Extenso-Piezometer Developed for Femern Large Scale Tests

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1 Introduction

Large-Scale Geotechnical field tests were initiated in the summer of 2010 in conjunction with the planned design and construction of the Fehmarnbelt Fixed Link between Rødbyhavn (Denmark) and Puttgarden (Germany) - a mega project conducted by Femern A/S to be realized either as an 18 km bridge or most likely a submerged tunnel crossing.

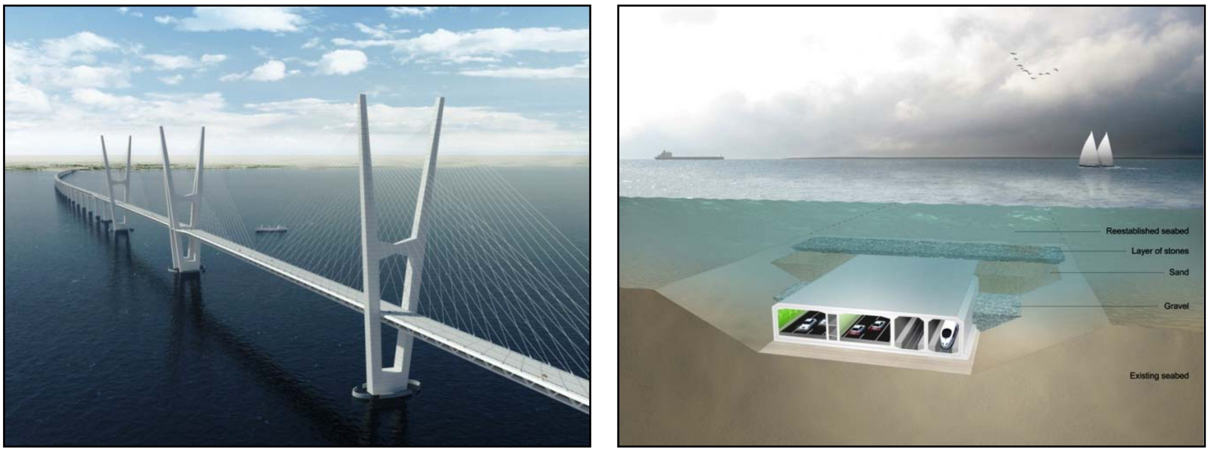

Figure 1: Bridge and immersed tunnel concepts evaluated for the Fehmarnbelt Fixed Link (illustrations from Femern A/S http://www.femern.com/)

Large deposits of very fat and plastic Palaeogene clay are present close to the surface at the German (south) side of the Fehmarnbelt strait. The behavior of this swelling clay is important to understand for the project and the purpose of the ongoing Large-Scale Tests is primary to compare and calibrate the results from the extensive soil investigation and laboratory test program completed in 2010.

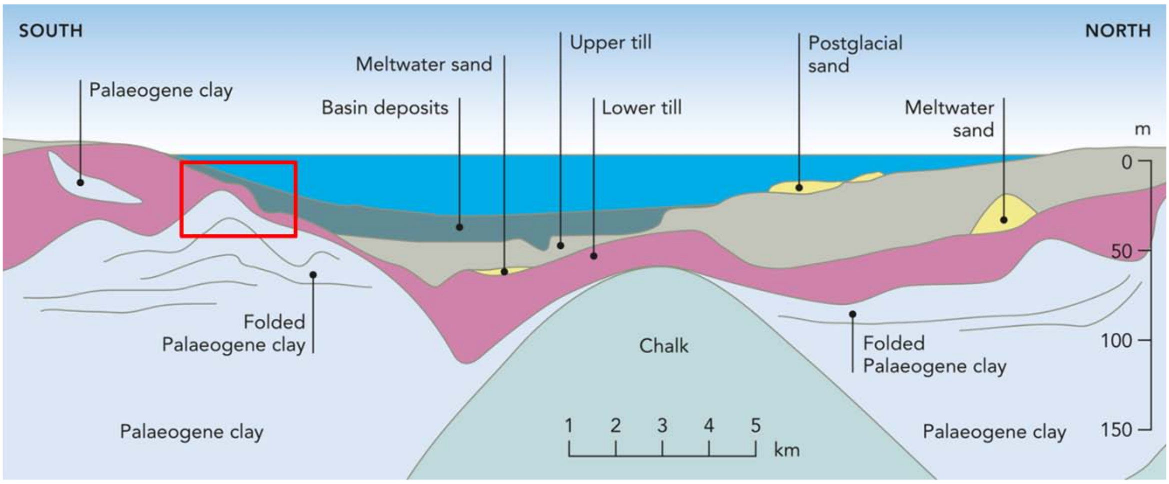

Figure 2: Geology along the Fehmarnbelt strait crossing (section of crossing affected by the Palaeogene clay marked in red)

As part of the test program, a large test excavation was made into the Palaeogene clay at the German side. The required excavation for a tunnel or bridge construction was simulated by removing 10m of the overburden, initiating the swelling process of the clay which is monitored by in-situ instrumentation. The most important parameters to measure during the scheduled test period of 3-4 years are soil heave and negative pore pressure distribution with depth. A novel instrument concept, the “Extenso-piezometer”, was developed by NGI for this purpose. These instruments were installed to different depths in the bottom of the excavation. The deepest (25m) instrument also acts as a reference datum for all heave measurements as the swelling of the clay is expected to be negligible beneath this depth.

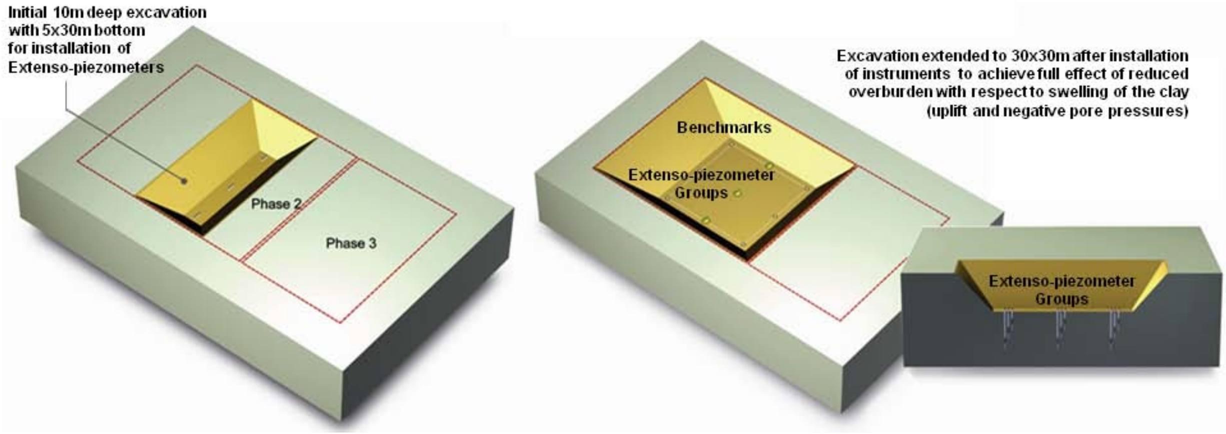

Figure 3: Test excavation and instrumentation (illustration Femern A/S)

