6.2 *Make sure that signal cables and routing is correct during field hook-up!*

7 Corrosion and prevention

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 aluminium 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.

Figure 7.1 *Galvanic corrosion on metal enclosure with connectors in different metal grade (left). "Corrosion safe" synthetic enclsoure in Delrin for shallow water with connectors/outfitting in stainless steel (right)*

7.1 General recommendations to limit corrosion

- Don't "mix" metals (exception is for intentional cathodic protection)
- Determine local environmental conditions
- Isolate dissimilar metals

7.2 Types of corrosion to consider

For subsea instrumentation projects we will only consider corrosion in seawater, splash zone and marine environment

General, evenly distributed surface corrosion

Generally not a big problem and usually easy to calculate and deal with. Requires:

- Presence of oxygen or other reactive agents
- Anodic/cathodic reactions simultaneously on the same surface

Avoided by using correct material for seawater, e.g. Inconel 625, Hastelloy C, 254 SMO, Titanium or suitable SS316L. However, when choosing material, consider also "Galvanic corrosion" and "Crevice and pit corrosion".

Galvanic corrosion

This is potentially the most dangerous type. In a galvanic cell system it is the anode that corrodes while the cathode remains unaltered.
Occurs when dissimilar metals in direct contact + electrolyte
Can also be generated by stray currents in the water from (damaged isolation)

Prevention:

- Direct corrosion towards "sacrificial" metal parts (anodes)
- Isolate dissimilar metals from each other. Important to use isolation materials with sufficient resistivity.

NOTE: Titanium does not in itself corrode significantly, but it "lends" its surface area to the materials it is in contact with. Thus mixed use of Titanium together with other metals may increase corrosion problems in the other metals.

Crevice and pit corrosion

Can be potentially dangerous for seals and O-rings. Some stainless steels in seawater are especially susceptible to this form of corrosion. Occurs in/at:

- Cracks and crevices where electrolyte is stagnant
- Under paint or other surface covers

Metals susceptible to this form of corrosion:

- AISI 316
- Ni-Cr alloys
- AISI 400 - series

Metals unaffected by this type of corrosion:

- Titanium
- Hastelloy "C"
- Inconel 625
- 254 SMO

7.3 Selection of materials

General discussion of materials are given below, with pros and cons for each.

- **Titanium and Titanium alloys:**
  Regarded as the best choice for subsea applications due to high strength, low specific gravity and very good resistance to all types of corrosion in seawater. However, it is also more expensive and more difficult to machine than steel. Can be long delivery times.

- **Stainless steel alloys**
  Most ordinary types of stainless steels are not very suitable for use in seawater especially due to tendency for crevice/pit corrosion. Should be kept isolated from other metals, and with free surface to seawater containing oxygen. However, Inconel 625, Hastelloy C and 254 SMO are regarded as good choices for subsea use and close to Titanium w.r.t. corrosion resistance. Again these materials are expensive and sometimes difficult to machine, thus SS316l or Duplex can also be used. 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 oxidisation process.

- **Aluminium Bronze alloys**
  "Marine" aluminium.

- **Anodized aluminium**
  Good corrosion resistance in seawater. However, this requires that the anodizing layer is intact and does not become scratched or damaged. If anodizing layer is not intact, the aluminium is very suspect to galvanic corrosion. Try to avoid if weight is not a problem.
  NOTE: Machining of parts must take into consideration the changes in dimensions caused by the anodization process, e.g. O-ring grooves and mating surfaces with small tolerances.

  Avoid use of pure aluminium in seawater applications.

- **Ordinary steel (e.g. St 52)**
  Not suited for pressure vessels due to the need for anodic protection or surface coating. The steel is susceptible to corrosion around gaskets, O-rings etc. where surface coating is not possible. Can be used for construction material when coated and combined with cathodic protection, but materials with higher galvanic potential should be totally isolated from the steel.
- **Non-metallic materials**
  Probably best choice for reducing 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 that absorb water such as Nylon should be avoided due to swelling. Delrin (or POM C) is a cost efficient choice for shallow and moderate water depths. Composite materials such as glass or carbon fibre laminated enclosures can also be used usually more expensive and only relevant for deep immersion.

7.4 Galvanic potential of materials

The galvanic potentials are illustrated in the figure below. The essential point to remember is the larger the difference in galvanic potential, the higher the driving force for corrosion (battery effect). A system that is constructed entirely of one kind of material has zero in difference in galvanic potential. Combining ordinary and stainless steel (ST52 and 316) gives a large difference in galvanic potential and therefore increased corrosion.

