Assessment of Methods for Inspection and Instrumentation of Grouted Connection

Doc no.:	90394
Ver:	v1
Date:	14.09.2020

Document overview

Client:

Petroleumstilsynet

Document name:	**Document number:**
Assessment of methods for inspection and instrumentation of grouted connection	90394
Project name:	**Project number:**
Petroleumstilsynet – Grouted Connection	320-20083
Project manager:	**Department:**
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Abstract:

FORCE Technology Norway AS has performed an assessment of the maturity and quality of available methods for inspection and instrumentation of grouted connections between jacket and pile.

Keywords:	**Distribution:**
Ptil, Inspection, Instrumentation, Grouted Connection, Offshore, Pile, Sleeve, Jacket	

Current revision

Rev.	Date	Author	Checked by	Approved by	Reason for rev.
v1	14.09.2020	Pål Tuset / Rolf Hansson / Espen Elvheim / Julle Ekeborg	Pål Tuset	Tor Alexander Fjeldly	Issued for Information

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1 Summary

FORCE Technology has been commissioned by Petroleumstilsynet to gather and assess the maturity of the available inspection and monitoring methods for grouted connections on offshore jacket structures. The grouted connection applied in offshore jacket structures is transferring the structural load from the jacket to the seabed and soil through the pile, and is critical for the integrity of the offshore jacket structure. The grouted connection is a sandwich structure of grout between the steel pile and pile sleeve typically longer than 10m, located subsea at the seabed. Due to the structural properties of the grout, the loads are transferred as compressional load between shear keys diagonally placed on the pile and sleeve.

An update of the Norsok requirements for the grouted connection in 2013 identified additional forces that needs to be considered when a grouted connection i designed. These are bending moments and shear forces and come as an addition to the axial and torsional loads.

Recalculations according to the new requirements of the grouted connections on jackets deigned previous to the 2013 update, show that some of the grouted connections do not meet the margins to services life. These are that are installed and fully operational offshore, hence there is a need to determine the status of these grouted connections through either inspection or monitoring or a combination. Ideally such methods should provide information of the ongoing degradation early in the degradation process, making it possible to predict remaining service life, but should at least be able to detect that a grouted connection has fully degraded and lost its structural capacity. This is important to understand when such methods are used in an integrity management plan for the jacket to address the degradation of the grouted connection.

FORCE Technology has collected information on inspection and monitoring methods for grouted connections by directly contacting relevant companies, by searching the world wide web, and by advertising in social media.

Studies perform by FORCE Technology show that the degradation of the grouted connection starts towards the seabed. Due to the complex structure of the grouted connection and the difficult access to the area of primary interest towards the seabed, only three inspection methods have been brought forward of which two are considered field proven and only one may be predictive if deployed at different locations. One inspection technique is in the concept phase and may be predictive if the detection level proves to be adequate.

Of the five different monitoring methods brought forward, one is field proven and predictive in combination with a structural assessment, three are considered field proven and able to detect a degraded grouted connection. The last method is purely data processing using suitable sensors packages and includes damage detection techniques, outlier identification, machine learning, non-linear analysis and a combination of identifiers, which is considered to be a proven concept with a potential of being predictive.

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2 Introduction

2.1 General

Design of a grouted pile connection on an offshore jacket designed before 2013 was only based on transfer of axial and torsional loads from the jacket to the pile, according to the requirements in Norsok [1]. In 2013 new design requirements were added to Norsok [1]. The grouted pile connection is to be designed for:

- Failure of grout to pile interface shear due to axial load and torsional moment.
- Failure of the grout due to compressive stresses at the lower end of the grout due to bending moment and shear force in the pile.
- Fatigue of the grouted connection for alternating interface shear stress due to axial load and bending moment in the pile.
- Fatigue of the grout due to contact pressure and friction forces creating shear stresses at the lower end caused by bending moment and shear force in the pile.

The purpose of the grouted pile connection is to transfer the load from the jacket down to the pile and into the seabed i.e. the support of the jacket. A failure in this connection may jeopardise the complete installation, hence the integrity of the grouted connection is crucial.

Re-calculations according to the new 2013 requirements of older installations designed with acceptable margins according to the pre 2013 requirements has shown high utilisations to a degree that the grouted connection may fail. Since these connections are installed and the recalculations cause concern on the integrity of the grouted connection, inspection or monitoring of the connection is needed to get control of the status of the connection and to ensure the integrity of the connection.

The nature of a grouted connection with the sandwich structure of steel, grout and steel, the different mechanical properties of the steel and the grout, and the method of transfer of the loads between the two steel layers, makes the grouted connection difficult to handle.

Although there has been a requirement in the Norsok standards [1] to inspect the grouted connections yearly, the uncertainty introduced by the new requirements, additional load cases and the results of the recalculations, increases the focus on what available methods exists for inspection and monitoring of the grouted connection and what is their ability to predict or detect a failure, since these methods become instrumental in knowing the actual condition of the asset.

This document assesses maturity and quality of available methods for inspection and instrumentation of grouted pile connections.

The assessment includes the following:

- Create an overview of available inspection methods
- Assessment of maturity, quality and reliability for identified inspection methods
- Create an overview of available instrumentation methods
- Assessment of maturity, quality, reliability and long-term characteristics of identified instrumentation methods.

Chapter 2 of this document provides an introduction to the subject of the study, how information has been collected and describe work to collect background information and parameters used for the evaluation of the inspection and instrumentation methods.

2.2 Grouted connection

2.2.1 Introduction

A typical grouted connection between pile and sleeve for an offshore jacket structure is showed in Figure 2-1. The space between pile and sleeve is filled with grout and weld beads (shear key's) are made on both pile and sleeve to increase the load capacity of the connection.

The purpose of the grouted connection is to transfer the load from the jacket down to the soil through the pile. The grouted connection shall according to the updated Norsok requirements in 2013 [1] be designed for axial load, shear load, torsion and bending moment. For jacket designs before 2013 the design required only that axial and torsion loads were accounted for. Recalculating these early designed and installed jackets and their grouted connections according to the present requirements show for many cases that the connection does not have the required margin to failure, as some of these loads were not part of the original design.

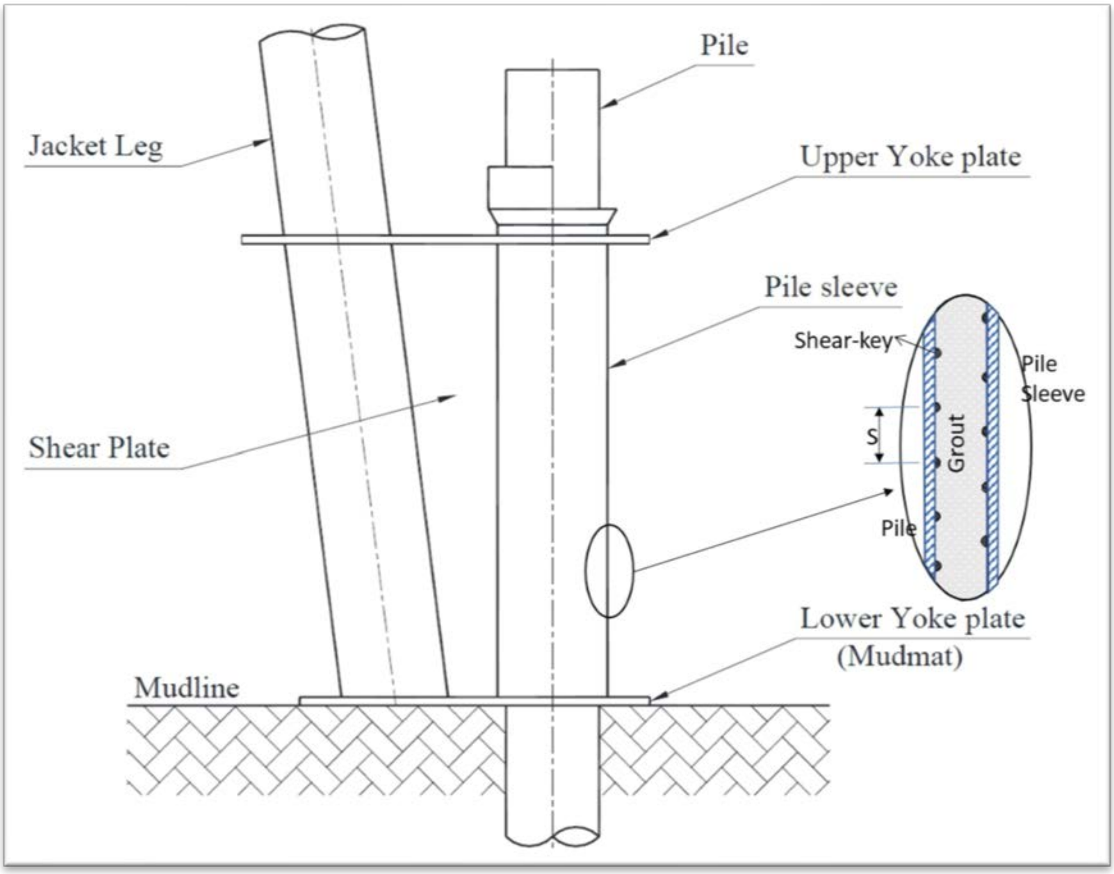

Figure 2-1 Pile / sleeve connection showing the jacket leg, the upper and lower yoke plates, the pile, and the insert showing the weld beads and the pile and the pile sleeve forming the shear keys. Illustration from N-004.

2.2.2 Pile cluster

There are different designs of the pile sleeve connections ranging from a single pile per leg to 2 or 3 piles per leg or for instance 7 as shown in Figure 2-2. The method to transfer the load from the jacket to the pile differ between designs to achieve a robust jacket design, for instance by braces or through the use of shear plates as shown in the Figure 2-2.

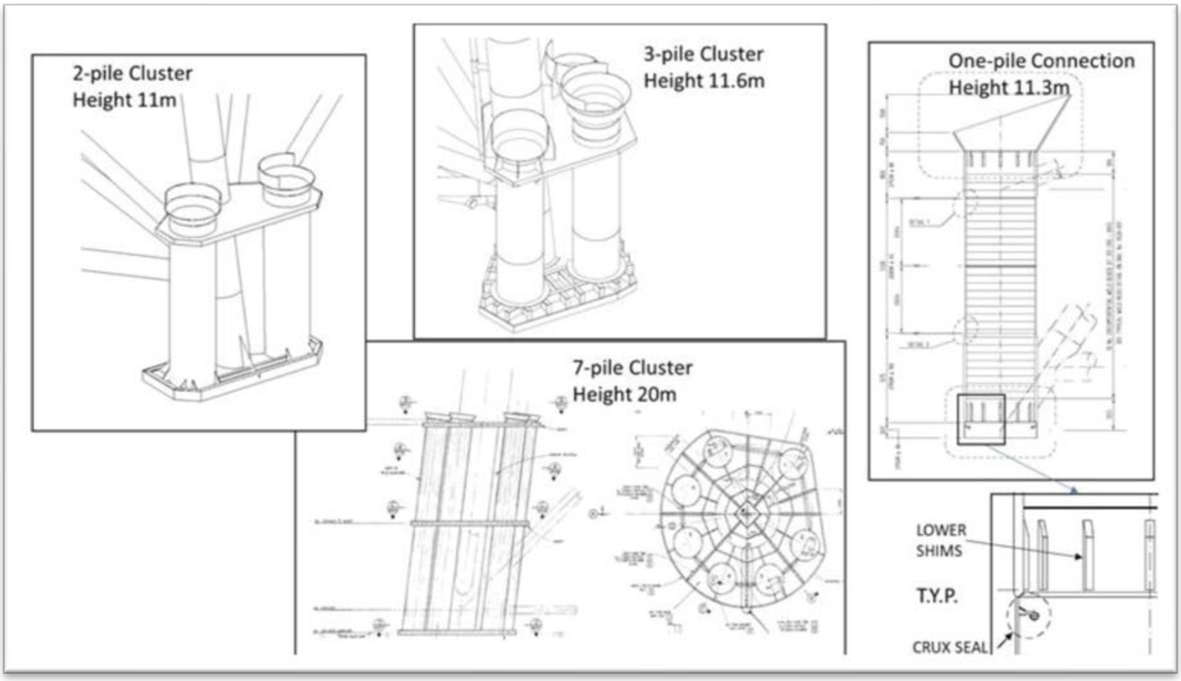

Figure 2-2 Different pile clusters showing a "one pile" connection top right, to a 7 pile cluster connection at down centre. Note the pile heights ranging from 11m to 20m for these real cases. The insert shows the lower details of the "one pile" connection with the Shims (centraliser) and the Crux seal. Illustration from Aker BP & Equinor.

The main difference between a "one pile" connection and "multi pile" connection is shown in Figure 2-3. For the one pile connection the platform main bracing is connected directly to the pile sleeve while for more piles a pile cluster arrangement is applied and the load transfer is through Yoke and shear plates.

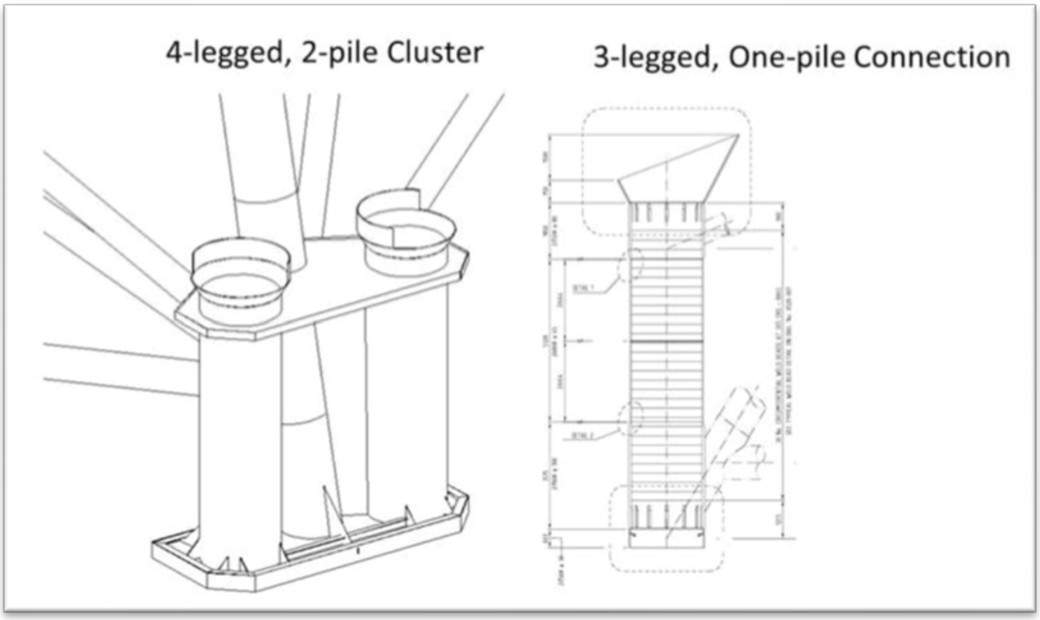

Figure 2-3 For a "one pile" connection on a 3-legged jacket, the main brace is typically directly connected to the sleeve (right), but for a "multi pile" cluster on a 4-legged jacket the connection to the main brace is through Yoke and shear plates (left). Note the horizontal lines of the weld beads in the "one pile" connection. Illustration from Aker BP & Equinor.