Planning and follow up of the Large-Scale Geotechnical field tests was done by the joint venture Rambøll/Arup with NGI as advisor. The main contractor for the marine works is Per Aarsleff A/S (http://www.aarsleff.com) with GEO (Danish geotechnical institute, http://www.geo.dk) as subcontractor. NGI designed and supplied the special monitoring systems described in this paper directly to Femern A/S.

2 Instrumentation challenges and technical solutions

The task to monitor the swelling of the Palaeogene clay beneath the excavation involved many challenging conditions such as:

- The test site is far from shore and the bottom of the excavation is located 20m under water without any infra structure available (fixed structures etc.)
- Difficult installation conditions under water in the excavation with close to zero visibility and rapid re-sedimentation.
- Limited time available for installation, maintaining in-situ conditions with limited disturbance. The swelling process starts immediately after removal of overburden and the measurements should start as soon as possible after excavation.
- After making the initial instrument trench (to minimize the effect of removed overburden) the excavation was expanded to full size while the instrumentation should be in operation.
- Representative pore pressure (suction) measurements are difficult in this type of fat and impervious clay.

- The only reliable reference for soil heave measurements is a “deep datum”, 25m below the bottom of the excavation, requiring drilling through the stiff clay.
- No existing instrumentation solutions could be used and the equipment had to be designed and supplied within 3 months in order to allow for installation within best weather conditions during summer 2010.

The unique “Extenso-piezometer” solution proposed by NGI to Femern A/S is an instrument that combines a down-hole tell-tale rod/anchor system with a hydraulic piezometer/standpipe system. The down-hole assembly is hooked up to an instrument head above the seabed for recordings of both vertical displacement and differential (pore) pressure. All long-term recording instruments at the test site were hooked up to a self-contained logging station (sled) parked near the excavation for autonomous logging and easy down-loading of data by a pick-up cable. Three Extenso-piezometer groups, each consisting of three instruments for recording heave and pore-pressure at three different depths, were installed in the initial trench. Immediately after instrument installation the trench was expanded to the full foot print (30x30m at the bottom) of the excavation and the swelling process was monitored.

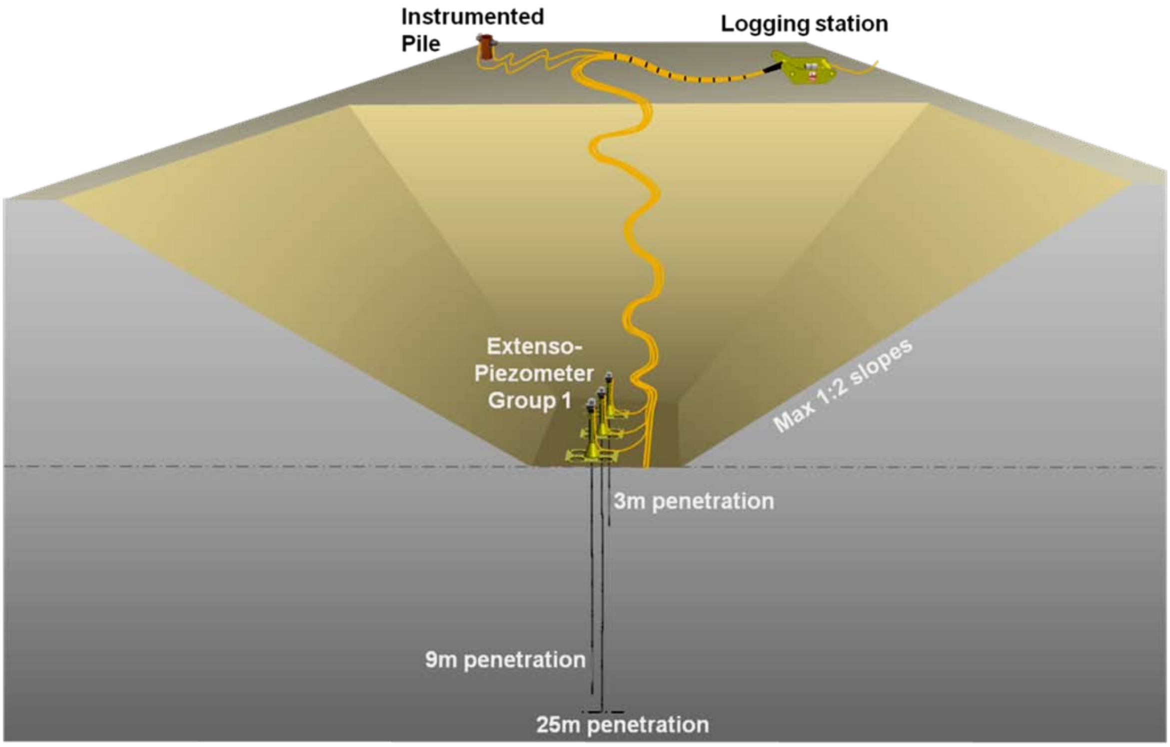

Figure 4: Initial trench with the first group of instruments hooked up to the logging station (the test program also includes Pile load tests and one instrumented pile)

3 Extenso-piezometer Design

The instruments have modular design allowing the down-hole assembly to be installed by a standard geotechnical drill/CPT rig operated from the deck of a jack-up platform. The seabed completion and hook-up to the logging station were performed with assistance from divers. Outlines of the Extenso-piezometer instrument are given in figure 5. Although the instrument was developed to measure swelling (heave and negative pore pressures) it can also be used to measure settlement and positive pore pressures in the sediments when overburden is added instead of reduced.