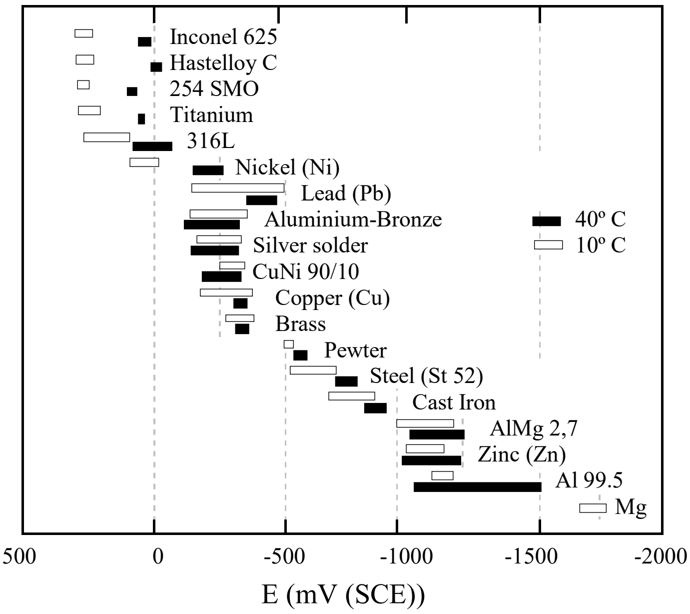


Figure 7.2 Galvanic potential of various common metals and alloy

7.5 Cathodic protection

Cathodic protection (CP) is a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell. The simplest method to apply CP is by connecting the metal to be protected with a piece of another more easily corroded "sacrificial metal" to act as the anode of the electrochemical cell. Anodes made of Zinc, Magnesium or Aluminium alloys are most common in the offshore industry. These can be bolted on the bare metal to be protected. They can be purchased from most Marine Suppliers in a variety of sizes. The anodes must be in direct electrical contact with the structure, e.g. grind away paint before bolting or welding these to the structure also remember to grind to anode itself.

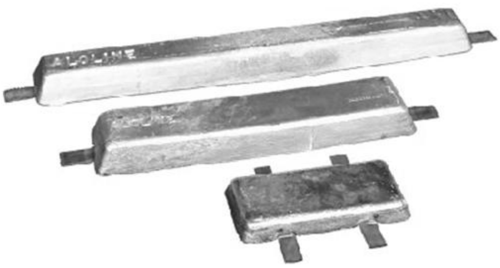


Figure 7.3 Example of zinc anodes

7.6 Surface treatment

Not all surfaces should be treated or covered. For example, do not paint certain materials, e.g. stainless steels or other materials that require supply of oxygen for surface protective layer. This is also valid for isolation materials, which cover parts of the metal surface (see galvanic isolation).

- **Zinc or other metal coating:** useful for construction material, e.g. ordinary steel, which is only required to have a limited lifespan in seawater. However, this method is not suitable for steel pressure containers because the coating will act as the sacrificial anode and the corrosion product may contaminate the O-ring grooves and cause leakage.
- **Epoxy paints** is useful for construction material, e.g. ordinary steel, which is only required to have a limited lifespan in seawater. 'Subsea System 7' is a standard surface treatment based on 2-component epoxy paint. Painting is not suitable for steel pressure containers because the coating cannot be used on the O-ring grooves which will thus corrode.
- **Anodized aluminium** may be useful for short time exposure to seawater. Anodized parts should be galvanically isolated from other metals.

Note for if a surface should be visible under water bright colours should be used (white or yellow). The standard colour used for subsea equipment in the Oil and Gas industry is yellow RAL 1004.

Figure 7.4 Visibility and contrast under water (structure coated with RAL 1004)

7.7 Galvanic isolation

If dissimilar metals must be used together, then they must be galvanic isolated from each other. Below are shown some examples of isolation methods.