2.2.3 Considerations regarding jacket designs

Figure 2-3 illustrates two different jacket designs, a 3-legged jacket and a 4-legged jacket. Depending on depth, environmental conditions like waves, current and wind, weight, soil conditions, purpose of the jacket, etc., jackets are designed with different number of legs and different number of pile connections per leg. The behaviour of these jackets will be different, and this difference should be taken into account when the appropriate inspection or instrumentation method is evaluated. It is expected that a failure of one grouted connection on for instance a 6-legged jacket, with one or more grouted connections per leg, will be much more difficult to detect than a failure of a grouted connection on a 3-legged jacket with one pile per leg due to symmetry and redundancy. If a failure occurs on a 3-legged jacket, it will be visible in the global behaviour of the jacket, and it is essential to know in advance that this is developing. For a 6-legged jacket the other connections may take up part of the load, and hence it will be more difficult to detect loss of a connection, and the loss may be less critical to the integrity of the jacket.

2.2.4 Degradation of a grouted connection

In order to evaluate different inspection and monitoring methods with regards to establishing the condition of the grouted connection, it is important to understand and describe how a grouted connection will degrade and finally fail. To establish a common understanding of the grout degradation and the consequences of such degradation FORCE Technology have performed some assessments of grouted connections as part of the study:

- Degradation of grouted connection with shear keys
- Natural frequency changes of the jacket due to degradation of the grouted connection
- Relative displacement between pile and sleeve due to degradation of the grouted connection
- Topside displacement due to degradation of the grouted connection

The purpose of “Degradation of grouted connection with shear keys” is to get an indication where in the connection the grout starts to degrade, and signatures of the degraded grout.

The purpose of “Natural frequency changes of the jacket due to degradation of the grouted connection” is to estimate the changes in the natural frequencies of the jacket as the connection goes from a fully functional connection through partially degraded to full failure.

The purpose of “Relative displacement between pile and sleeve due to degradation of the grouted connection” is to get an indication of relative displacement between pile and sleeve when the jacket is exposed for 1-year storm conditions combined with degraded grout.

The purpose of “Topside displacement due to degradation of the grouted connection” is to get an indication of topside displacement when the jacket is exposed for 1-year storm condition combined with degraded grout

The results are presented in section 2.5, 2.6, 2.7 and 2.8 as summaries. The details are presented in Appendix B and Appendix C.

2.3 Methods for identifying available methods

To establish a list of available inspection and monitoring methods for grouted connections on offshore jackets, FORCE Technology has followed three different routes:

- Performed search on the web for key words and phrases, following any leads to identify suppliers
- Direct communications to companies and contact persons that work with subsea non destructive testing, subsea structural monitoring, performs subsea inspection maintenance and repair, IMR, or companies that plans such activities
- Advertising in social media

2.3.1 Search on web

Search on the web did not provide new candidates for the study. Based on the findings FORCE Technology do believe that the grouted connection does not have the same attention world-wide as it has in Norway.

2.3.2 Direct contact to possible companies

Relevant companies based on FORCE Technology’s knowledge of the market in non destructive testing, and structural health monitoring and in particular specialised in subsea applications have been contacted by email where the purpose of the study was presented and any relevant information requested. Example of the email is shown in Appendix A.

The companies and contact points have been followed up by e-mail and direct phone calls, in order to find information relevant to the study. FORCE Technology received most of the relevant information through this approach.

2.3.3 Advertising in social media

The study was advertised and shared on social media, to reach more broadly for information on existing or possible inspection and monitoring methods. The advertising and detail information is showed in Appendix A.

The advertisement was addressed to recipients in Norway, Houston, London, Aberdeen and Perth.

Some companies that were in line to be contacted directly, responded first to the advertisement. Some of the responses showed an interest, but no present experience with addressing existing grouted connections.

2.4 Technology readiness level

Part of the scope of the study is to rate the maturity of the available technology. A natural method or scale for the maturity of technology is the Technology readiness level as defined in API 17N Subsea production system reliability, technical risk, and integrity Management [2], ranging from a concept to a field proven technology or, the technology maturity assessment in the DNVGL recommended practice for Technology qualification [3] where the technology and the application is ranged by degree of novelty to define the need for further qualification before it can be deemed field proven. The technology readiness level does not describe the suitability of the method to be either predictive or detective, except through descriptions of the method and how the results can be used where such statements will form the technology readiness level.

Table 2-1 Technology readiness level from [1] ranging technology from a concept to a field proven system

TRL	API 17N
0	**Unproven Concept** Basic R&D, paper concept
1	**Proven Concept** Proof of concept as a paper study or R&D experiments
2	**Validated Concept** Experimental proof of concept using physical model tests
3	**Prototype Tested** System function, performance and reliability tested
4	**Environment Tested** Pre-production system environment tested
5	**System Tested** Production system interface tested
6	**System Installed** Production system installed and tested
7	**Field Proven** Production system field proven

2.5 Degradation of a grouted connection

Understanding the degradation mechanism in a grouted connection and how it propagates is crucial when it comes to assessing the detection methods and their ability to detect and monitor the progressing degradation, i.e. to predict a future failure of the grouted connection if the degradation can be detected and followed early in the process, or if the method only is able to detect a full failure having happened.

To understand the degradation mechanism of the grouted connection, FORCE Technology has done a simplified assessment based on two different ways to transfer the load from the jacket into the grouted pile connection:

1. The load from the jacket is transferred into the grouted pile connection by a brace
2. The load from the jacket is transferred into the grouted pile connection by a shear plate

The stress variation seen in the grouted connection depends of how the load from the jacket is transferred to the pile, but the results indicate for both cases that a failure of the grout is most likely initiated at the bottom towards the seabed and escalates up the pile.

From Norsok [1] it is known that external loads like axial loads, bending moments and torsion applied to the grouted connection may crush the grout, this is expected to be more critical the closer you get the mudline. These sections close to the seabed are stiffer than the sections higher up on the connection and hence the stress level will be higher.

The details are presented in Appendix B.

2.6 Natural frequency

A possible method to monitor and detect degradation of a grouted connection is to measure the natural frequencies of the jacket and changes to them. To be able to assess the ability of such monitoring methods to detect the progress of a degraded grouted connection, we need to estimate how a damaged grouted connection will influence the natural frequency.

As a part of our evaluation program Force Technology has investigated degradation of the grouted connection for two platform configurations.

- 3-legged jacket with one pile in each corner
- 4-legged jacket with 2-piles in each corner.

Figure 2-4 show a typical Pile/Sleeve connection for a 4-legged platform with 2-piles in each corner.

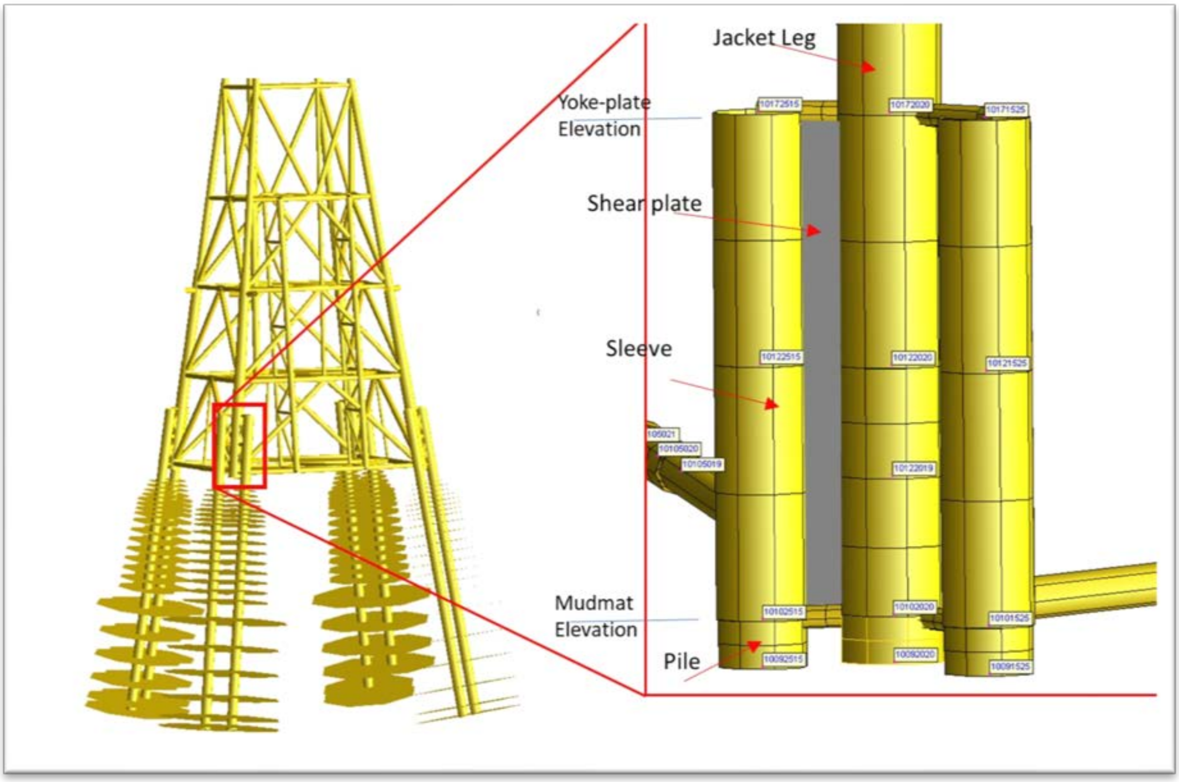

Figure 2-4 A pile model (left), and the pile and sleeve nodes (right) for a 4-legged jacket with 2-piles at each leg used in the model to characterise changes in the natural frequency with degraded grouted connections. Illustration from FORCE Technology.

In the analyses the pile and sleeve are modelled as separate beam elements and connected by nodes using master-slave coupling. The pile nodes as master nodes and sleeve nodes as slave nodes. The slave node's degrees of freedom (DOF) may be fully dependent on the master's DOF, or fully released, i.e. in order to model intact and total damaged grout respectively, ref a) and c) in Figure 2-5.

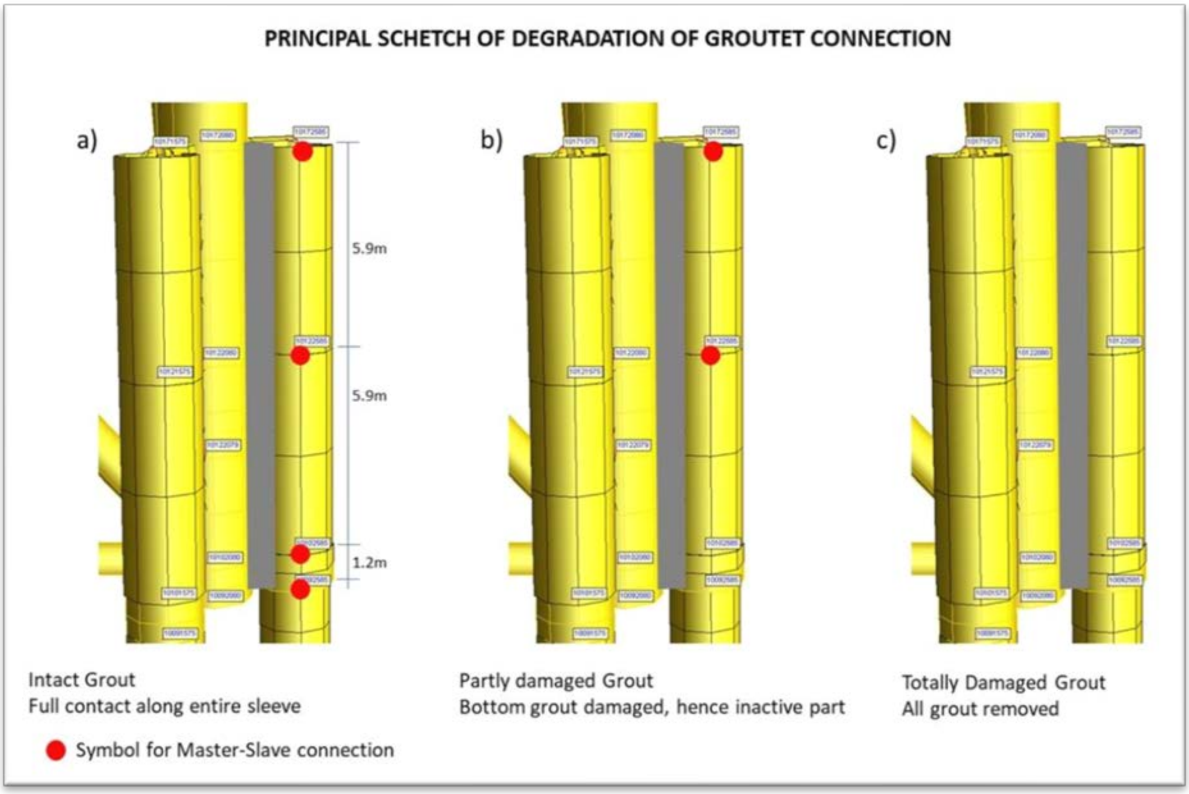

Figure 2-5 Different levels of degraded grouted connection, from the Intact grouted connection (left), the partially damaged grouted connection (middle), to the fully degraded connection (right). The example is for the 4-legged jacket with two piles per leg. The red dots illustrate master-slave connection nodes between pile (master) and sleeve (slave) used to simulate the change in grouted connection at the node. Illustration from FORCE Technology.