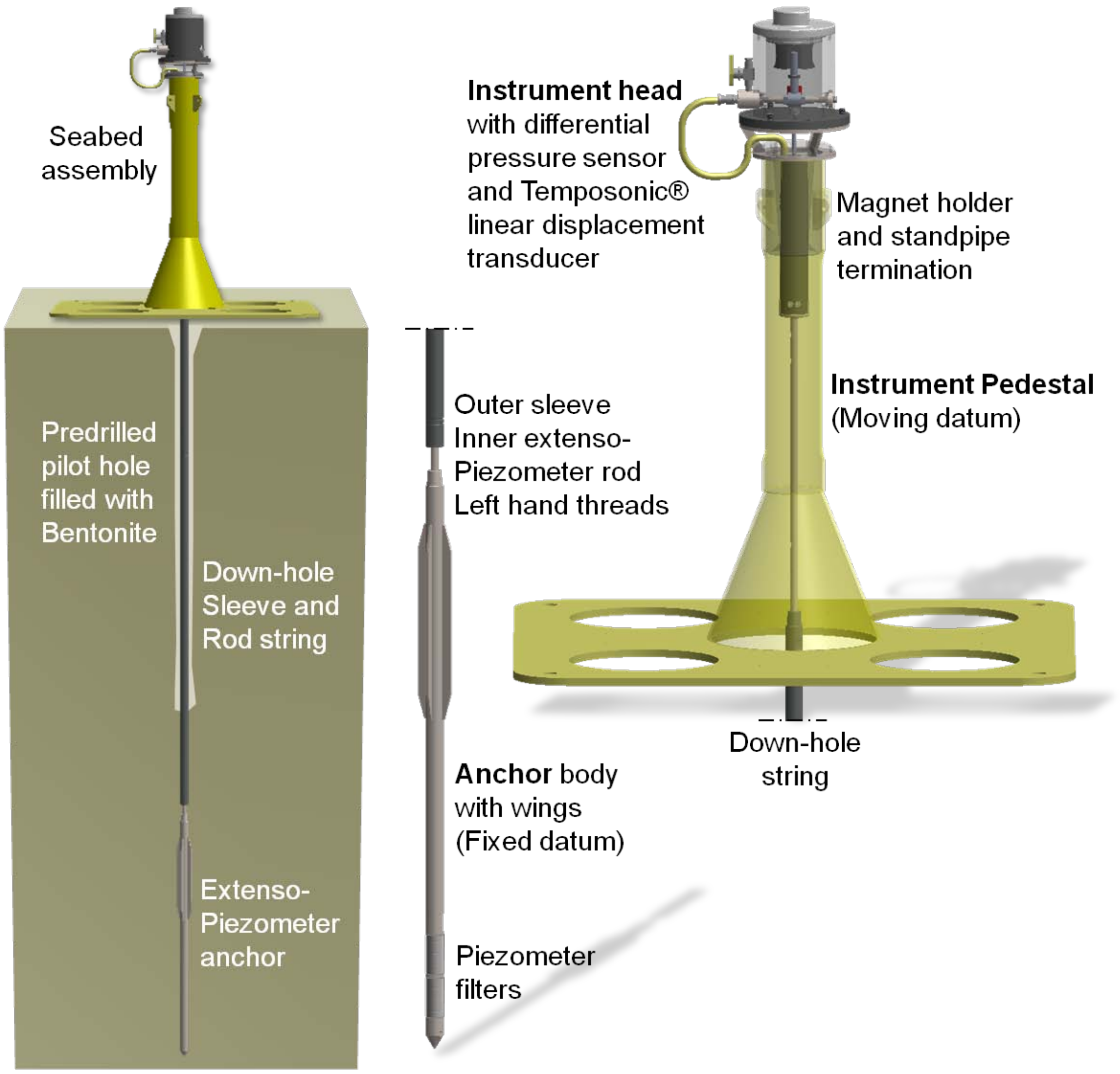

Figure 5: Outlines of the Extenso-piezometer assembly

The “down-hole” part of the instrument consists of an anchor which is penetrated into virgin soil for fixture of the “Tell tale” extensometer rod and to seal the piezometer filters for any drainage to sea. The piezometer system consists of a stand-pipe (hollow extensometer rods) from the filter up to the instrument head at the surface. The pore pressure is measured by a differential pressure transmitter and directly compensated for the ambient hydrostatic pressure. Heave is measured with a Temposonic® linear displacement transducer.

The extensometer rod segments are run inside a sleeve assembly (Ø45mm CPT pipes), giving structural strength and holding the string together when tripped down and finally penetrated to target depth. After the anchor is at target depth, the sleeve is released from the inner rod by rotating the sleeve opening the left-hand threads above the anchor (equipped with wings to increase rotational capacity). The tell tale rod can then move freely inside the grease filled sleeve preventing the anchor to be pulled up by the swelling clay. Since the hollow rod assembly also acts as a piezometer standpipe, each joint has double O-ring seals to prevent leakage.

”Up-hole”, a Temposonic reference magnet holder with a hydraulic jumper hose termination is connected to the last rod sticking up from the seabed. Next, the instrument pedestal is guided in place by divers over the magnet holder. After seating, the base of the pedestal is secured to the seabed by soil screws and sand bags. The instrument head is finally mounted on top of the pedestal with the Temposonic® sensing rod inserted into the magnet holder and the hydraulic hose hooked up to the differential pressure sensor by a quick connector.

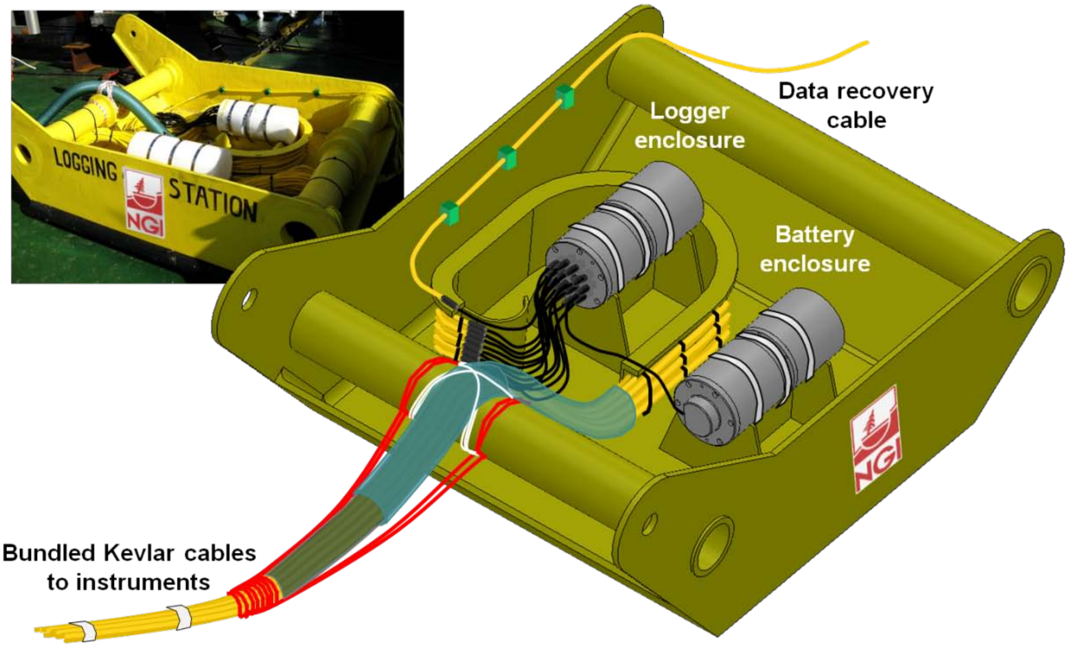

Figure 6: Outlines of NGI’s seabed logging station (sled) hooked up to the instrument array in the excavation for standalone operation.