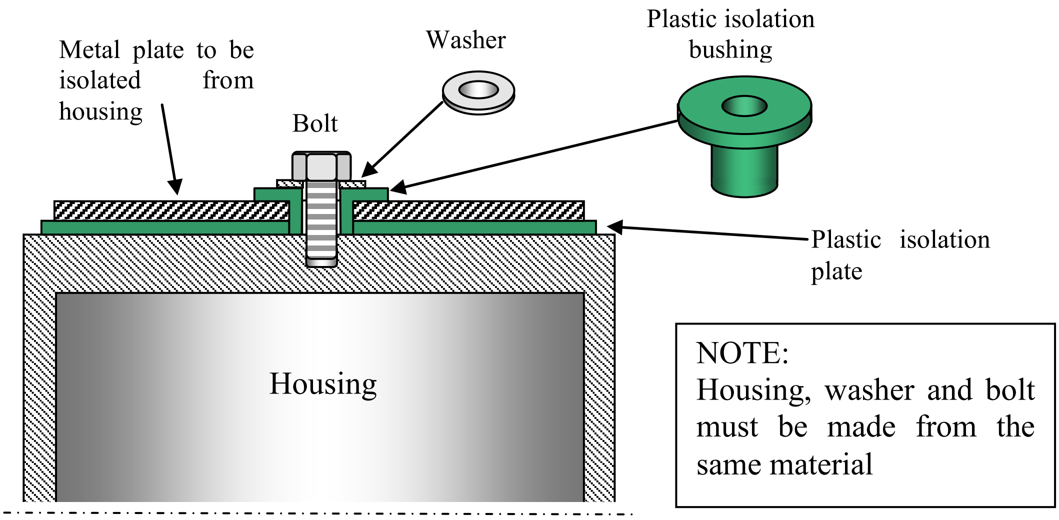


Figure 7.5 Dissimilar metal plate isolated from housing

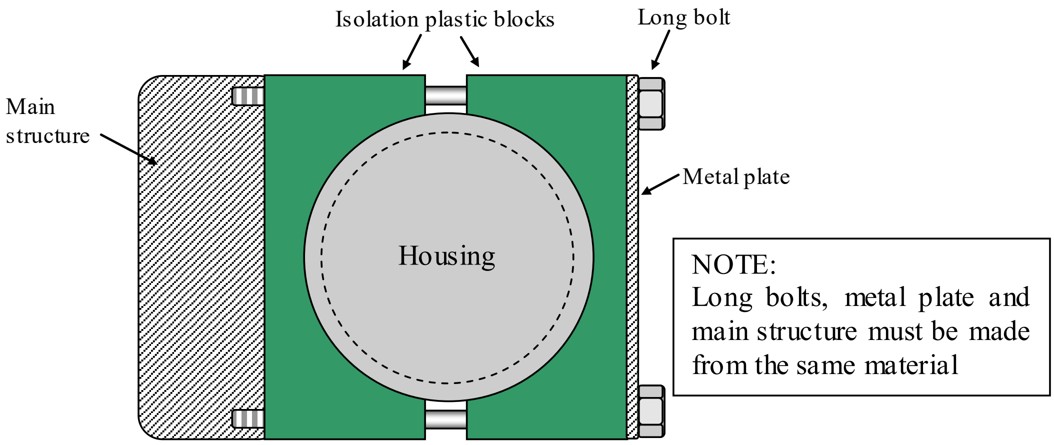


Figure 7.6 Dissimilar metal structure isolated from housing

8 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 straightforward 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 that must be opened after pressure testing.

8.1 Basic considerations

A common practice is to dimension and test pressure vessels for 1.5 x working pressure for safety reasons. However, over dimensioning containers adds weight. Always pressure test prototypes.

Size depends on what goes inside. Plan internal layout to minimize size and to keep dimensions and weight down. However, make sure that inserting and fastening the contents is still straightforward.

Choice of material will depend on environmental factors and expected duration of submergence.

The integrity against water ingress depends on two major failure aspects.

1. Structural collapse of the enclosure due to external over pressure
2. Leaking seals

Figure 8.1 An unpleasant view when opening a subsea enclosure

Leaking seals is most critical for shallow water applications as many O-ring and gasket seals actually becomes tighter with increase pressure. The most difficult leaks to detect is creeping leaks that may take long time to develop, these will normally not be detected by pressure testing for limited time.

Sometimes a water ingress detector (two electrodes in the bottom of the enclosure sensing the difference in conductivity when immersed in salt water) can flooding of the electronics if it is possible to recover the enclosure before it is too late. Other times the inside arrangements (electronics attached high up and screened from water droplets) may prolong the operational life if the enclosure or connectors are subjected to creeping leaks.

8.2 Pressure sealing approaches

Insert lids with O-ring grooves are 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.

NOTE: include a means to grip the lid so it can be lifted off. The O-rings and internal/external pressure difference may make the lid sit very hard. 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.

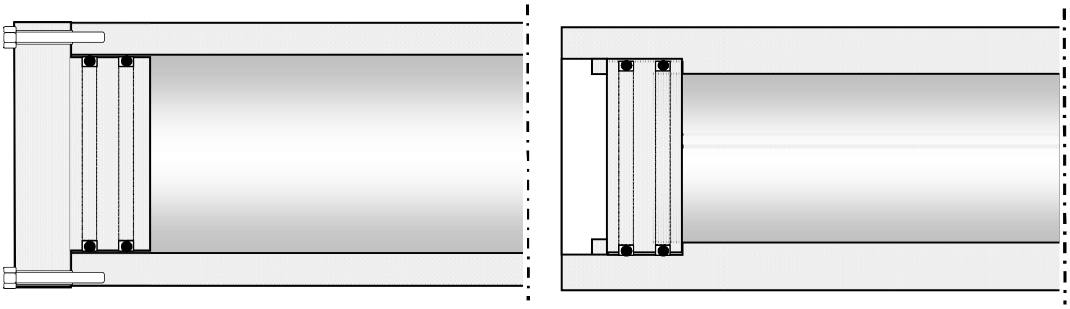
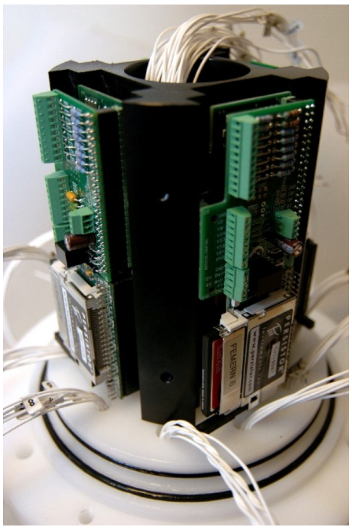


Figure 8.2 Insert lid container: Held in place by bolts (left) or by locking ring (right)

From mechanical strength, a cylinder enclosure is preferred. For larger diameters, the wall thickness must be increased. 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 that 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, squeezed cable leads is probably one of the most common reasons for failure.



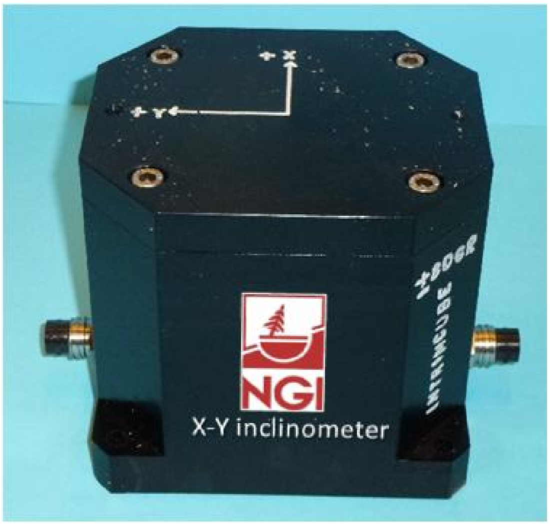


Figure 8.3 (Left) Electronics fixed to lid and hooked up to bulkhead connectors on the lid. (Right) Inclinometer housing with connectors on the body and no outfitting attached to the lid.