To investigate how the structure will respond to different stages of a degraded grouted connection several structural analyses has been performed for both jacket structures, 3-legged and 4-legged. The stages investigated, ref Figure 2-5, are Intact grout a) with no degraded grout, partly damaged grout b) starting from the bottom with degraded grout to a level lowest Master slave connection and full failure in grout c). The partly damage grout levels for the 3-legged jacket is 20%, 60%, 75% and 99% and 10%, 55% and 99% for the 4-legged jacket.

The results from the analyses show that for partly damaged grout the changes in the global behaviour of the jackets natural periods and global displacement using linear theory, is very small. Significant change of linear natural periods and global displacement is first seen when the grout is fully damaged.

The details are presented in Appendix C.

2.7 Relative displacement between pile and sleeve

One of the proposed methods to monitor the grouted connection is by monitoring the relative displacement between the pile and the sleeve. In order to evaluate the method, FORCE Technology has performed a simplified assessment to estimate the relative displacement between pile and sleeve for two different kind of jackets:

1. 3-legged jacket, one pile per leg, braces
2. 4-legged jacket, 2-piles per leg, shear plates

For partial degradation of the grouted connection the relative displacement between the pile and sleeve is up to ~3mm for 3-legged jacket and up to ~6mm for 4-legged jacket. When the connection is destroyed the displacements increase to ~5mm and ~60mm respectively.

The partly damage grout levels for the 3-legged jacket is 20%, 60%, 75% and 99% and 10%, 55% and 99% for the 4-legged jacket.

The displacement is based on 1-year storm condition and is estimated from the model close to the mudline.

Note that this is an indication, the displacement is highly dependent of the geometry of the connection.

The details are presented in Appendix C.

2.8 Topside displacement

It is expected that the topside displacements will change due to changes in the grouted connection. To estimate the sizes of the displacements FORCE Technology has performed a simplified assessment of two different kind of jackets:

1. 3-legged jacket, one pile per leg, braces
2. 4-legged jacket, 2-piles per leg, shear plates

The changes in horizontal displacement based on partial damage of the grouted connection is up to ~7mm for the 3-legged jacket and up to ~5mm for the 4-legged jacket. When the connection is lost the total horizontal displacement is >7m and ~120mm, respectively. The estimated total horizontal displacement at intact condition is ~450mm and~70mm, respectively.

The partly damage grout levels for the 3-legged jacket is 20%, 60%, 75% and 99% and 10%, 55% and 99% for the 4-legged jacket.

The estimated displacements are based on 1-year storm condition.

Note that this is an indication, the displacement is highly dependent of the jacket geometry and pile design.

The details are presented in Appendix C.

3 Inspection

3.1 General

The study is highlighting the ability to detect anomalies in the grouted connection by inspection or monitoring methods. A grouted connection for an offshore jacket is by nature a geometry that is closed for volumetric inspection and is subsea towards the seabed. The integrity issues that are relevant for the grouted connection makes it desirable to have an inspection method able to inspect the connection from the outside and detect initial degradation for early warning of possible failure. The most common inspection methods; Ultrasonic puls/echo technique, radiography/CT technique or electromagnetic methods will probably be difficult to use in a conventional way for local detection of a degrading grout. The study aimed at finding any supplier or community that has used more novel methods/techniques or used conventional methods in a more unconventional manner to detect inner anomalies in the grouted connection, and by this provide early warnings of beginning failure, or beginning degradation that possibly can lead to failure.

Unfortunately, it has proven to be difficult to obtain information regarding inspection methods. There are indications that some development work is ongoing in the industry, but this information is not shared and provided to this study.

3.2 Visual inspection

Visual inspection is by far the most common method for inspection of grouted connections. By using divers or remote operated underwater vehicles, the part of the grouted connection that is visually accessible at the top can be cleaned and inspected. High resolution video cameras can detect anomalies in these accessible parts of the connection and document the condition. Any anomalies detected can by this also be re-inspected to follow and monitor any change over time. Excessive movement in the connection can also be detected visually. Follow up of excessive movement in the connection visually, to monitor change over time will be difficult.

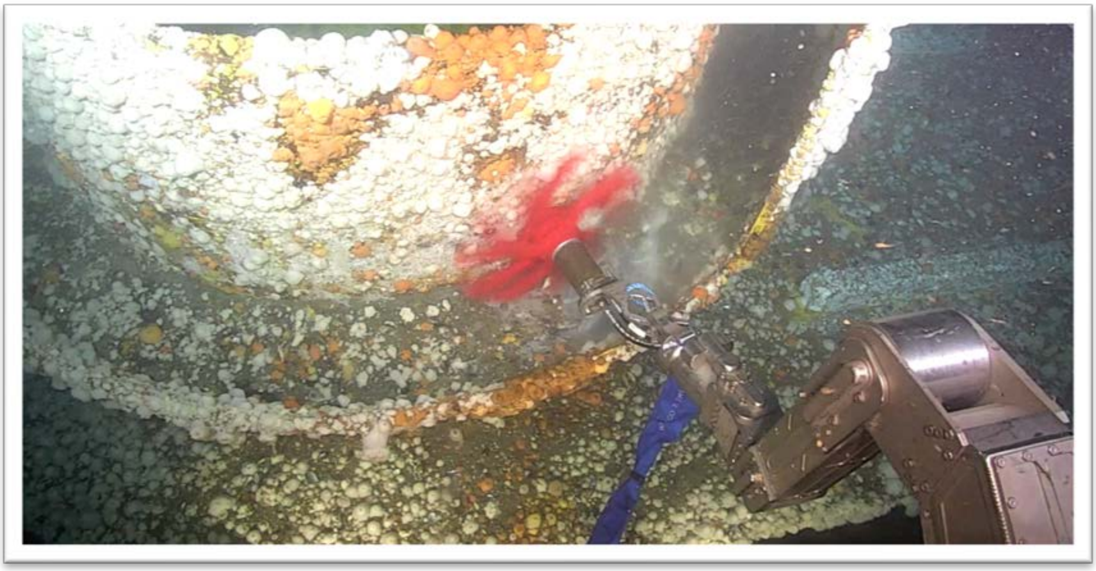

Figure 3-1 Cleaning of grouted connection for close visual inspection using ROV. Picture from DeepOcean.

Figure 3-2 Area cleaned and ready for visual inspection. Picture from DeepOcean.

The detection level of anomalies and movement will depend on inspection conditions and equipment, so probability of detection for anomalies is not easily determinable.

Criteria and levels for anomaly registration will probably vary between the field operators and ROV companies. From a structural point of view, any excessive damage to grouting in accessible areas, i.e. at the top of the grouted connection, or detection or registration of movement is not considered early warning, but is an indication of a connection that may have more severe grouting connection issues.

Figure 3-3 Close up of photo #2. Picture from DeepOcean.

3.3 Retrieving core samples

Retrieving core samples of the grouted connection has been used to get physical sample coupons of the connection, making it possible to inspect the adherence between grout and steel, observe any indication of crushing or hairline cracks in the grout, or lack of filling and voids at the sampled location, and to test and verify the quality of grout in compression.

Figure 3-4 Core sample of steel and grout from a grouted connection. Picture from IK Norway.

Although core sampling is not non-destructive, it can still be considered as an inspection method in the sense that it provides information on the condition of the grouted connection from a local area at the time the core sample was taken. Regarding ability to provide early warning of degradation or failure, core sampling does have limitations, since it is a snapshot of the condition at the time and location when the sample was taken.

3.4 Mechanical resonance technique, Interface Wave Method

3.4.1 Description of the method

A concept for an inspection technique is based on detecting changes in the resonance properties of the pile sleeve grouted connection, in particular for the sleeve. The technique is based on the principle that a local mechanical perturbation in the radial direction will initiate a propagation of the perturbation, circumferentially and axially from the local perturbation.

A given frequency of perturbation may coincide with resonance frequencies in the object resulting in a standing wave type of patterns. The frequencies where this happens depends on the properties of the resonating object. A set of such resonance frequencies characterises the properties. Changes in the properties of the material being tested will change the resonance frequencies and changes in the geometric distribution will change the location where such resonances may be induced. At low frequencies such resonance effects can be detected and recorded by accelerometers connected to a data recorder.

3.4.2 Description of supplied information

Simulation of a grouted connection has been performed for a case with the grout is intact and a case where the grout is degraded, sweeping the frequency of the locally applied perturbation to the sleeve from 100Hz to 10kHz. The simulated piece has inner diameter Ø=1145mm and outer diameter Ø=1410mm, with thicknesses of 80mm, 100mm and 75mm for the sleeve, grout and pile respectively. The simulation does not include weld beads, or shear keys. The data for the non-degraded connection shows resonances at some distinct frequencies, and the perturbation propagates around the circumference and along the length of the sleeve. The amplitude of the resulting perturbation at a location depends on the frequency and the condition of the sleeve. It is found that a simulated degraded grouted connection has some additional resonance frequencies and a change in the perturbation amplitudes around the circumference and along the length.

As a next phase, physical tests using accelerometers and a shaker to inflict the perturbation has been done in the laboratory on a grouted connection of two pipes with length 1500mm, OD=267mm/WT=6.5mm and OD=219mm/WT=6.5mm. Data from both simulations and physical test show different behaviour for a non-degraded grouted connection and a degraded connection. The degraded grout in the physical test is in the mid 1/3 of the connection and is simulated by filling this area with grout in powder form. It is assumed that the tests are done in a dry condition, where the simulated degraded grout is dry power with no adhesion to the wall. The simulations and the actual test data shown similarities, although no perfect match.

3.4.3 Future plan

The next phase is to test further degradation scenarios, before the system is prepared for ROV deployment. Software for real time analysis will be developed.

3.4.4 Comments to the received information

It is the understood that the grouted connection did not have any weld beads or shear keys and was not under stress during the testing. The degraded grouted area was created by adding a section of crushed grout as powder, with very limited adhesion between grout and sleeve or pile.

A simple assumption is to assume that a degraded grout implies a crushed grout lacking bonding to the sleeve for a length of the connection for the full circumference at the shear keys. This correlates well with changes in resonance frequency and amplitudes for a steel pipe bonded and damped by a bonding grout, compared to a steel pipe where the damping from the grout is missing due to lack of bonding. Relating such lack of bonding to a failure of a grouted connection in terms of structural capacity where the load bearing is the compression of the grout between opposite side weld beads, is not trivial, and perhaps not possible, but a local lack of bonding of the grout to the sleeve may indicate that an unwanted process is underway.

Since the data collected is compared to either a simulation or an earlier measurement, the techniques may be an inspection technique, being deployed and measuring locally on the sleeve, but may also be a monitoring technique if the techniques is repeated over time.

3.5 Evaluation

Technology readiness level for the inspection methods are as shown in Table 3-1.

Table 3-1 Technology readiness level for inspection methods, where P = predictive (predict a future failure, early detection) and D = detective (detect a failure after it has occurred)

Inspection	Unproven Concept	Proven Concept	Validated Concept	Prototype Tested	Environment Tested	System Tested	System Installed	Field Proven
Visual inspection								D
Retrieving core sample								P
Mechanical resonance technique, Interface Wave Method		D						

3.5.1 Visual inspection

Visual inspection is the most common method, and a method that have been used for many years, hence it's considered field proven. The method is considered be detective in the sense that the grouted connection is expected to be fully degraded for the method to detect abnormal behaviour. Due to the accessibility the common method is to inspect the grout by looking down from the top part of the sleeve. Since the grout degradation most likely starts at the bottom and escalate upwards, the integrity may be lost when the degradation can be detected. The criticality related to grout degradation/grout failure is highly dependent of jacket configuration, i.e. number of pile sleeve connections.

For example, the simulation performed by FORCE Technology with a one pile per leg 3-legged jacket, showed that the horizontal displacement of the topside was 6m for 1-year storm condition when one pile lost its integrity due to a total grout failure.

3.5.2 Retrieval of core sample

Retrieving core samples is a method that has been used for many years, hence it's considered as a field proven method. But it has some limitations.

The core sample can show if the grout is intact, partly damage or totally damaged. If the core sample is intact the grout above the sampling point is most likely also intact but the sample cannot provide information on the status below the sampling point. If the core sample is damaged the grout below is also most probably damaged but it's not possible to conclude on the grout quality above the sampling point without taking new core samples.

The grout damage can be:

- Crushed grout at the weld beads
- Diagonal cracks from weld beads to weld beads
- Crushed grout due to bending moment

The position for the core sample depends on the purpose of the sample, the future use of the hole and the local loads in the pile and sleeve. A core sample is typically 100mm in diameter and the spacing between the weld beads where crushing of the grout is expected to happen, is normally ~300mm.

3.5.3 Mechanical resonance technique, Interface wave mapping

The received information describes results from tests and simulations. There are similarities between the test and the simulations for the non-degraded and degraded cases, although not perfect match. The work performed matches the technology level of being a proven concept, although the use of a simplified degraded grout using powder with no adhesive bonding to the sleeve wall might make the results to optimistic and does not address the uncertainties in the signature of a grout failure when the grout is degrading. Since the degraded section in the test is a large section of the pipe, approximately 1/3 of the length, it is unclear how small sections of loss of bonding, can be detected.

The received information does not describe what a degraded grouted connection is in terms of remaining structural load capacity nor if the effect changes of a for a limited extent of the degradation. Since the observed effect is a local effect, and does not depend on the grouted connection being excited by a load when the measurement is performed , the techniques is an inspection technique, and may be predictive in detecting changes in extent of areas with lack of bonding of the grout to the sleeve, although the effect of this lack of bonding on the load bearing capacity is yet to be shown.

4 Instrumentation

4.1 Digital twin

4.1.1 General

A digital twin in the Structural Health Monitoring, SHM, definition is a tuned finite element model of the physical object that matches the excursion, responses and local loads of the physical object for a given load case. With a digital twin the finite element model can be used to find the local loads on a member or a hot spot in the structure, and the local utilization and fatigue may be calculated without measuring the loads locally. The sensors and system to measure the loads and the structural response are preferably positioned in an area where it is easy to install and operate a monitoring system at the same time as the received data is possible to distinguish and relate to the structures actual structural responses.

To make a digital twin one needs the loads, for instance wave, current and wind sensors, in combination with sensors providing excursion and local loads on selected members, for instance accelerometers, inclinometers, extensometers, GPS, load cells and strain gauges. The finite element model can then be calibrated to match the measured natural or eigen frequencies and mode shapes, and the local stresses for the loads applied.