The logging station has a 24 channel data logger and a battery pack allowing for 2 years of operation without replacement. The station is made of fiberglass and designed as a sled which can be deployed or retrieved in a vertical position for launching in deep waters with a strain relieved cable bundle attached. The seabed cables are light weight with Kevlar reinforcement and thick PUR jacket.

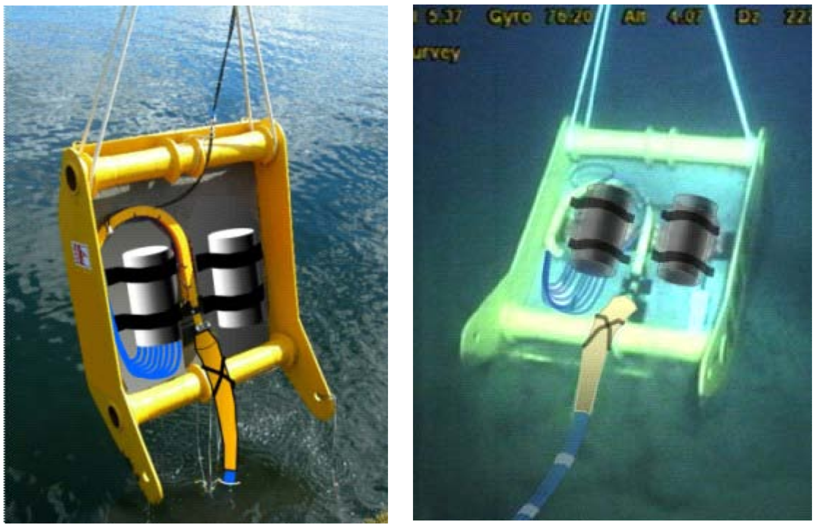

Figure 7: Vertical deployment and recovery of the logging sled with cable bundle attached (left). Landing of the sled on the seabed (right)

4 Test site and installation

The test site is located at the German side of Fehmarnbelt in about 10m water depth were the Palaeogene clay deposits are close to the surface. The onshore base is however located at the Danish side in Rødbyhavn as the Danish authorities (Femern AS) have the main responsibility for the construction work and marine activities in conjunction with the Large-Scale tests.

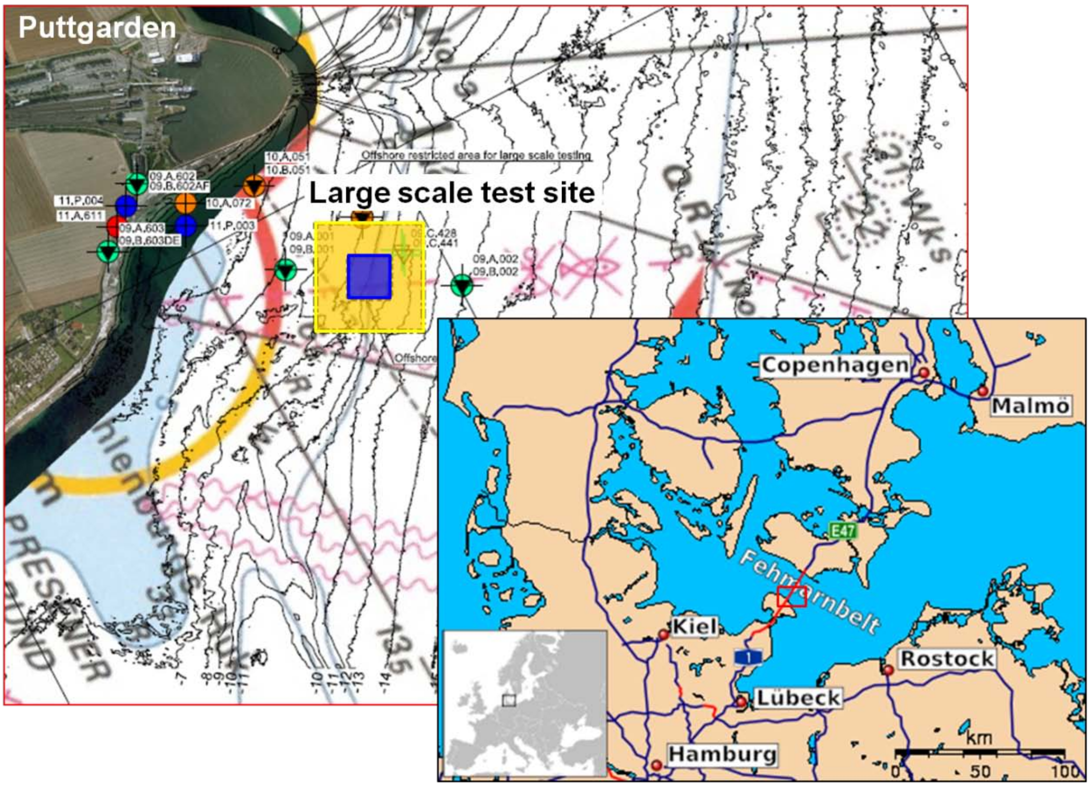

Figure 8: Location of the Large scale test site at Fehmarn belt

The offshore test program started in summer 2010 and also included tensile load tests on piles installed into the Palaeogene clay. The testing include both driven steel piles and bored grouted piles. One of the steel piles has been instrumented by NGI to monitor pore pressure dissipation after driving.

The piles are driven in groups of 9 including 5 test piles and 4 reaction piles. The testing is conducted under water using a submerged reaction frame and a hydraulic jack which is moved and connected to the pile to be tested.