Other alternatives for securing the enclosure lid(s) are shown below:

Figure 8.4 From left to right, Lid flange plates with through bolts, external stress rods and enclosure with threaded lokcing ring/collars

Glass sphere containers are used without O-rings and bolts and the seal is obtained between the edges when the two half spheres are squeezed together. This solution is normally used for deep waters and the air must be pumped out from the sphere to keep the halves together prior to immersion.

Figure 8.5 Glass spheres with protective shells

8.3 Internal pressure relief

Mainly relevant for deep-water installations.

Three sources may cause internal pressures in the containers:

- Leaky container bringing seabed pressure back to the surface. Hazardous when opening for repair/service.
- Internal corrosion/chemical effects. E.g. some seawater intrusion causing corrosion and gas production. Battery damage creating gas production.
- Mechanical: pressure build-up (or suction) when trying to assemble the container or take it apart. (O-rings make a seal preventing the air from going in or out)

For large containers (for example battery packs), pressure relief may be beneficial and provided by:

- One-way valve to bleed high internal pressure. Verify that this valve is tight the other way (e.g. into the container).
- Seal screw/release valve on container which can be opened by personnel

For shallow water application, it is sufficient to open the containers with care.

8.4 Pressure compensation

Mainly used for submerged solenoid valve packs.

Oil filled pressure compensated system are often used where electrical or mechanical parts part tolerate oil submergence and the ambient pressure. Pressure compensated systems can be made much simpler and lighter than pressure tight containers, and the seals are simply required to keep the oil in place instead of having to seal against high pressure. Pressure compensated systems open up the possibility of using other materials than metal or glass. Machining tolerance requirements are also much less stringent. Cabling can also be much simpler: wire leads inside of a flexible tube filled with oil (e.g. like a garden hose sealed at the connector using a hose clamp), instead of expensive subsea cables and watertight cast terminations.

An example: Oil filled electrical junction box with attached flexible / compressible oil filled cable conduits, where the conduits act as the pressure compensating media in the system. No pressure tight seals are required and the container does not have to resist high ambient pressure since internal and external pressures are equalized. It is, however, very important that the system is totally saturated with oil (no air pockets left) unless the pressure compensator has large volume capacity.

NOTE: Verify that all components can tolerate immersion in oil and the expected ambient pressure at deployment!

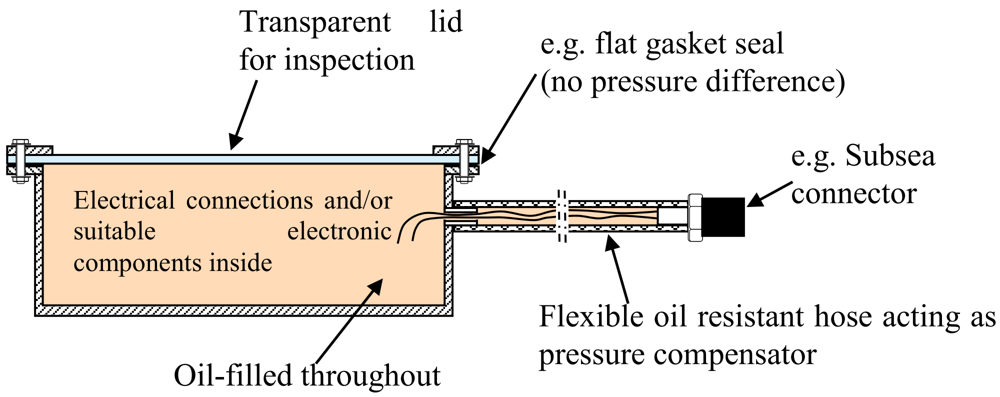


Figure 8.6 *Example of oil-filled pressure compensated system with flexible hose acting as compensating medium*