Updating and tuning the finite element model to respond with the excursions and frequencies measured for the known loads is a continuous process and can be used to detect deviating behaviour or changes in the finite element model reflecting changes in the load bearing capacity. Detecting changes in the behaviour can also be in combination with machine learning techniques etc.

Technology readiness level for inspection methods, where P = predictive (predict a future failure, early detection) and D = detective (detect a failure after it has occurred)The digital twin is an updated structural analysis model tuned to reflect actual behaviour of an offshore jacket structure in real time. The monitoring equipment is to be located above splash zone.

The True Digital Twin technology has several unique features such as for example:

- ✓ All monitoring equipment is located above the splash zone, usually only on topside
- ✓ Able to predict the structural behaviour for all locations of a structure, also the ones located below water, based on a few sensors
- ✓ Able to quantify the actual uncertainties in the analyses models
- ✓ Advanced damage detection methods for detecting small changes in structural behaviour

Examples of features to be evaluated when assessing damage detection are:

Acceleration; Displacement; Tilt; Strain/forces; Wave load; Wind load; Temperature; etc.

Some pre-liminary studies have been performed to assess the potential for damage detection of grouted connections for offshore structures. The studies consist of two parts. The first part is detailed FE modelling of the behaviour of grouted connections exposed to cyclic loading. The second part is modelling and simulation of the response of an offshore jacket structure with grouted connections exposed to wave loading. The changes in response for a typical 4-legged offshore jacket structure in the North Sea at a water depth of 90 m. Each jacket leg is connected to a pile cluster consisting of 3 piles.

These simple studies have been based on some assumptions since the present description of the real behaviour of damage in grouted connections for pile clusters are sparse.

The assumption for Damage Case 1 is that a crushing zone is developed around the shear keys in the grouted connection, i.e. when the crushing zone is developed it will result in free movement between the pile and the sleeve, as illustrated in Figure 4-1. The damage case is modelled for one out of three piles in a pile cluster for one jacket leg.

Damage Case 2 may be a more realistic damage case where the developed damage is modelled by hysteresis curves based on data from experimental tests from cyclic loading of grouted connections, see Figure 4-2. For both cases some reserve capacity of the jacket structure is still present, i.e. total collapse of the structure is not activated at this stage.

The results from the simplified studies Damage Case 1 and Damage Case 2, indicate that for a typical jacket, damage of one or several grouted connections will results in a change in the response, of such a magnitude that it might be detected by advanced damage detection methods.

More work is required to determine when it is possible to detect a progressing grout degradation using such methods.

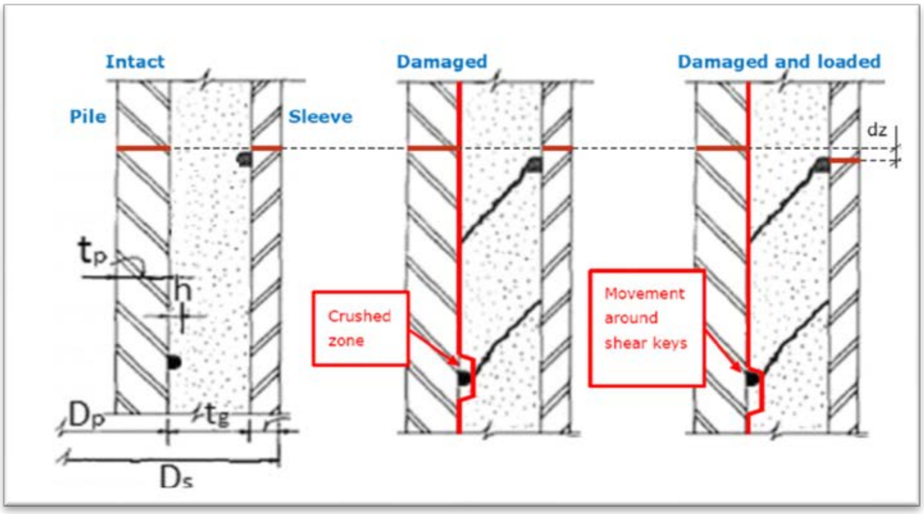

Figure 4-1 Illustration of pile sleeve connection with grout degradation for Damage Case 1 showing the intact connection (left), local crushing of the grout at the shear keys with the diagonal shear (middle) and the loaded connection with resulting relative movement between pile and sleeve(right). Illustration from Ramboll.

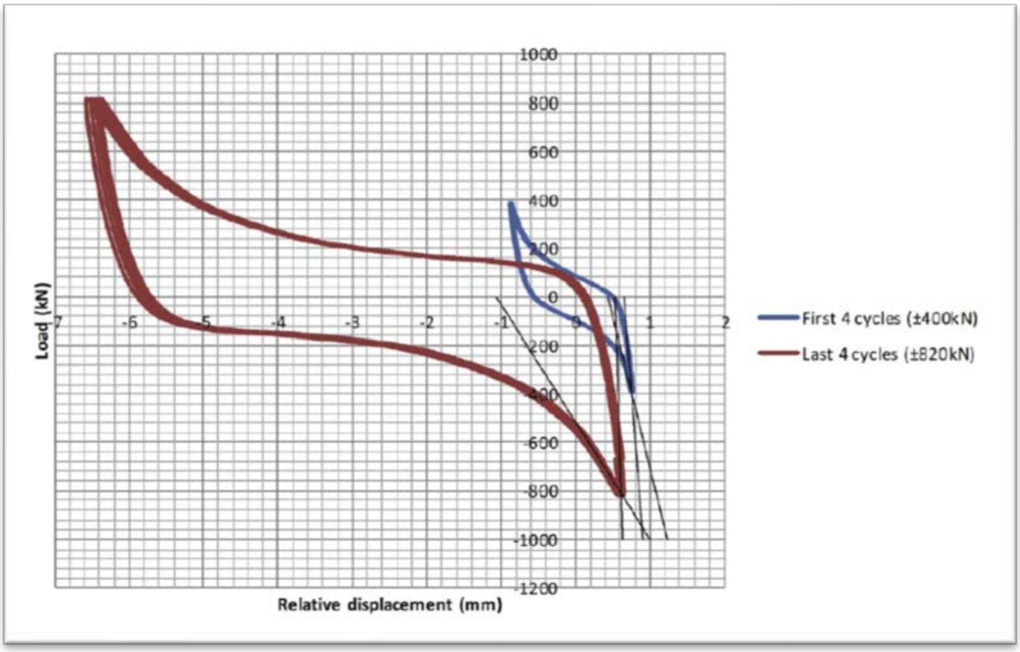

Figure 4-2 The load response hysteresis curves for the four first load cycles on a grouted connection (blue), and the last 4 load cycles before failure (red) used in Damage Case 2. Illustration from [4].

Damage Case 1 - Changes in Natural Frequencies

Results from the performed analysis for Damage Case 1 indicate that the changes in natural frequencies are quite small and could be difficult to measure under real-life conditions using traditional methods.

The challenge is not to measure small changes in natural frequencies, but to relate a small change in natural frequency to damage. Due to the size of the change and other effects influencing the natural frequency, the damage should not be evaluated by changes in natural frequencies only, but in combination with other parameters. Examples of other parameters are presented in the following sections.

Damage Case 1 - Changes in MAC (Modal Assurance Criteria) factors

Changes of the mode shapes can be detected by assessment of the MAC factors (Modal Assurance Criteria). The MAC factor is a mean of comparing mode shapes. For two identical mode shapes the MAC factor is 1.0, whereas two completely different mode shapes have a MAC factor close to 0.0.

Results from Damage Case 1 indicates MAC factors in the range of 0.60, which is very low and hence can be detected.

Damage Case 1 - Changes in Displacement Pattern

Changes in the displacement amplitude are in the range of 1-2 mm for the intact structure and 5-6 mm for a degraded structure. Detecting these differences in real-life conditions are much more complex due to several reasons, such as noise and lack of static reference point.

Damage Case 1 - Other Changes

Other possible changes have not been assessed but might for instance be changes in damping.

Damage Case 2 – Changes in Displacement Pattern

As several issues are not sufficiently investigated yet it is assumed that the grouted connection is damaged to a point where the axial load and deformation behaviour in the connection can be described by a hysteresis loop similar to the ones shown in Figure 4-4, and assuming that wave loading in a given time series is large enough to cause plastic deformation and move through the hysteresis loop. The analysis performed for is based on non-linear, plastic model behaviour.

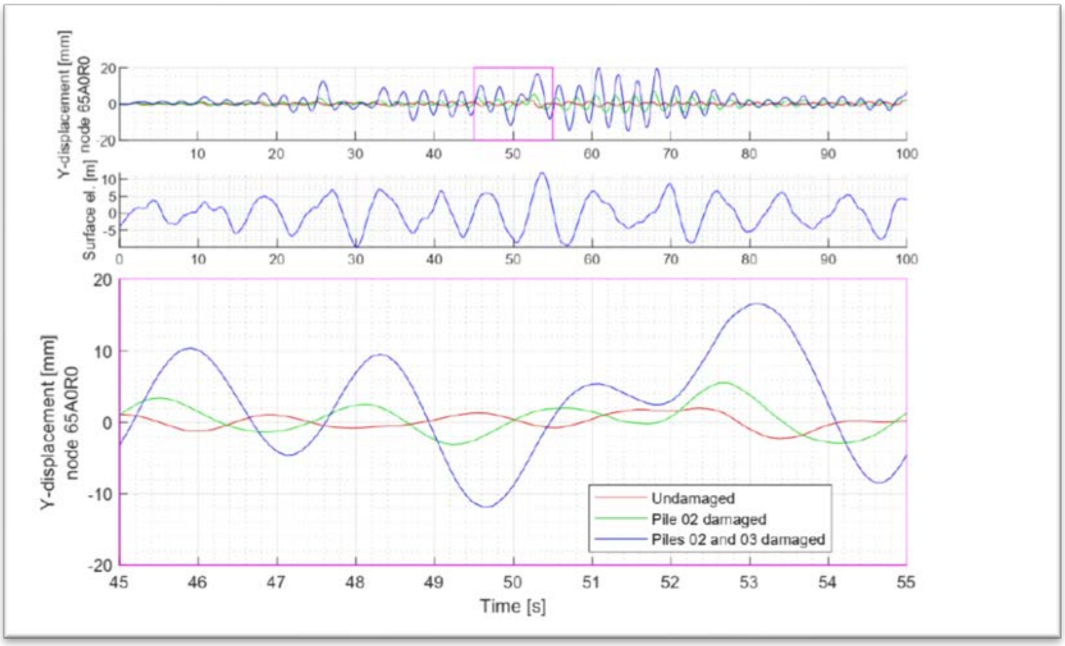

Figure 4-3 Data from simulations for Damage Case 2, where the two top cures is (top) the displacement in y direction with time at a defined node in the model, for the case of undamaged (green), 1 pile damaged (red), and 2 piles damaged (blue), when the corresponding surface elevation of the waves is as shown in middle graph. The lower graph is a zoomed view showing the displacements for a 10 second period. The displacements are in millimetres, the time scale is seconds and the wave surface elevation is in meters. Illustration from Ramboll.

The study was not intend to be extensive and resolved and tested and discussed all issues, only to test a feasibility. For instance, are assumptions made on the progression of the degradation, that one pile connection at a time degrades. Most probably the forces will be distributed to the other piles, which will develop damage in parallel. Proper modelling of soil conditions needs to be addressed, etc. Consequently, many issues still need to be addressed for realistic modelling of the behaviour of damaged grouted connections before going into a more detailed investigation of what can be detected by advanced methods.

The indication from the performed investigations is that damages to grouted connections most likely can be detected by the application of advanced detection algorithms for early warning purposes.

4.1.2 Damage detection method

Damage detection based on detecting deviation from normal behaviour is typically based on Machine Learning (AI) either as Supervised, Semi-Supervised or unsupervised learning. Supervised learning requires monitoring and training on provided datasets for a period of time to recognising and identifying damage. Unsupervised training is based on occurrence and identification of outliers by distancing algorithms, and one can search for the cause of the outliers once identified.

A semi supervised learning method is the use of advanced clustering approaches and the probability of the data point in belonging to different clusters. This is used for pattern identification, and the pattern is related to a change in the structure.

The next level of improvement is the use of Big Data approaches, and a probabilistic approach to system representation, for a probability distribution of prediction models.

4.2 Instrumentation pile/sleeve

4.2.1 Description of the method

A possible method to detect a failed grouted connection is to measure the displacements between the pile and the sleeve at a location where there may be displacements large enough to be measured at an early stage in the development of the failure, such that the information can be used to predict a future failure.

A displacement between the pile and the sleeve can be measured at the top of the connection, where both components are available, to fix an extensometer between them, for instance in the form of an Linear Variable Differential Transformer (LVDT) sensor or a proximity sensor that attaches to the Pile and the sleeve through magnets etc.

Displacements in the grouted connection and in particular at the bottom or in the lower part of the grouted connection, where the grouted connection is expected to start failing, is not directly available for measurements unless access to the pile is made from the sleeve.

4.2.2 Description of supplied information

A hole with 100mm diameter is drilled through the sleeve and grout to the pile. The drilling operation being a core drill, will in addition to providing access to the pile also provide a core sample of the grout at the location of the hole. The core sample will include the interface to both the sleeve and the pile, and any damage due to compression between diagonally opposite weld beads, see section 3.3.

A sensor system measuring the relative movement between the pile and the sleeve is installed in the hole. The system consists of:

- An optical target installed on the pile
- A retrievable and re-installable optical sensor installed in the hole on the sleeve
- A locking and sealing system, reducing to a minimum the exchange of water in the hole, or cavity
- A polymer insert in the cavity reducing the disturbance of the optical path due to particles and debris
- A subsea computer, recording the data and storing locally the gathered information.
- A power source, for instance a cable to topside or subsea battery
- A means of communication, a cable to topsides, a subsea ROV stab connection or a hydro acoustic link

In addition, the system consists of ROV or diver tooling to make the hole, gather the core sample, install the optical target on the pile, the sensor fixation to the sleeve and installation of the sensor in the hole.

Such a system has been developed and has been deployed subsea on a pile sleeve connection for 3 winter seasons measuring the local displacements, see illustration in Figure 4-4.