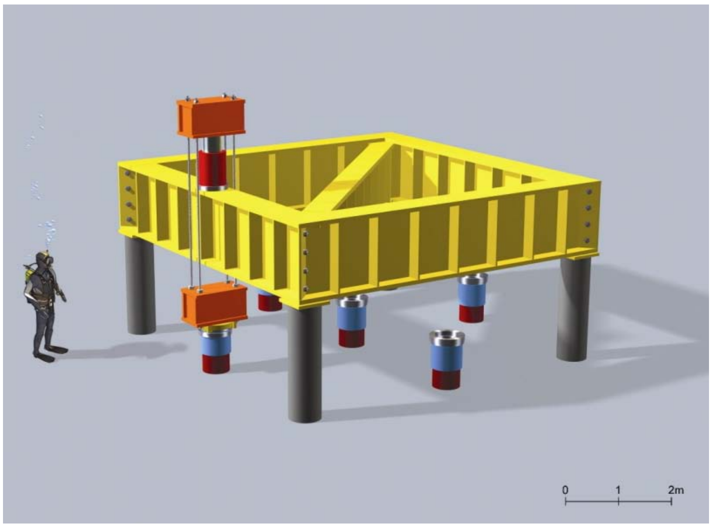

Figure 9:
Arrangement for subsea Pile load testing (picture Aarsleff A/S)

Before, during and after the excavation work, high resolution multibeam echo sounder surveys were conducted by Danish GEO in order to control the work progress but also to monitor slope stability and possible seabed deformation inside and in the vicinity of the excavation.

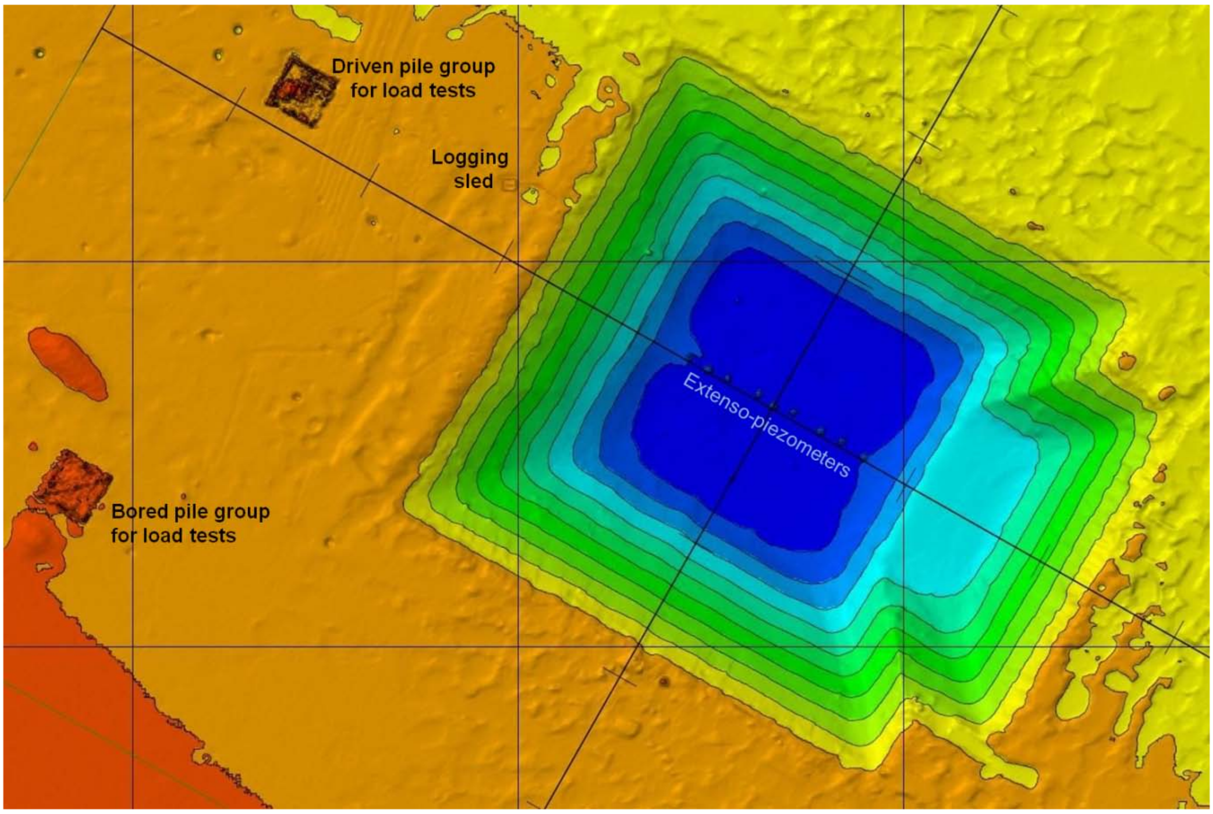

Figure 10: Seabed topography mapped by Multibeam survey (GEO). The Extenso-Piezometers are clearly visible at the 30x30m bottom of the test excavation

As shown in Figure 3, the Extenso-piezometers were installed in a trench excavated prior to the main excavation was started. GEO used one of their land based CPT rigs for the pilot hole drilling and final push-in of the anchors using top drive from a jack-up rig. All down-hole parts were limited to one meter length and installed in similar fashion as normally done for offshore CPT testing (although with more different parts).

Figure 11: Different parts used in the down-hole assembly (from left to right, standpipe rods, filter tip, anchor body and outer sleeve sections)