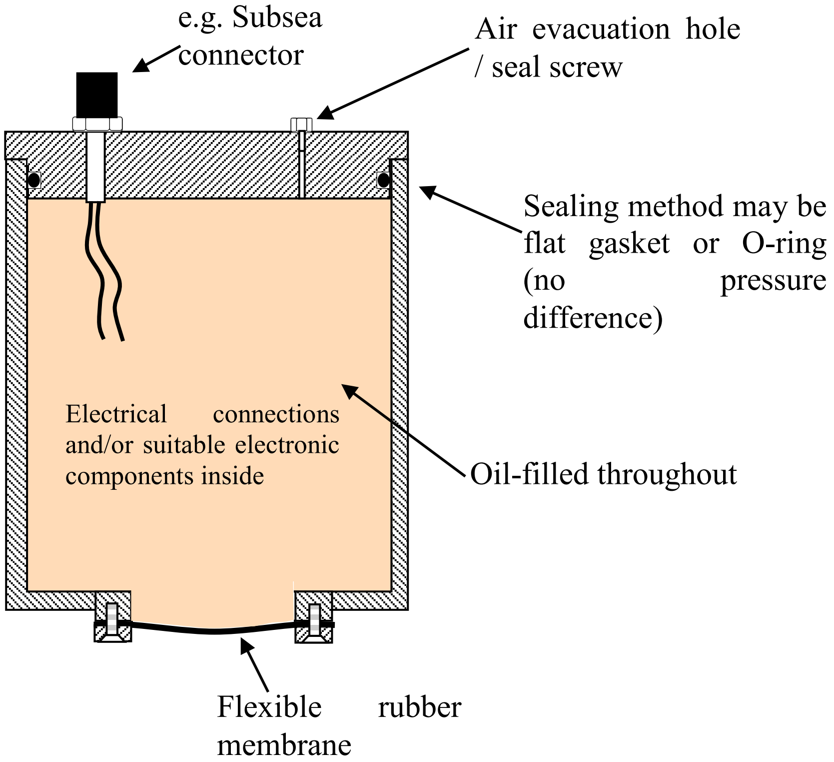


Figure 8.7 *Example of oil-filled pressure compensated system with flexible rubber membrane acting as compensating medium*

8.5 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
- Glass-to-glass for high pressure applications (glass containers only)

Incorporate 'double barrier' philosophy when possible, e.g. use two O-rings to make the seal. When using pressure compensated systems, the oil itself is one of the barriers, and if available space is tight it is OK to use only one O-ring or gasket.

8.6 O-rings

- 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 (seawater, oil, etc.) – check!
- O-ring dimensions (thickness) influence sensitivity to small particle impurities, and "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.

8.7 Selection of grease for seals and connectors

Silicon grease most commonly used.

Molycote 111 (clear): Most common. However, if used over long timespan (under high pressure?) this grease may crystallise and become hard, thus causing leakage.

Molycote 44 (pink): Also frequently used. Does not tend to crystallise over time. Is more lubricating than 111 and will penetrate O-rings and may cause slight swelling; however, this is usually not a big problem.

Vaseline: Previously quite commonly used. However, due to its temperature sensitivity (becomes harder when cold) it is no longer used by NGI.

Aqualube: No experience with this at NGI, however many ROV operators use this for their ROV instrument containers and have recommended this highly to NGI.

9 Subsea connectors and cables

Leakage integrity of subsea connectors and cables is also very important to ensure long term functioning of the subsea instrumentation system

9.1 Subsea connectors

Subsea connectors are defined as bulkhead (BH) connectors if mounted on an enclosure and inline (IL) if they are moulded on a cable end. A connection is made up by a male (with pins) and female connector part. The standard convention is that a connector which can be powered ("Hot end") should be female, although this may not always be the case. There is wide range of subsea connectors with different layout and function available in the market. For the subsea instrumentation and application relevant in the context of this report, we are focusing on four major types which are further described below:

Type 1 Neoprene connectors with overmolded pin seals

This is perhaps the most common (and less costly) option. These connectors are normally not internally water blocked (continuous pins) they can be wet mated (not recommended) and nor supplied for fibre optic lines. The connectors should be fixed with locking sleeves. NGI use the micro type of connector, which is recommended for up to 8 pins configuration. Some of the biggest suppliers are Seacon (wetcon), Subcon, Impulse, Burton......all brands are more or less similar.

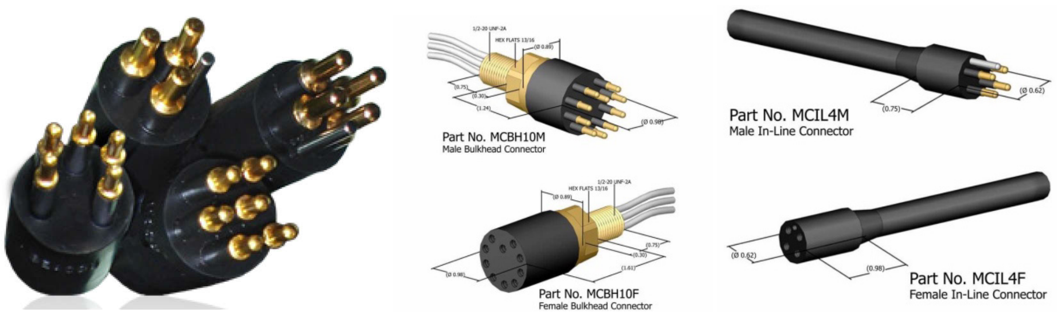


Figure 9.1 (From left to right) Neoprene connectors with overmolded pin seals (Wetcon Micro). Outlines of Bulkhead and Inline connectors

Type 2 Metal shell connectors

These connectors are more robust and normally water blocked. They must be dry mated, available both for electric and fibrotic connections. Suitable for critical operation and for larger amount of pins than the overmolded connector.