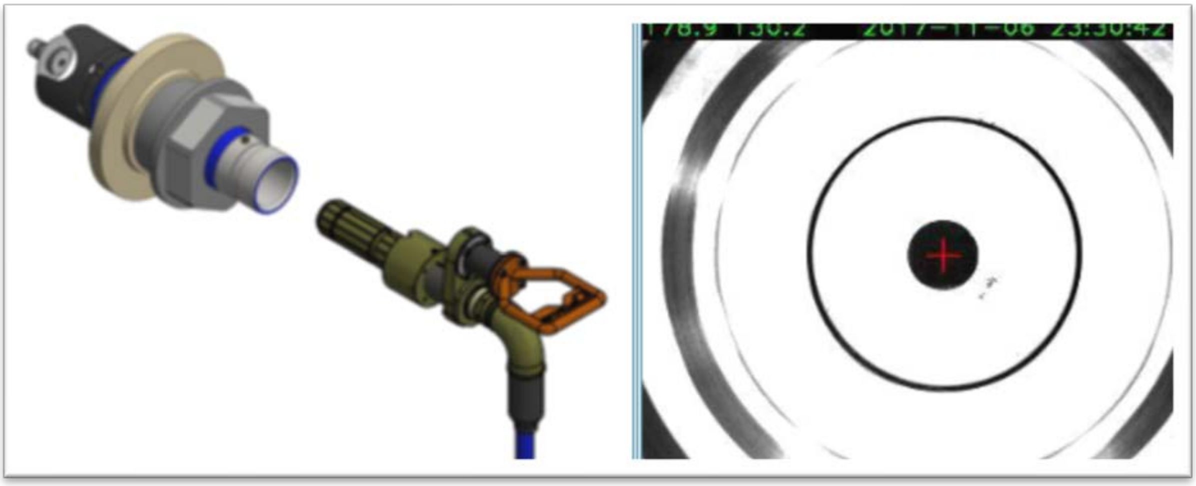

Figure 4-4 The ROV installable sensor with target, protection sleeve and fixation to the hole in the sleeve. Right the optical target showing the identified centre position of the target relative to the sensors, with coordinates top left and date and time, top right. Illustration from FORCE Technology.

During the deployment period, the fourth winter season commencing August 2020 the sensor has been left installed, and only the subsea stand with battery and local storage has been retrieved and reinstalled. Data and images of the optical target show that the integrity of the sensor and the volume in the cavity between the sensor and target is ensured.

The recorded data show no movement in vertical or horizontal direction, except for an occurrence, showing a shift of 4mm coinciding with a storm. No other structural monitoring data is available for the jacket for the period. Although the data show a permanent change in the target position it is not confirmed that this movement is due to structural loads, and not an artefact of the installation.

4.2.3 Future plan

The system to day exists as an autonomous system, battery powered. The system can be connected to a cable to topside, providing online data, that can be correlated to other structural monitoring data and processed in real time.

4.2.4 Comments to received information

The method requires a hole drilled through the sleeve and grout to the pile. Some argue that such an inlet of seawater into the grouted region may degrade the grouted connection. The method also requires that the failure method for the grouted connection actually results in a displacement between the pile and the sleeve in a rage that can be detected, from 1/10th of a millimetre or more. For the method to be predictive the sensor should be installed at a low level of the grouted connection, where the grout damage is expected to start.

4.3 Evaluation

Technology readiness level for the inspection methods are considered to be as shown in Table 4-1.

Table 4-1 Technology readiness level for instrumentation methods, P = predictive and D = detective

Instrumentation	Unproven Concept	Proven Concept	Validated Concept	Prototype Tested	Environment Tested	System Tested	System Installed	Field Proven
Frequency / Mode								D
Displacement								D
Damage detection		P			D			
Instrumentation pile/sleeve								P

4.3.1 Frequency / Mode

The Natural Frequency and Mode Shape methods are classified as a detective and field proven methods.

The methods detect failure by identifying changes in the behaviour by comparing the measured response from accelerometers to the normal behaviour of a tuned structural model, and knowledge of the applied loads, the waves using linear theory.

This method will, when it is set up correctly, be able to detect full failure of a grouted connection but should be very challenging to detect partly damaged connections, ref the discussions in section 2.6.

Detection of changes in the Natural Frequency and Mode Shape for non-linear effects require analysis by advanced non-linear system identification methods. The application of more advanced methods may make the method more applicable to detect early damage development in combination with other indicators.

4.3.2 Displacement

Displacement method is classified as a detective field proven method.

By use of correct types of accelerometers and algorithms or other displacement sensors, the displacements can be calculated and monitored in real time. The method will be able to detect a fully degraded grouted connection, due to the size changes in the behaviour, ref. section 2.8, but should be very challenging to detect partly damaged connections.

4.3.3 Damage detection

Damage detection using outlier analysis and machine learning (AI) are classified as a proven concept regarding ability to predict grout degradation but classified as environment tested method regarding ability to detect grout failure.

Methods for damage detection ranges from simple algorithms such as different kinds of outlier analysis (e.g. Mahalanobis, other) to more advanced methods based on Machine Learning and Artificial Intelligence algorithms. The methods are known and can be utilised. The challenge is to have available training set of data for a degraded grouted connection, and possibly the signal amplitudes of such failures. The results from the simple simulations indicate that early warning of damaged grouted connections may be facilitated by adopting a combination of methods and indicators using sensor system installed topsides.

4.3.4 Instrumentation pile / sleeve

To measure the relative displacement between pile and sleeve is a method that have been used for 2-3 years, hence it’s considered as a field proven method. The method require that some work is done to give meaning to the measured displacement from a remaining capacity point of view. Structural analysis with relevant jacket configuration and with relevant weather condition for example 1-year storm must be performed that gives criteria for the measured displacement.

The analysis must be able to correlate the measured displacement into how much of the connection that is intact, for example 2mm relative displacement indicate that 3m of the grouted connection is damaged, displacement > 15mm indicate total loss of the integrity of the connection, etc..., see section 2.7.

The conclusion is that the method can give an early warning of failure if a calibration with structural analysis has been performed.

5 References

[1] N-004, "Design of Steel Structures", NORSOK Standard, Rev.3, February 2013.

[2] API17N, Subsea Production System Reliability, Technical Risk, and Integrity Management, Second Edition, American Petroleum Institute, 2017.

[3] DNV GL AS, DNVGL-RP-A203 Technology qualification, 2017.

[4] Testing of Jacket Pile Sleeve Grouted Connections Exposed to Variable Axial Loads. Journal, Marine Structures 58. Atle Johansen, Gunnar Solland, Andreas Lervik, Martin Strande, Terje Nybø., 2018.

5.1 Contact information

The contact information for further information is given below:

General FORCE Technology Norway AS Nye Vakås vei 32 NO-1395 Hvalstad Norway Phone: +47 64 00 35 00 https://forcetechnology.com/no/	**Instrumentation pile / sleeve** FORCE Technology Norway AS Nye Vakås vei 32 NO-1395 Hvalstad Norway Phone: +47 64 00 35 00 https://forcetechnology.com/no/
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Displacement Ramboll Group A/S Hannemanns Allé 53 DK-2300 Copenhagen S Denmark Phone: +45 51 61 10 00 https://ramboll.com/energy	**Interface wave mapping** NGI Sognsvn. 72 NO-0855 Oslo Norway Phone: 47 22 02 30 00 https://www.ngi.no
Core sample IK-Norway Christian August Thorings veg 9 NO-4033 Stavanger Norway Phone: +47 51 44 32 00 https://ik-worldwide.com	**Visual inspection** IMR contractors

Appendix A. Establish overview of available methods

Email

Dear Sir/Madam, if you are not the correct contact person, please forward this e-mail to the correct individual or department.

FORCE Technology has been awarded a contract from the Norwegian Petroleum Safety Authority, PTIL, to perform a study on available inspection and instrumentation methods for inspection of grouted connections between jackets and piles. These connections are critical, and thus surveillance of these connections by instrumentation or inspection is key for the jacket's structural and technical integrity.

See link https://my.mercell.com/permalink/123287531.aspx for information regarding the assignment. Please note that the link will require registration.

As part of this study FORCE Technology will approach key suppliers to gather any relevant experience and assess the maturity and quality of any methods available. The presentation of methods and FORCE Technology's assessment will be presented in the study and will be publicly available information. All information will be referenced to the supplier that has provided the information.

FORCE Technology's assessment will consider availability of method, considerations regarding probability of detection and confidence will be made, but for novel methods, suppliers must provide test and qualification records. Qualification records from third parties will be given more weight than internal qualification records when assessed. Conceptual studies without practical experience can also be shared, but these should be supported by enough technical descriptions.

Your company is given the opportunity to provide information of any experience gained on relevant projects. This would include white papers presented on conferences or web pages, PowerPoint or similar presentations, conceptual studies or any other report presenting methods, experience and/or results from jobs performed, related to grouted jacket/pile connections.

Please forward any information to one of the persons below. These can also be contacted for more information:

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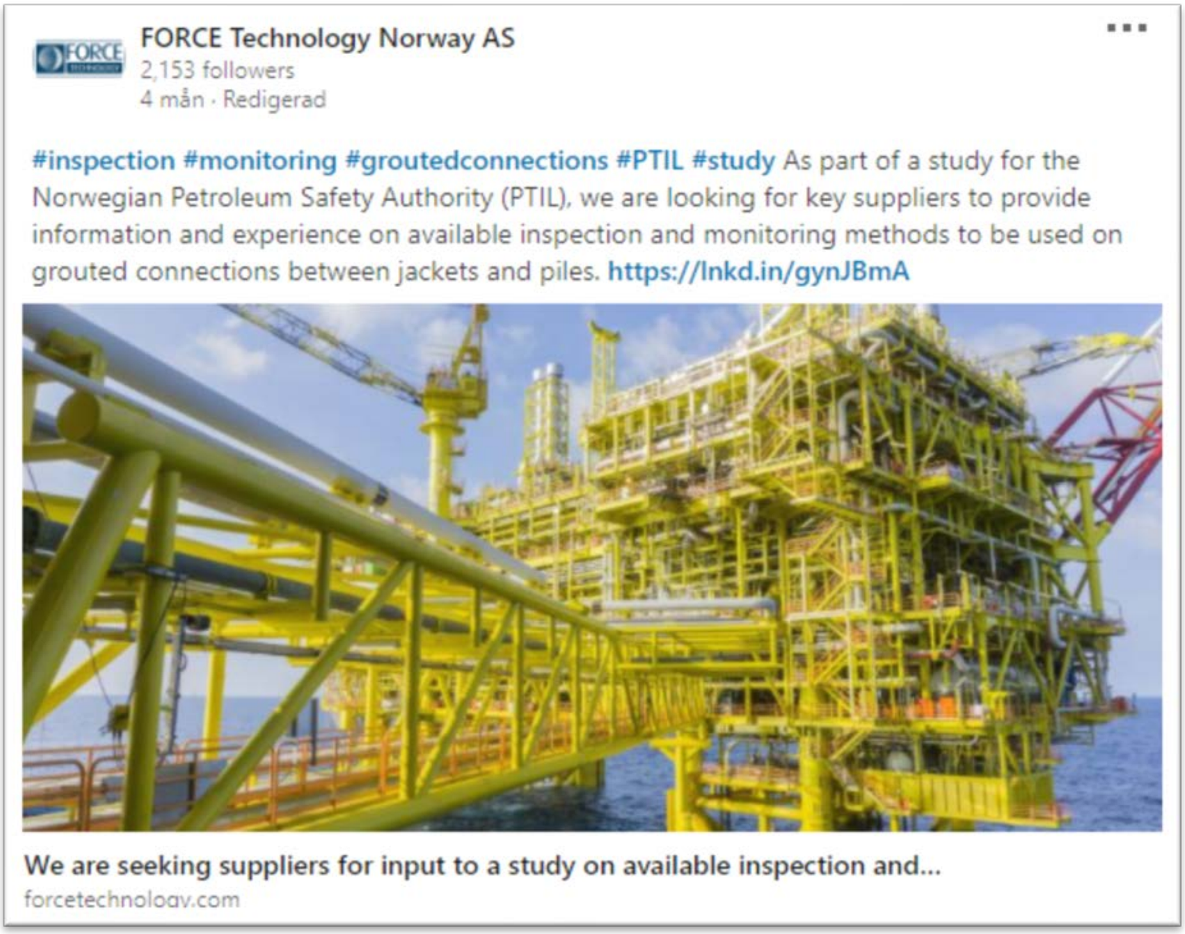

Figure 5-1 Advertising LinkedIn

As part of a study for the Norwegian Petroleum Safety Authority (PTIL), we are looking for key suppliers to provide information and experience on available inspection and monitoring methods to be used on grouted connections between jackets and piles.

FORCE Technology Norway AS has been awarded a contract from the Norwegian Petroleum Safety Authority (PTIL) to perform a **study on available inspection and monitoring methods for grouted connections between jackets and piles.** These connections are critical, and surveillance of these connections by instrumentation or inspection is of importance for the jacket's structural integrity.

As part of the study, FORCE Technology will approach **key suppliers to gather relevant information and experience and assess the maturity and quality of the available method.** The presentation of available methods and the present maturity will be presented in the study and be publicly available. All information will be **referenced to the supplier that has provided the input.**

FORCE Technology's assessment will consider availability of the method as well as elaborations regarding the probability of detection, and confidence in the results from a structural integrity perspective. The suppliers are encouraged to provide test and qualification records where available. **Qualification records from third parties will be given more weight** than internal qualification records. Conceptual studies without practical experience can also be shared, but these should be supported by sufficient technical descriptions.

For your technology to become part of the study, we invite you to share open information of any experience gained on relevant projects. This could include white papers presented on conferences or web pages, PowerPoint or similar presentations, conceptual studies or any other report presenting method, experience and/or results from jobs performed, related to grouted jacket/pile connections. **Information may be shared under an NDA if required.**

Please forward any information to one of the persons below. These can also be contacted for more information:

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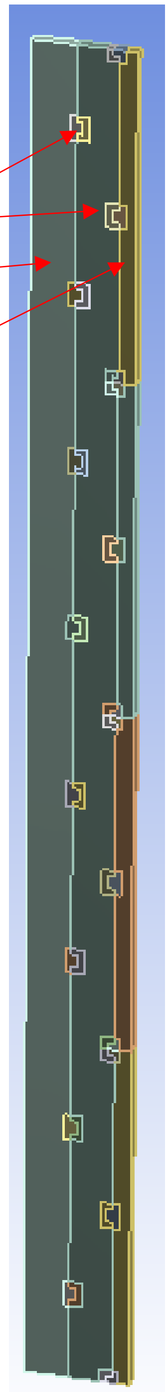
Figure 5-2 Advertising FORCE homepage

Appendix B. Damage / Failure of grouted connection



Where the grouted connection start to fail has an impact for how the inspection and instrumentation should be done. FORCE has done a simplified assessment based on axial load. A section of the grouted connection is modelled, sleeve, grout, well beads and pile are included. The model can be seen in the figure to the right. The dimensions are based on a real grouted connection:

- Sleeve Ø = 2650mm, thickness 30mm
- Grout thickness 76mm
- Sleeve Ø = 2438mm, thickness 80mm
- Weld beads width 44mm, height 23mm, spacing 278mm

The modelled connection height is 2400mm, in reality it should have been 10000mm but it has no impact for this assessment.