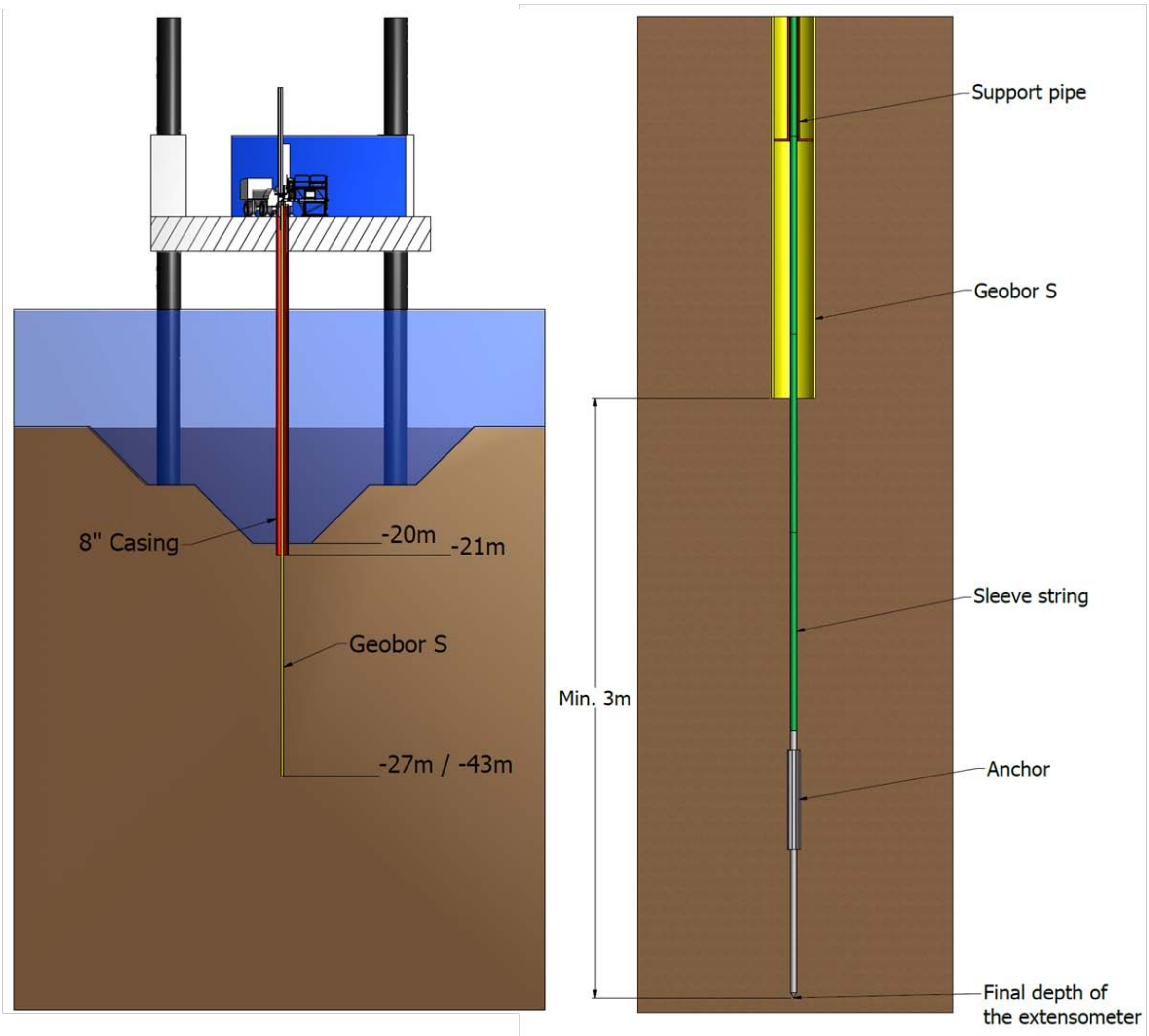

Figure 12:
Set up for pre drilling and final push of down-hole anchor assembly (illustration GEO)

Due to the stiff Palaeogene clay only the shallow instruments (3m) could be installed without pre-drilling, for the other locations the instruments were installed in a pilot hole. However, the anchors were always pushed at least 3m into virgin soil in order to provide a fixed point and sufficient seal above the piezometer filters. In addition, the open hole was filled with a Bentonite mix after the down-hole assembly was installed.

In order to minimize the excess pore pressure build up during push-in of the anchor the piezometer standpipes were left open to sea for some days before the up-hole completion was commenced with assistance of divers.

Due to rapid re-sedimentation in the instrument trench the working conditions for the divers was difficult but manageable.

Figure 13: Deployment of pedestal in the sea

The seabed completion was performed in 5 steps:

Step 1. Installing the pedestals
Step 2. Installing the instrument heads
Step 3. Running cables to pick-up point
Step 4. Hooking up cables to the logging station at the surface
Step 5. Deploying logging station at the seabed

The instrument head was connected temporarily to the logger allowing for real-time control during hook-up and final adjustments of zero points.

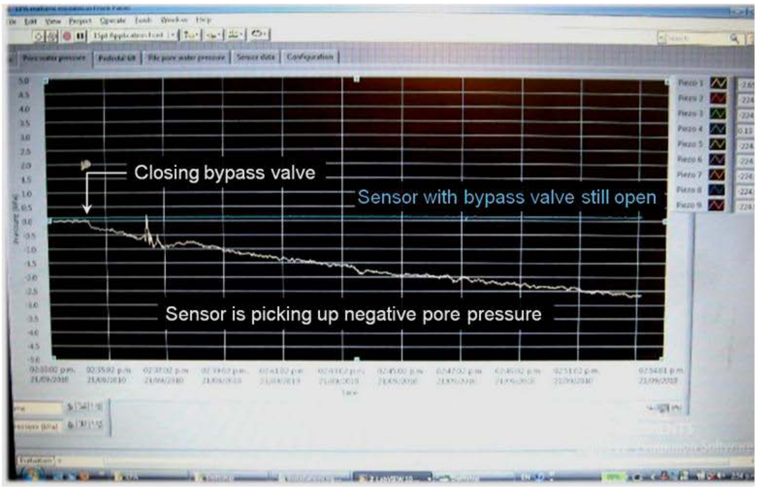

Figure 14:
Hook up of a sensor cable for online check during installation (left). Real-time plot showing one differential sensor picking up negative pore pressure when the bypass valve to sea was closed (right).

Finally, all cables were laid-out to the parking position of the logger sled and secured with sand bags. The cable bundle was picked up to the surface and connected to the logger at the surface. All sensors were checked before the logging station was deployed to the parking position for autonomues data logging at the seabed (protected from waves and heavy boat traffic).

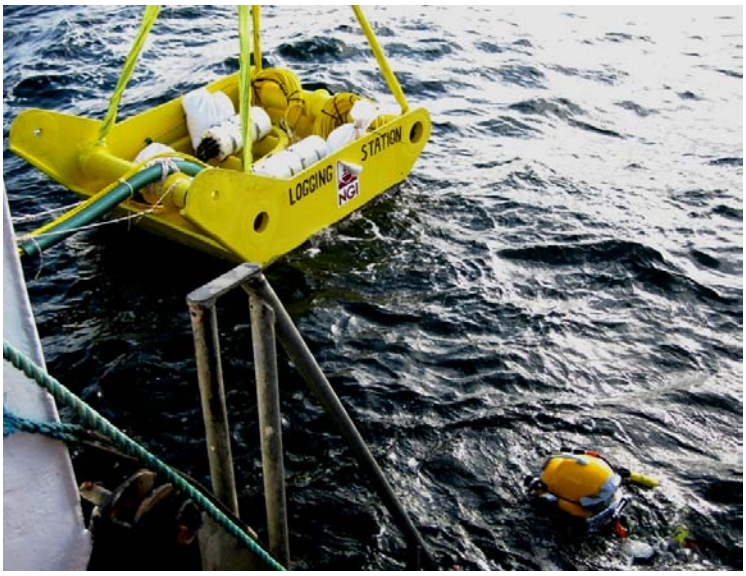

Figure 15:
Logging sled launched to "safe" parking at the seabed after completed hook-up

5 Other instrumentation provided by NGI for the Large Scale field tests

As mentioned earlier one of the driven steel piles (to be load tested) is instrumented by NGI to measure pore pressure dissipation after driving. The pile load test program shall investigate time effects on pile capacity and the instrumented pile is used as a reference for re-consolidation by means of monitoring the dissipation trends.