Figure 9.2 Metal shell connectors from Seacon 55 series (left) and Burton 5500 series (right)

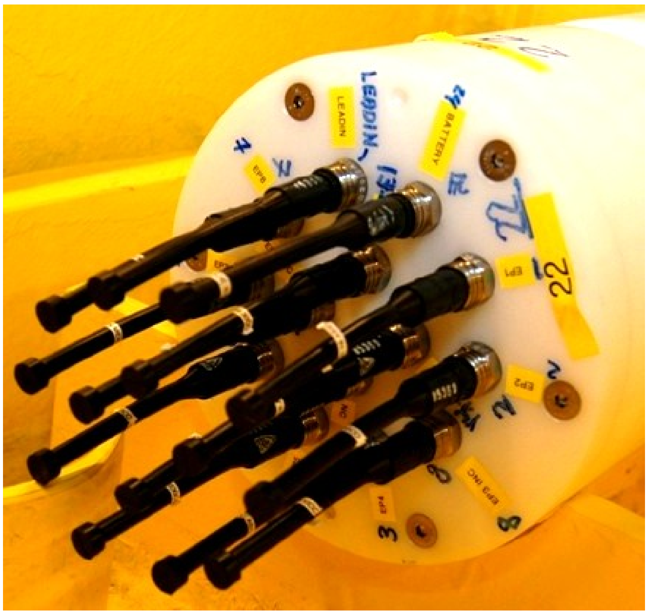


Figure 9.3 Not mated connectors should always be protected by dummy connectors!

Type 3 Penetrators

These provide a fixed connection and normally used for continuous fibre optic lines through a bulkhead (enclosure).

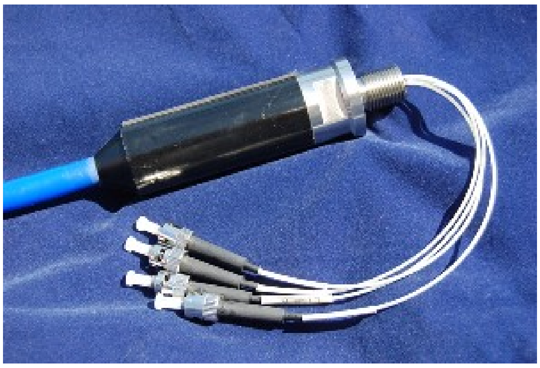
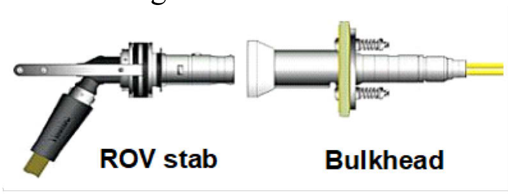


Figure 9.4 Fibre optic penetrator

Type 4 Subsea mateable connectors

This is the most expensive type of connector made for safe underwater mating and disconnection usually by ROV, the connector is oil filled with several barriers. The bulkhead connectors are usually mounted on a panel providing rigid support for ROV mating.



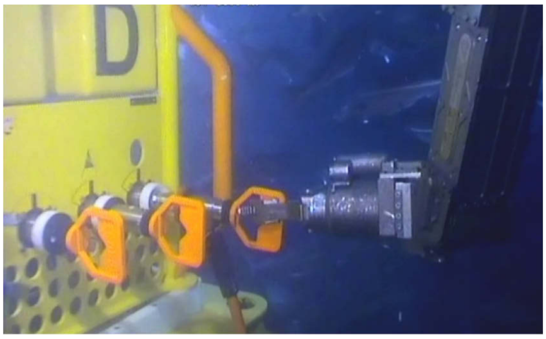


Figure 9.5 Subsea mateable connection with ROV stab on cable end with and panel mounted bulkhead receptacle

NGI use the Tronic type of connectors but there are also more affordable brands which are suitable for diver operation, also inductor type of connectors are now available in the market.

9.2 Subsea instrumentation cables

The subsea connector tails are usually moulded on to the signal cables. There is also a wide selection of underwater cables available in the market. For these types of applications NGI use Kevlar reinforced cables with Polyurethane (PUR) jacket. This is a robust but yet flexible and light cable type suitable for long-term immersion in salt water. The PUR jacket is suitable for overmolding can be exposed for seawater/sun light exposure and resistant against abrasion.

Composition:	Solid PUR jacket and Kevlar braiding
Electrical:	4 x twisted pairs
Outer Diameter:	12,9 mm
Breaking strength:	1000 kg
Bend radius:	138mm (Static)
Bend radius:	201mm (Dynamic)
Weight in air:	250kg/km
Weigh in water:	60 kg/km

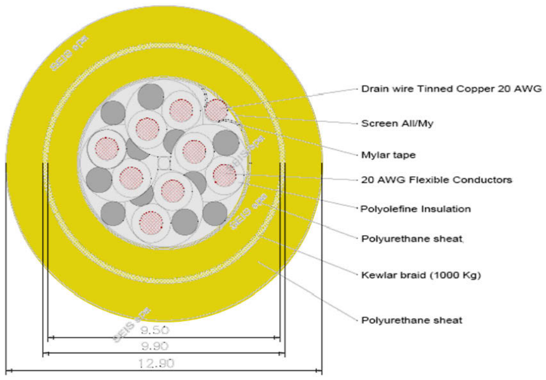


Figure 9.6 Example of configuration and specification for a typical Subsea Instrument cable (PUR/Kevlar)

Figure 9.7 Lead in instrument cable assembly with moulded neoprene connector ends

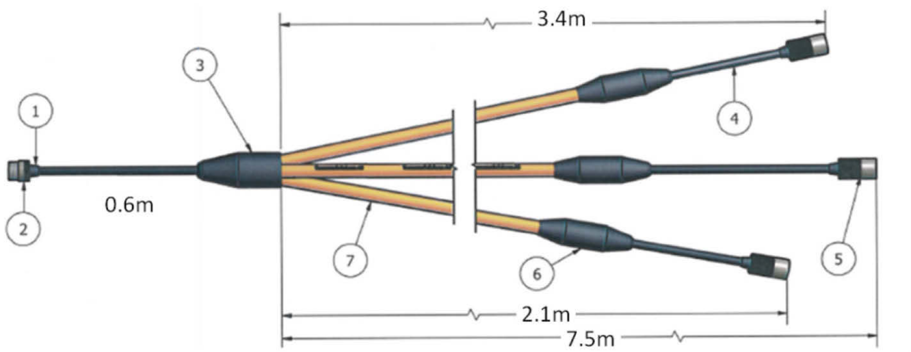


Figure 9.8 For hooking up one lead in cable to several instrument enclosures moulded splits can be used (more cost efficient than using subsea junction boxes)

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.