The sleeve, pile and weld beads has steel properties and the grout has concrete properties.

All weld beads are fixed to the sleeve respectively the pile. The contact between pile/sleeve/weld beads and grout is based on frictional contact without friction.

The pile is fixed in vertical direction at the bottom. Both sides of the cutted section is defined with symmetrical constrain, i.e. frictionless support.

Two different loads are applied that shall represent two different kind of load transferee from the jacket. The first is simulating a shear plate and the second is simulation brace, see figure below. The load is based on 100-year storm condition, in this case ~24.1MN. But the load is adapted to the size of the section.

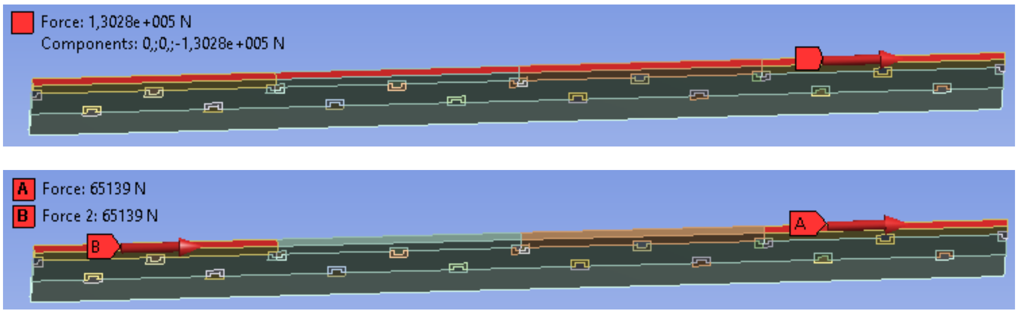


Figure 5-3 Grouted connection and loads

The resulting von Mises stress for the connection and the shear stress for the grout is showed in Figure 5-4 and Figure 5-5. As showed in the figures the highest stresses occurs at the bottom of the connection.

It's also known that grout may be smashed du to external load, this is expected to be more critical the closer you get the mudline, this area is more stiff compare to higher up on the connection.

The conclusion is hence that the grouted connection most likely will start to fail at the bottom of the connection and escalate upwards.

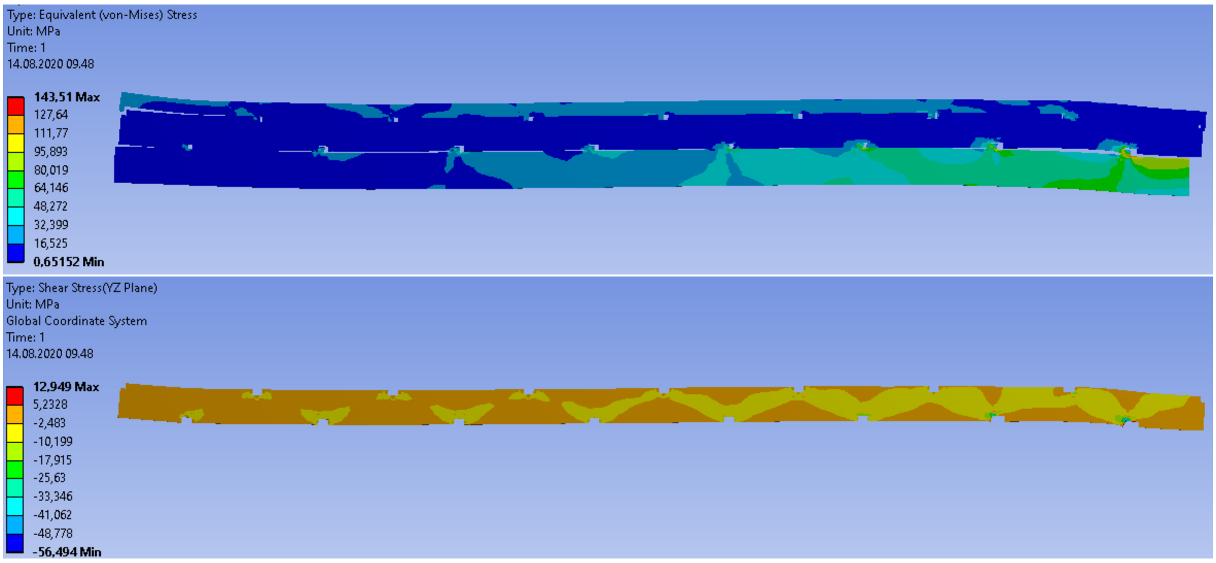


Figure 5-4 von Mises stress and shear stress grout based on shear plate

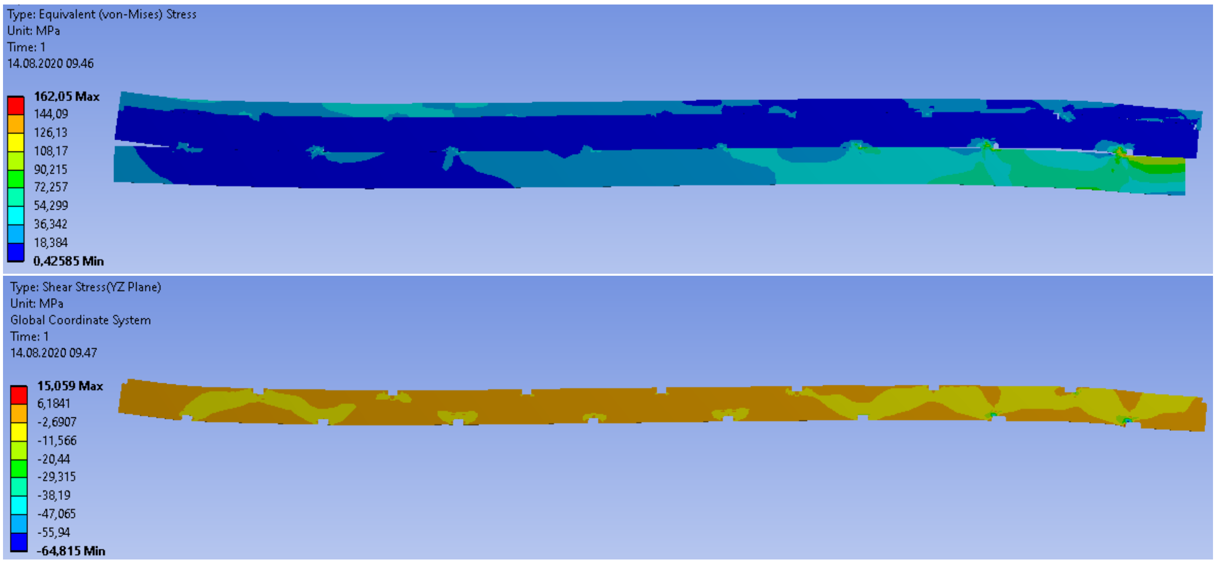


Figure 5-5 von Mises stress and shear stress grout based on brace

Appendix C. Natural Frequency / Relative Displacement Pile / Sleeve / Topside Displacement

Table of contents

1 Methodology

1.1 General

The nonlinear FE analysis software USFOS has been used to simulate how grout damage and grout failure impact the global behaviour of jacket platforms. Two different jacket platforms are analysed; one 3-legged platform with 3 piles and one 4-legged platform with 8 piles, i.e. 2 piles in each cluster. It should be noted that this study is a simplified study with several assumptions and simplifications as described below.

1.2 Analysis

1.2.1 Analysis model – 3-legged jacket

An existing model of a 3-legged platform in the North Sea was used. The model was adapted and used as-is. The jacket has one pile at each leg. The pile dimension above mudline is Ø2438 x 70/80 mm and sleeve dimension is Ø2750 x 45 / 80 /100 mm. The pile was modelled until 1 meter below mudline, and soil springs were used as boundary conditions.

The piles and sleeves were originally modelled as pipe elements with diameter and thickness equivalent to the size of the combined pile and sleeve. To simulate grout damage and failure, the piles and sleeves were modified using separate elements for the pile and for the sleeve. The sleeve was modelled outside the pile. The sleeve and pile nodes were connected using master-slave coupling, with the pile nodes as master nodes, and sleeve as slave nodes. The slave node's degrees of freedom (DOF) may be fully dependent on the master's DOF, or fully released, i.e. no coupling.

The sleeve, and the part of pile inside the sleeve was modelled by four elements and five nodes, as shown in Figure 1-1.

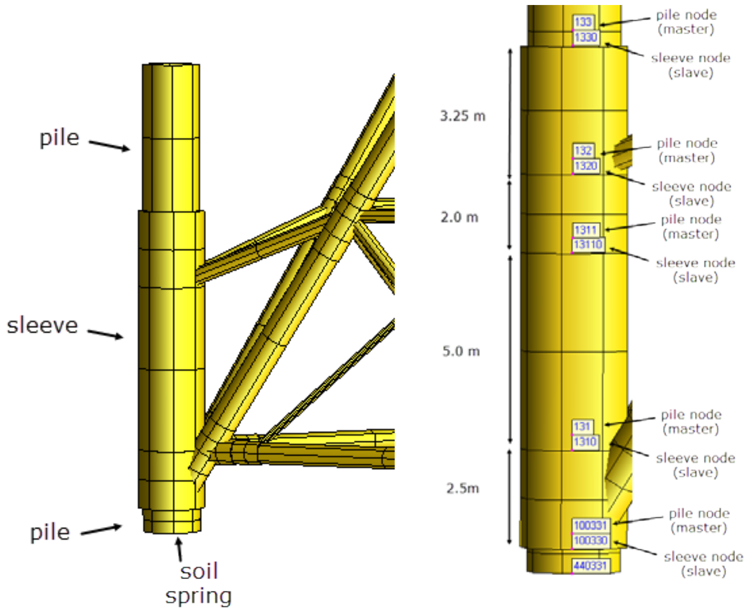


Figure 1-1 Pile model, and pile and sleeve nodes, 3-legged jacket

1.2.2 Analysis model – 4-legged platform

An existing model of a 4-legged jacket platform in the North Sea was used. The model was adapted and used as-is. The jacket has two piles in each cluster. The pile dimension above mudline is Ø2134 x 63 mm, and the sleeve is Ø2370 x 40mm and Ø2310 x 25 mm.

The soil was modelled with pile-soil interaction according to API. One of the piles were modelled inside the sleeve with master-slave coupling, as for the 3-legged jacket. Figure 1-3 through Figure 1-5 show the model of the pile cluster for the 4-legged jacket.

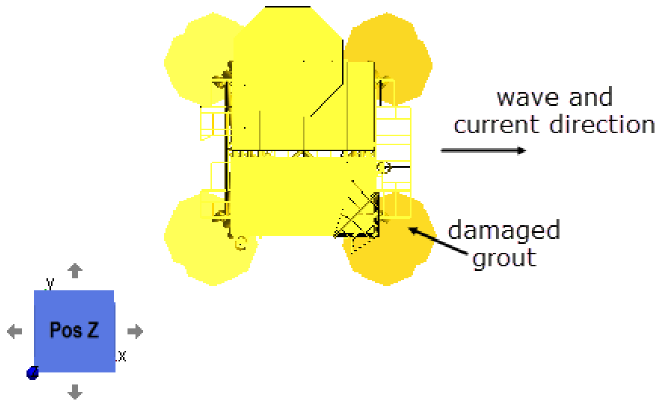


Figure 1-2 Analysis model, 4-legged jacket

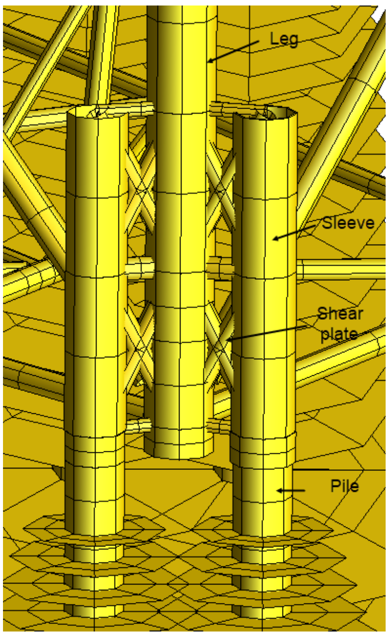


Figure 1-3 Pile model, 4-legged jacket

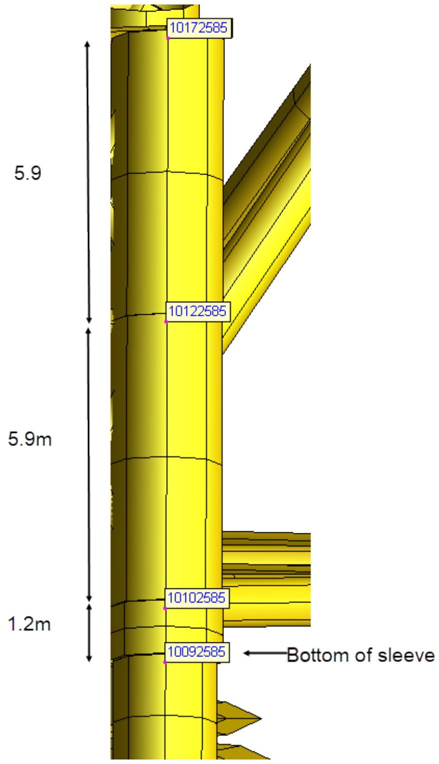


Figure 1-4 Sleeve nodes (slave)

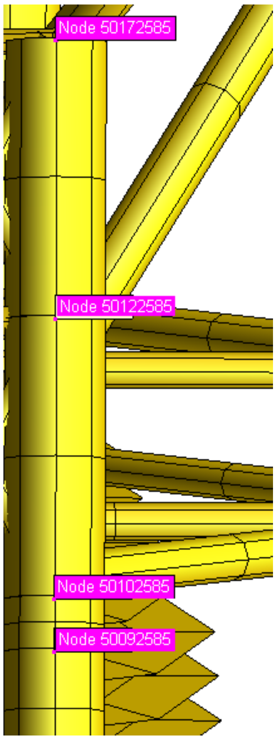


Figure 1-5 Pile nodes (master)

1.2.3 Assumptions

In the current analyses, it is assumed that grout failure initiates at the bottom of the sleeve, where the highest forces are seen. It is assumed that the damaged grout has lost its ability to transfer shear forces in axial direction, but that the grout is still present in the sleeve. I.e. the grout is still able to transfer radial (horizontal) forces. If the grout is removed, for example by falling out or washed out of the sleeve, it would in addition lose its ability to transfer radial contact forces. In that case, there would be horizontal displacement of the sleeve relative to the pile, which may give higher impact the global behaviour of the platform.