Designing instrumentation to survive pile driving is always a challenge. For this application NGI decided to use a safe approach without interference to the offshore pile driving operations. As for the Extenso-piezometers a modular arrangement using standpipe piezometers was used. The filter and standpipe assembly is self-saturating and no electrical parts or cables are mounted during driving.

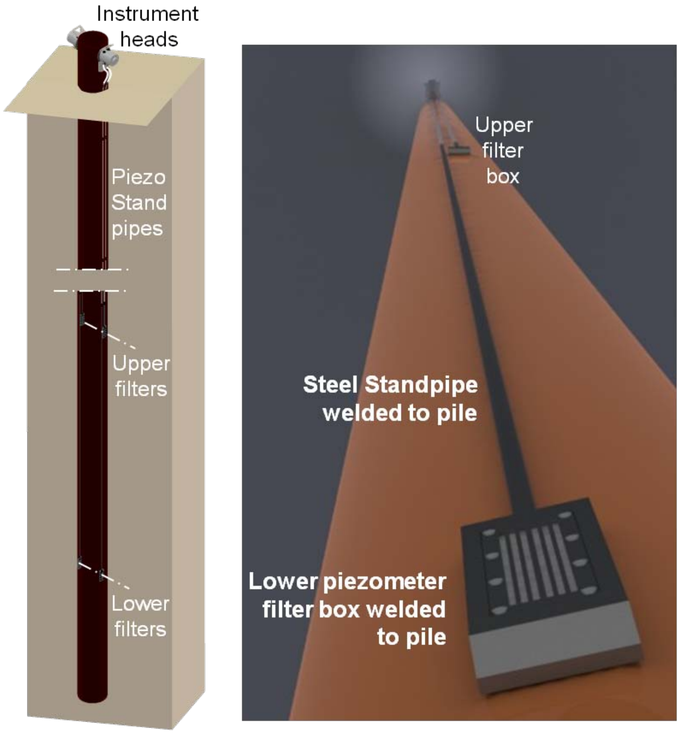

Figure 16:
Configuration of instrumented pile and filter/standpipe system (right)

After pile driving the instrument heads were hung off the pile top and the flexible jumper hoses connected to the standpipes by divers. The instrument response was checked during closing of the bypass valves and they were finally connected to the logging sled by lead-in cables.

Figure 17: Trial hook-up of instrument head at pile top before installation

NGI also provided a Reference Measuring Device (RMD), a multipurpose monitoring “toolbox” for vertical, lateral and inclination displacement measurements relative to a seabed datum. The elevation measurements are measured by a dual CLEM (Closed Loop Elevation Monitoring) system that derives elevation from hydraulic head measurements (independent of ambient hydrostatic pressure). Lateral displacements are measured by using dual taut-wire systems. The RMD system also includes biaxial inclinometers with magnet holders and a camera system. All data is recorded in real-time at the surface by means of an umbilical.

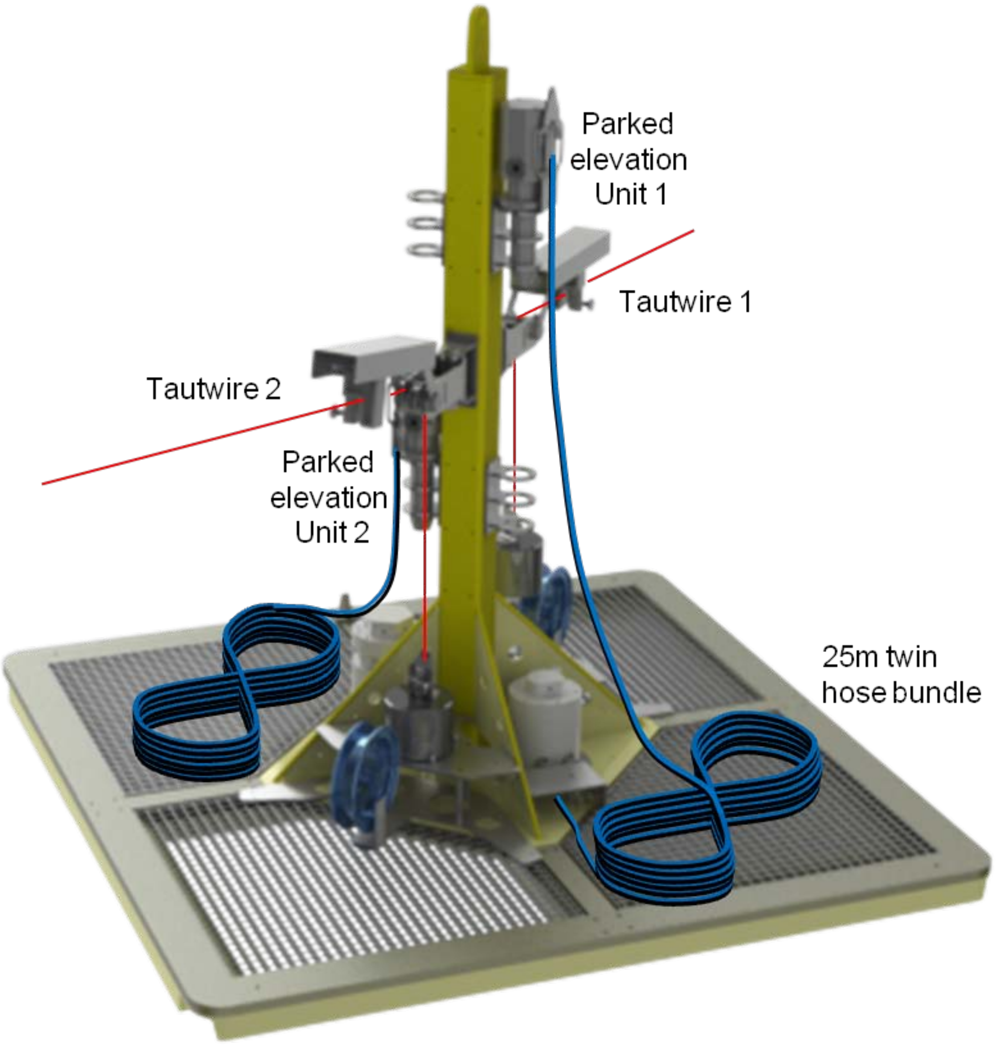

Figure 18: Reference Measuring Device on Seabed frame (Inclinometers and camera not shown)

The RMD unit is used during pile tests for independent measurements of pile displacement at some distance from the loading arrangement, it is also used to check elevation of reaction piles prior to and after load test and to survey possible elevation changes of benchmarks in the excavation with millimeter precision.