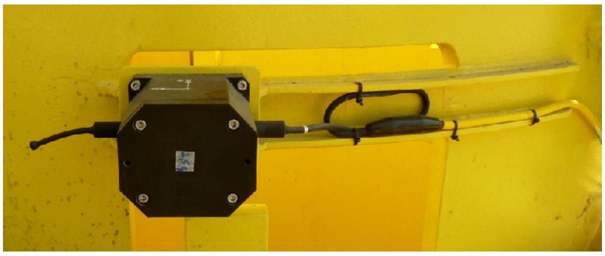


Figure 9.9 Example of proper cable routing

10 Electric system design

Some general aspects:

10.1 Signal and cable routing

For longer transmission distance and for hook-up of sensor arrays the sensor signal must either be:

- Current loop (4-20 mA) 2 or 3 wire system
- Vibrating wire (frequency)
- Digital for example RS485, CAN-BUS (RS232 is usually not suited for data transmission through long lines)

Some sensor systems also work with Ethernet output.

In general, a cable does three important things to a signal, it

(1) Attenuates the signal,
(2) 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) Exposes the signal to electromagnetic energy from other sources that can enter the cable and pollute the signal with noise.

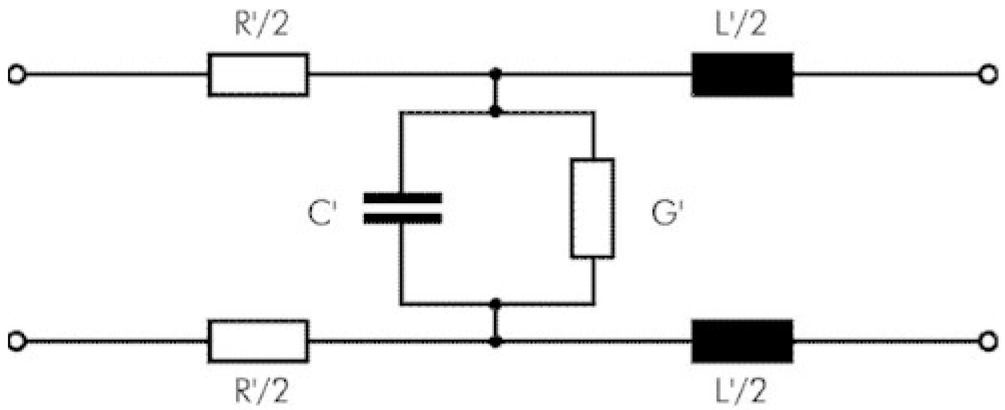


Figure 10.1 The cable in theory

For most signals twisted pair wiring is a good solution and propvides the best shielding against 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.

10.2 Grounding

One of the basic electronic laws tells us at 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 analogue 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 for most often result in noise on the analogue lines. To overcome this problem, use different ground loops for each of the different categories of electrical equipment.

Star ground 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.

On other problem with ground can arise when metallic under water cylinders 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 seawater, an additional ground loop is introduced. This may result in additional noise and corrosion problems.

For subsea instrumentation it is recommended to not connect the ground to sea.

10.3 Mains power supplies

There are two main power supplies on the marked: 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 top 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 below.

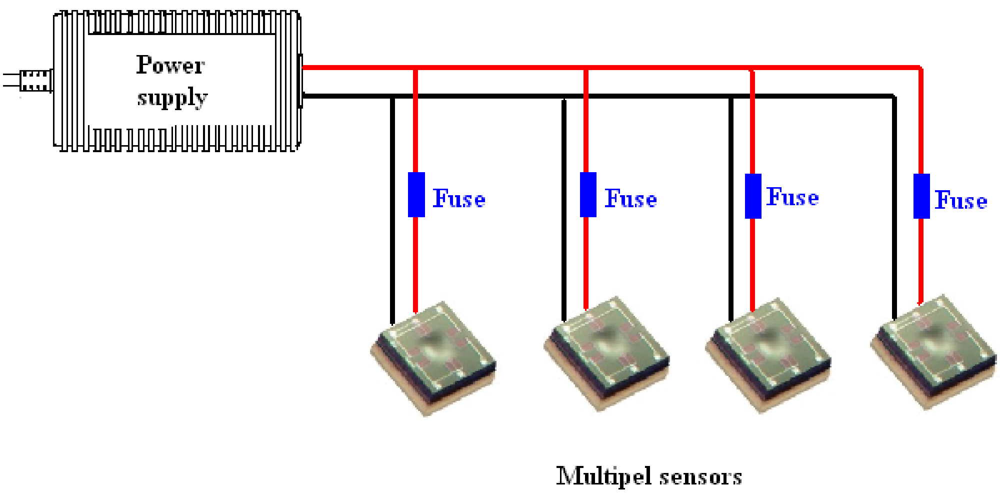


Figure 10.2 Main power supply with individual fuses for each unit

Isolating power supplies should be used for safety. Most linear and switched power supplies are isolating power supplies, meaning 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 on 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. Thus it is recommended to use fuses on both sensors sides of a current loop.