It is not a scope of this study to evaluate the capacity of any of the structure, the piles and sleeve, or the remaining intact grout when part of the grout is damaged. For all the partly damaged grout cases, it is assumed that the remaining grout has capacity to transfer the forces between the pile and sleeve.

In the simulations, the vertical displacement of the sleeve in the areas where the grout is damaged is due to elongation of the steel in the sleeve and pile when force is applied. The magnitude of displacement is thus a function of the pile and sleeve dimensions.

Furthermore, the cases simulating full grout failure are highly simplified. It is merely simulated by applying full axial release between the pile and sleeve elements. Neither friction, soil, potential horizontal displacement or other effects are not considered.

1.2.4 Loads

For the 4-legged and 3-legged jacket, dynamic analyses were run for 40 seconds and 60 seconds, respectively. The first 10 seconds, gravity and buoyancy were applied. The eigenvalues were analysed at 10.1 seconds.

For both jackets, waves and current were applied at 12 s. A typical 1-year storm was applied, with waves and current, but not wind, as described in Table 1-1 below.

/ Table 1-1 Environmental data, 4-legged jacket

Load	Value
Wave height	17.1 m
Wave period	11.6 s
Current speed at surface level	0.72 m/s
Wind speed	0 m/s

1.2.5 Analysis cases

For both jackets, a base case without releases was analysed, simulating undamaged grout. For the next cases, the sleeve nodes were successively released in vertical direction simulating increasing grout damage, until full grout failure. Table 1-2 and Table 1-3 below summarizes the analysis cases for the two jackets.

/ Table 1-2 Analysis cases, 3-legged jacket

Case	Description	Nodes released	Corresponding length of damaged grout
150	0 releases – undamaged grout	none	0 m
151	1 release	node 100330	2.5 m
152	2 releases	node 100330 and 1310	7.5 m
153	3 releases	node 100330, 1310, 13110	9.5 m
154	4 releases	node 100330, 1310, 13110, 1320	12.25 m
155	5 releases – full grout failure	all	12.25 m

/ Table 1-3 Analysis cases, 4-legged jacket

Case	Description	Nodes released	Corresponding length of damaged grout
120	0 releases – undamaged grout	none	0 m
121	1 release	node 10092585	1.2 m
122	2 releases	node 10092585 and 10102585	7.1 m
123	3 releases	node 10092585, 10102585 and 10122585	13 m
124	4 releases – full grout failure	all	13 m

1.3 Results

1.3.1 General

For each case investigated, the following results are reported:

- The three first eigenmodes of the structure
- Axial displacement of the pile and sleeve at the bottom of the pile sleeve
- Horizontal displacement at the topside, in X and Y direction

1.3.2 3-legged jacket

The eigenmodes for the five cases are shown in Table 1-4 below, in addition to percentwise changes from the base case 150. It may be seen for all the partly damaged grout simulations, the changes in the eigen periods are below 1%. For full grout failure, the change is significant for eigen period 1 and 3. The mode shapes change significantly for all the global modes.

/ Table 1-4: Eigenmodes, 3-legged jacket

Case #	Description	Eigen-period 1 [s]	Eigen-period 2 [s]	Eigen-period 3 [s]	Change Eigen 1 [%]	Change Eigen 2 [%]	Change Eigen 3 [%]
150	0 releases	2.64178	2.57859	0.502842			
151	1 release	2.64528	2.57989	0.503010	0.13	0.05	0.03
152	2 releases	2.65560	2.58283	0.503467	0.52	0.16	0.12
153	3 releases	2.65992	2.58378	0.503652	0.68	0.20	0.16
154	4 releases	2.66604	2.58492	0.503926	0.91	0.24	0.22
155	5 releases (full grout failure)	8.70766	2.60403	0.625660	69.66	0.98	19.63

The horizontal displacement at the Topside in X- and Y-direction for the six cases are shown in the graphs in Figure 1-11 through Figure 1-9 below. For the cases with partly damaged grout, the difference in displacement amplitude is in average 5-7 mm for each release. For full grout failure, the jacket has only two functional piles, and the displacement amplitude changes dramatically.

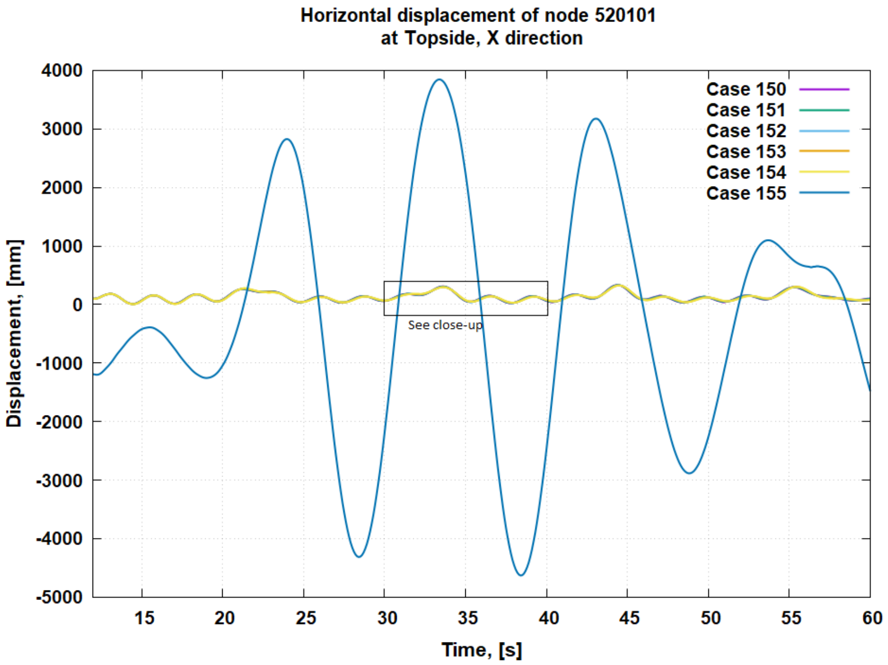


Figure 1-6 Horizontal displacement at Topside, X-direction, 3-legged jacket

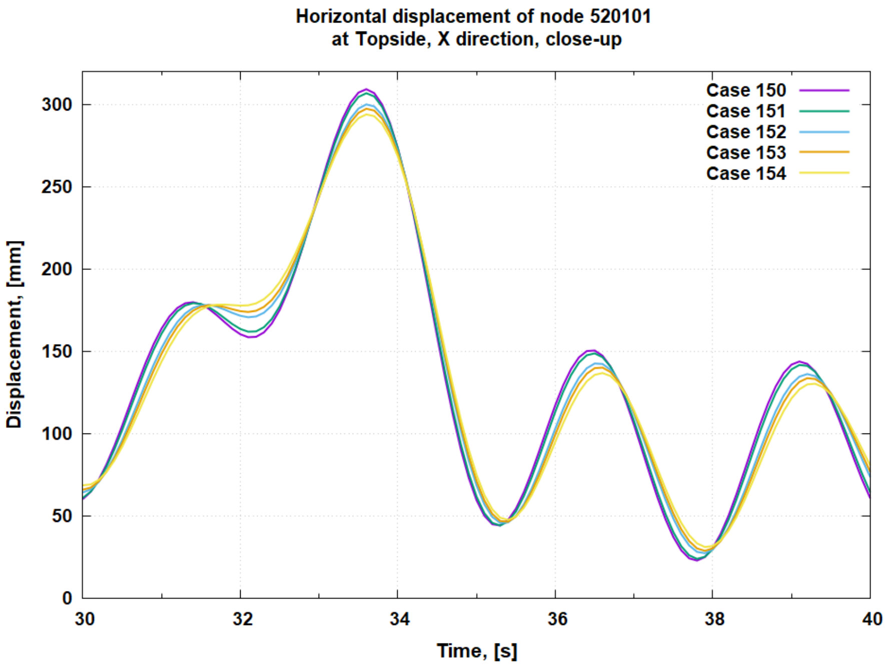


Figure 1-7 Horizontal displacement at Topside, X-direction, 3-legged jacket, close-up

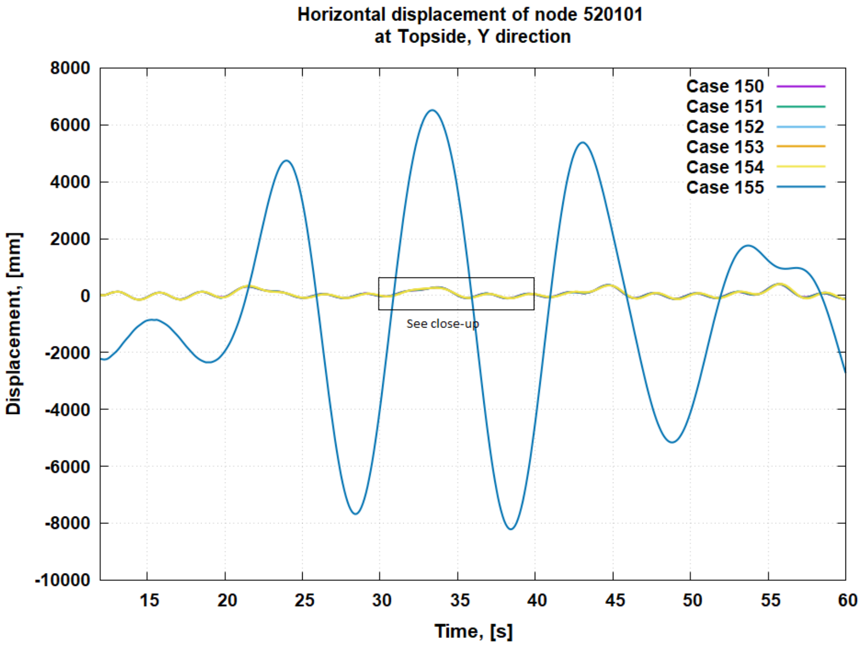


Figure 1-8 Horizontal displacement at Topside, Y-direction, 3-legged jacket

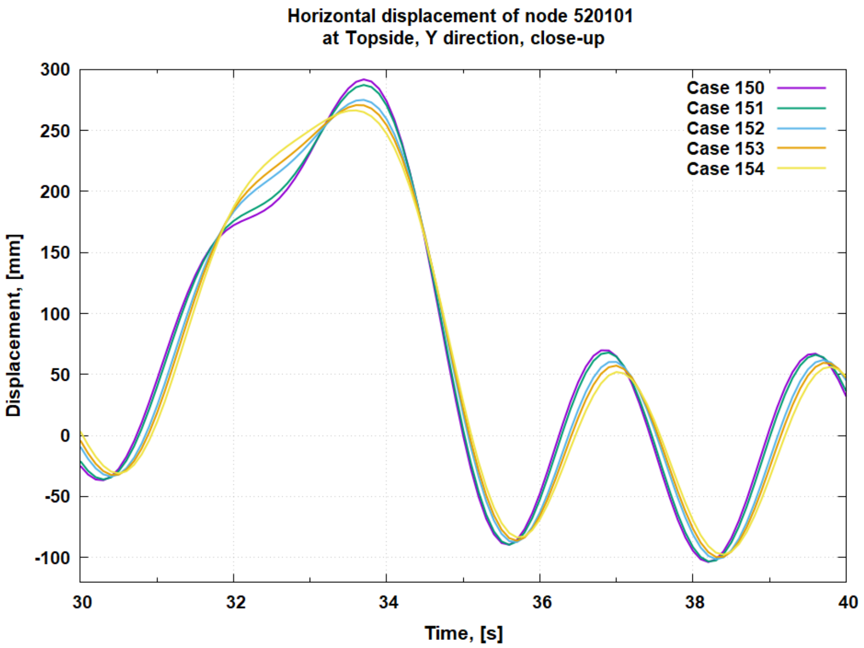
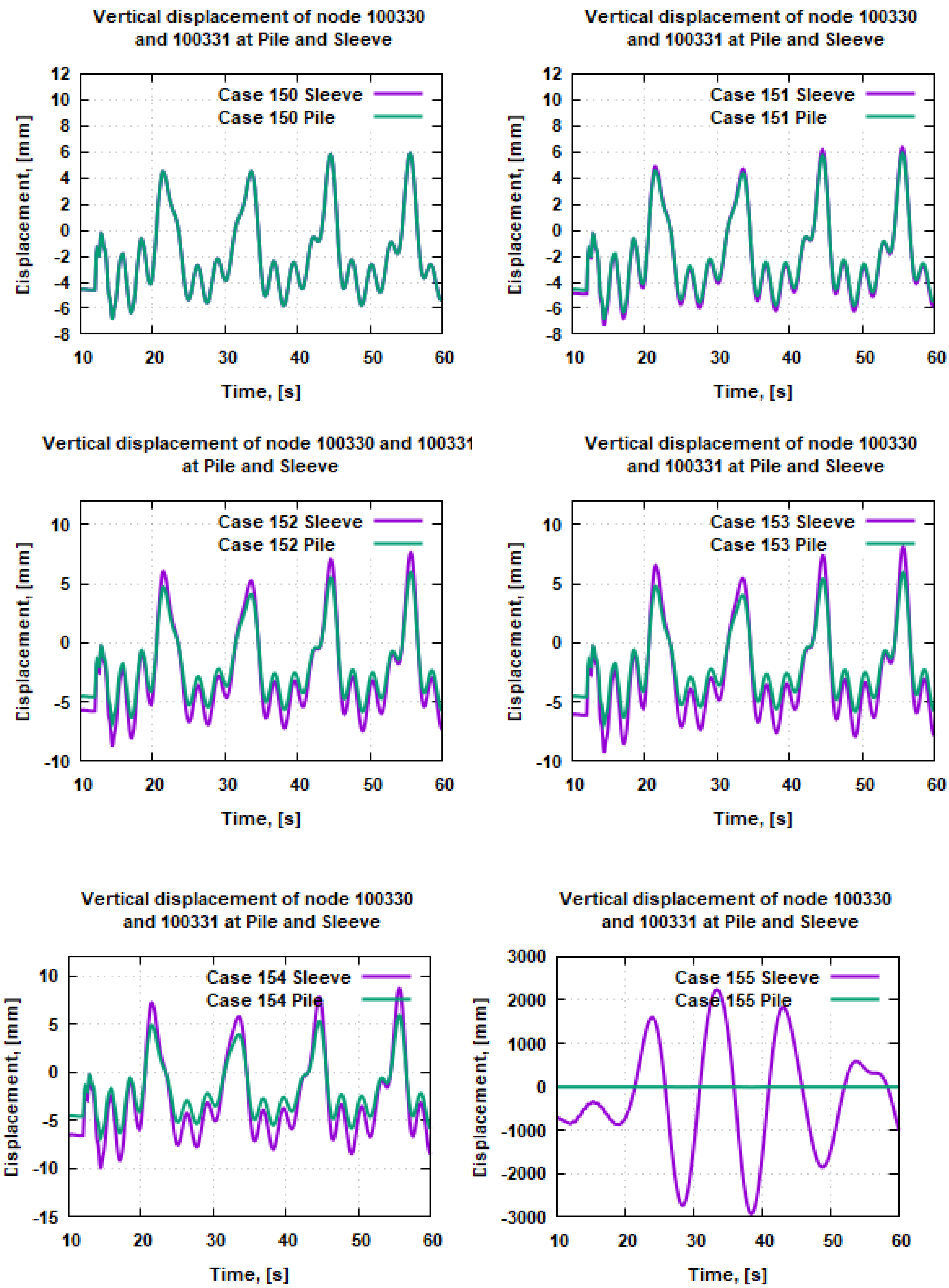