Figure 10.3 Burnt and galvanic corroded connector caused by stray currents in the water probably originating from a broken cable isolation

11 Testing and documentation

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

IMPORTANT: A test that is not documented in written form has no value at all in documenting quality control of the system. The documentation does not need to be extensive, it can be 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:

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 look at the design concept?
- Final design drawings. Pre-production control.

Manufacturing and procurement stage

- Orders of components (Send written orders; get quotes from several suppliers if possible
- 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
- Overall system testing (functional testing) before shipping.

Pre-installation checks

These checks are necessary before the system is installed subsea or put into operation the first time. Document pre installation checks in written form.

- System health/calibration check. Verify that all aspects of the system are operationally normal.
- Electrical test Perform instrument loop test, and test isolation against earth. Check power consumption against available battery power
- Assembly checks: Visually check system that everything looks correct and not damaged (particularly after transporting of equipment). Check all subsea connectors for proper assembly and greasing (if applicable).
- Check all bolts and screws (also internally in pressure vessels) for proper tightening.
- Check proper rigging and fastening prior to deployment.

Figure 11.1 NGI seabed monitoring station checked out and deployed into the sea

12 Offshore and Subsea installation considerations

It is advised that parts of the instrumentation system is pre-rigged (mechanical components, cables and some sensor systems) to save offshore installation time. However, consider the needs for retrofit and offshore/subsea installation and maintenance operations.

12.1 Dry/ submerged weight of equipment

In general, one should try to keep weight of equipment as small as possible to make offshore handling easier. Consider the following factors that 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. for deployment of 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.

12.2 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.

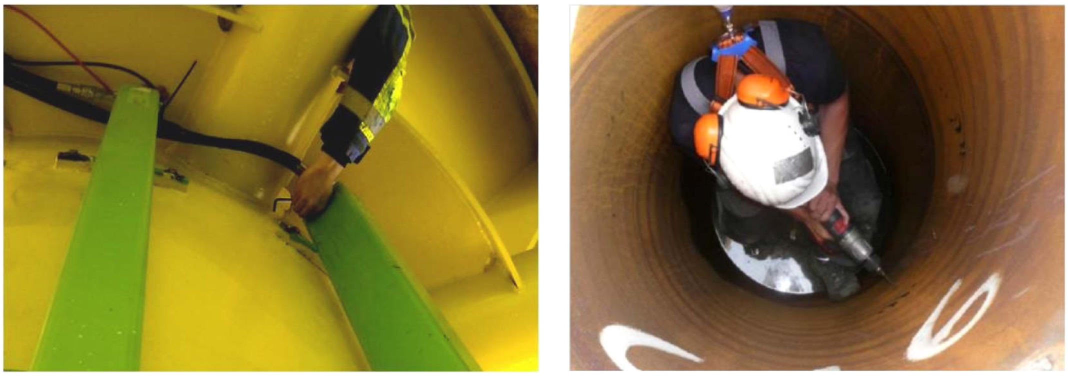


Figure 12.1 Difficult access for instrument mounting (left). Mounting instruments inside an installed offshore pile is not a comfortable or safe work place (picture from internet)

Figure 12.2 No longer a safe workplace!

12.3 System layout

Points to consider when designing a system layout

- Compact layout for handling on the vessel and during lifting through water column. Split into manageable sections if possible
- How is it installed - requirements for lifting or ROV/Diver intervention
- Access and handling by ROV/Diver, e.g. subsea mateable connectors, handles etc.
- Protection and securing equipment for rough handling
- If relevant Seabed conditions (e.g. soft mud, sand etc.)

12.4 "As installed" protection

Instrument and cables installed on the structure should if possible be protected against falling objects. For instrument systems placed on the seabed for long periods and in areas where seabed trawling takes place, some sort of protection must be constructed. A solution is shown for the NGI seabed monitoring station to the right.

Figure 12.3 NGI's seabed monitoring station with trawling shield and shallow skirts

12.5 Biofouling

Marine growth may be a problem for some hydroacoustic and mechanical systems. Special paints exist which reduce this problem, else regular service (cleaning) is required.

Figure 12.4 Sensor head before installation and with marine growth after some months of operation in tropical waters

12.6 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 structure and ability to operate moving parts. Also strength of lifting points when structure/item is to be recovered again. Corrosion of lifting slings/eyes can be a problem
- **Biofouling:** Marine growth covering visual indicators, moving parts etc. May also damage some synthetic materials. Subsea installations can also be attractive as habitat for marine life.
- **Leakage of some synthetic materials:** Neoprene plugs may leak over extended deployments (many years) due to water creeping along inside of the overmolded 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.
- **Mechanical protection:** The risk of human interference (for example fishing nets) increases as the length of time for deployment increases. The requirements for mechanical protection of the installation may need to be evaluated.
- **Long-term processes, e.g. settlements:** Check the geotechnical properties of the installation if appropriate - long term settlements, scour, induced sedimentation may cause difficulties (not sufficient slack in cables etc.)

Kontroll- og referanseside/
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