Figure 1-9 Horizontal displacement at Topside, Y-direction, 3-legged jacket, close-up

The vertical displacement of the pile sleeve and pile is plotted in the graphs below. When the grout is undamaged (Case 150), the pile and sleeve have identical displacement. The difference in the displacement between pile and sleeve increases gradually up to 3 mm as the damage increases. When the grout is fully damaged, the sleeve displacement amplitude is around 5 m, while the pile displacement is zero.



/ Figure 1-10 Vertical displacement of pile and sleeve, 3-legged jacket

1.3.3 4-legged jacket

The eigenmodes for the five cases are shown in Table 1-5 below, in addition to percentwise changes from the base case 120. It may be seen for all the partly damaged grout simulations, the changes in the eigen periods are below 1%. For full grout failure, the change is significant for the two first eigen periods. The mode shapes also change significantly for the latter case.

Table 1-5: Eigenmodes, 4-legged jacket

Case #	Description	Eigen-period 1 [s]	Eigen-period 2 [s]	Eigen-period 3 [s]	Change Eigen 1 [%]	Change Eigen 2 [%]	Change Eigen 3 [%]
120	0 releases	1.96464	1.92480	1.42774			
121	1 release	1.96492	1.92505	1.42775	0.01	0.01	0.00
122	2 releases	1.96796	1.92692	1.42804	0.17	0.11	0.02
123	3 releases	1.97491	1.93084	1.42798	0.52	0.31	0.02
124	4 releases (full grout failure)	2.88826	2.11725	1.43533	31.98	9.09	0.53

The horizontal displacement at the Topside in X- and Y-direction for the five cases are shown in the graphs in Figure 1-11 and Figure 1-12 below. For all the cases with partly damaged grout displacement changes approximately 0-5 millimetres. For the full grout failure, the displacement changes significantly.

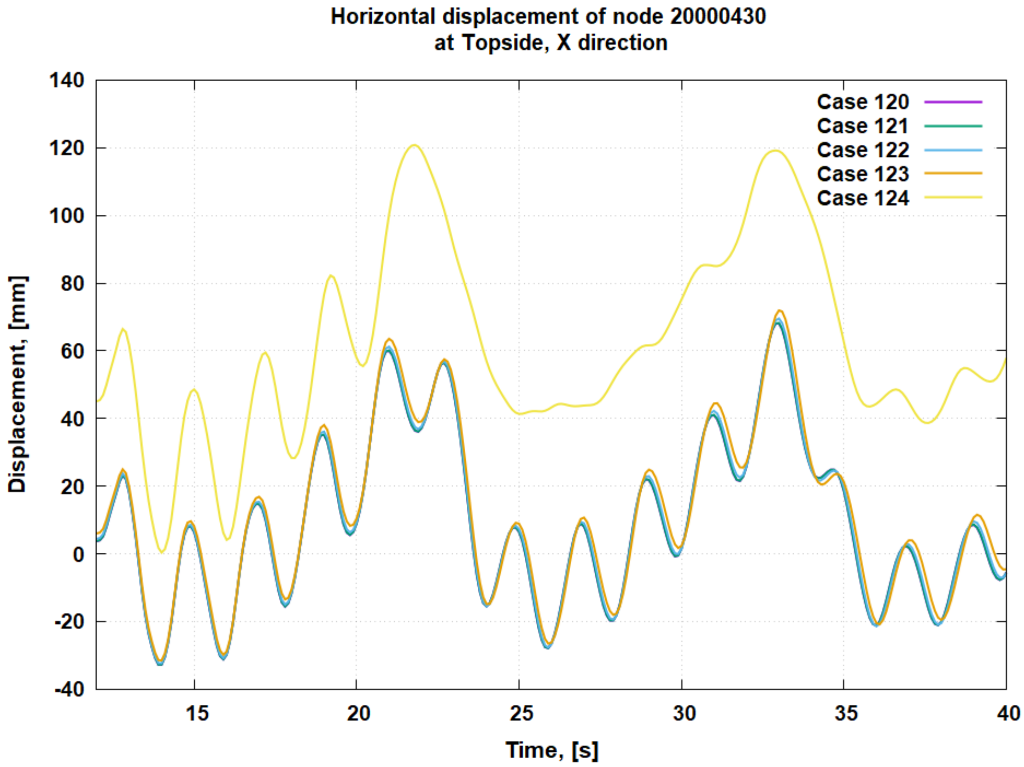


Figure 1-11 Horizontal displacement at Topside, X-direction

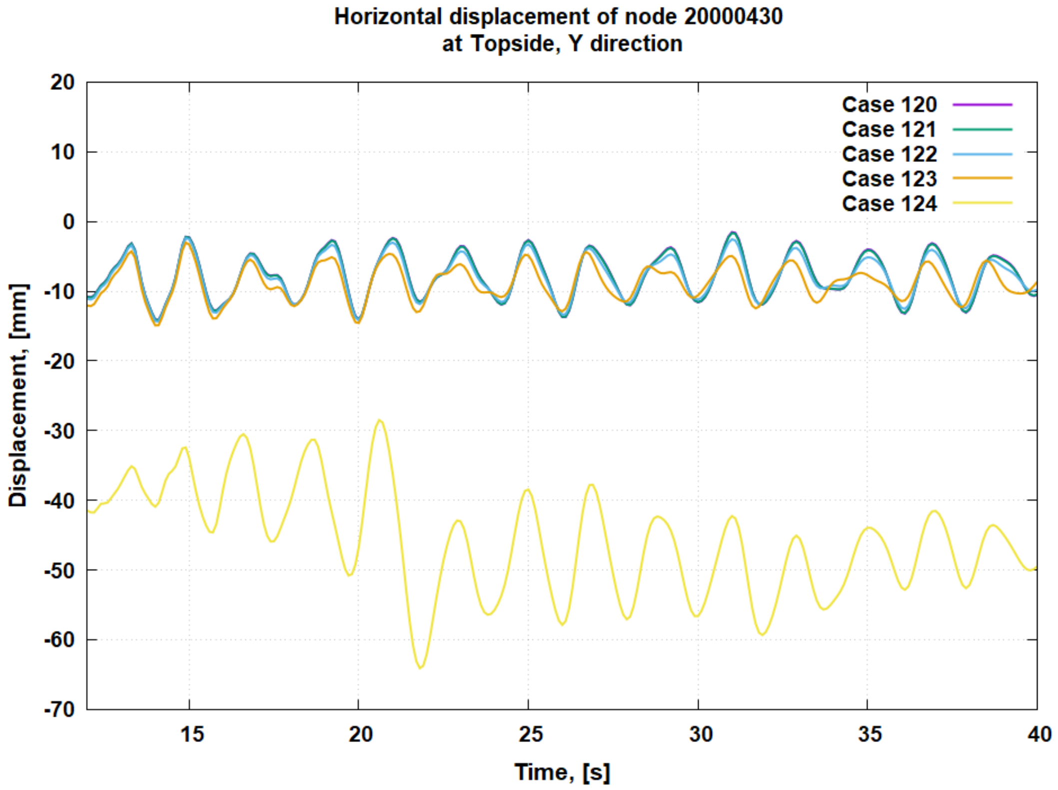


Figure 1-12 Horizontal displacement at Topside, Y-direction

The vertical displacement of the pile sleeve and pile is plotted in the graphs below. When the grout is undamaged (Case 120), the pile and sleeve have identical displacement. The difference in the displacement between pile and sleeve increases gradually up to 6 mm as the damage increases. When the grout is fully damaged, the sleeve displacement is around 60 mm, and the pile displacement is close to zero.

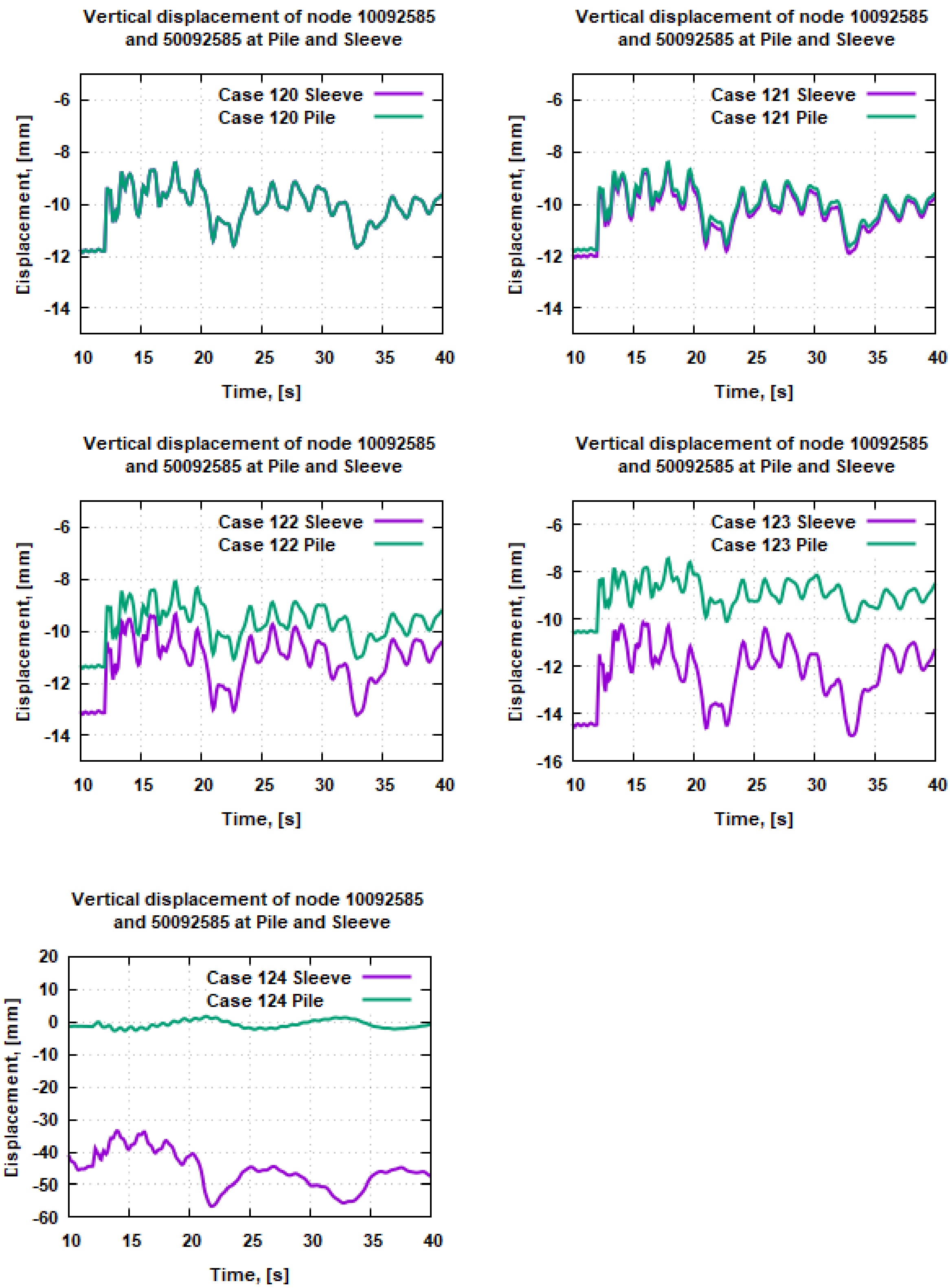


Figure 1-13 Vertical displacement of pile and sleeve, 4-legged jacket

1.4 Summary and conclusion

A simplified study of two different platforms in the North Sea has been performed to simulate how grout damage and failure may impact the global behaviour of jacket platforms.

Pile and sleeve elements were modelled with master-slave nodes, enabling switching between coupled and released degrees of freedom. Grout damage was modelled by successively releasing the sleeve in axial / vertical direction, simulating the grout losing its ability to transfer forces in the vertical direction in the released area.

The analyses indicate that for partly damaged grout, the changes in global behaviour of jacket platforms are very small. Significant change of eigen periods and global displacement is first seen when the grout is fully damaged.

1.5 Note

The current analyses assume only vertical displacement of the sleeve when the grout is damaged. If the grout is removed, for example by falling out or washed out of the sleeve, there would be horizontal displacement of the sleeve relative to the pile. Simulating horizontal release of the sleeve in the areas of damaged grout would show whether the global behavior of the platform changes more significantly.

If grout damage initiates in one of the piles in a cluster, grout damage in the other pile(s) in the same cluster would probably initiate before the grout in the first pile fails completely. Simulating partly grout damage in all the piles at each cluster would investigate whether the global behavior of the platform in this situation changes more significantly.

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