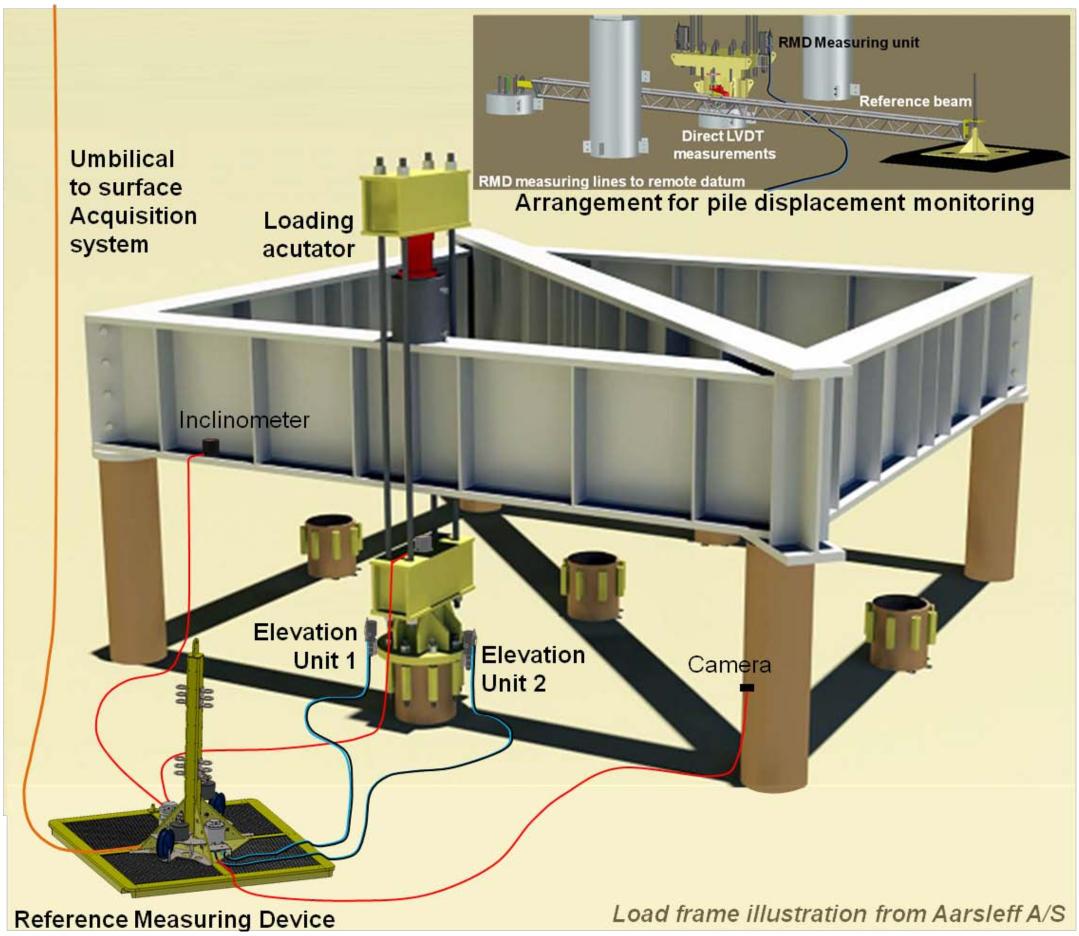

Figure 19: RMD used during Pile load testing

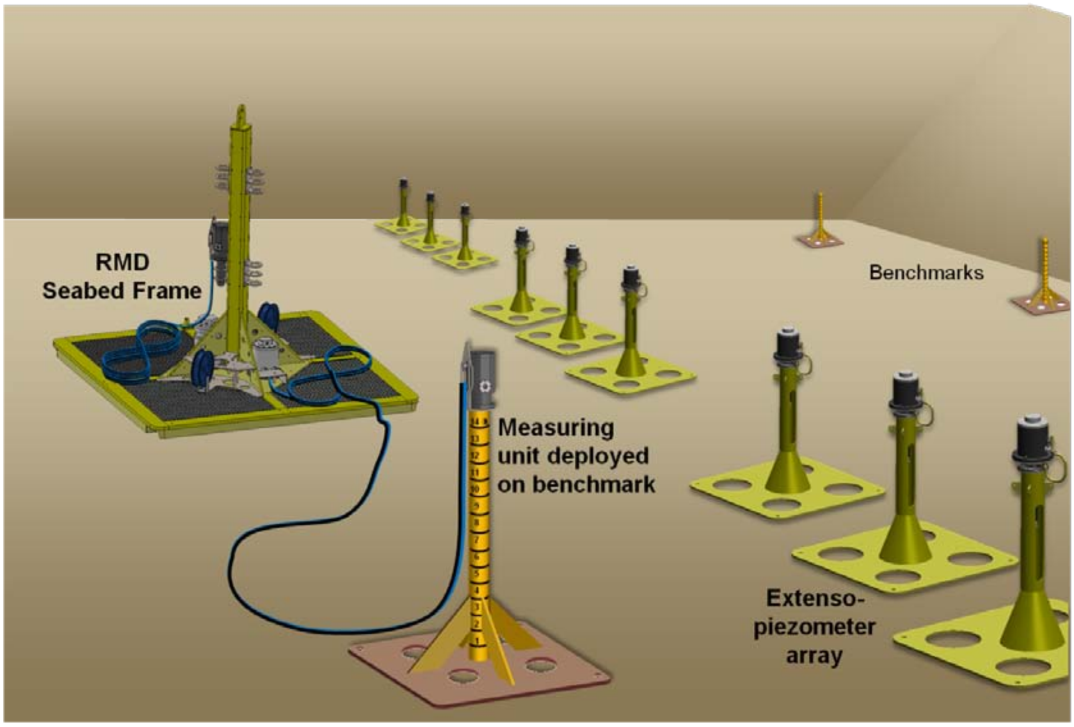

Figure 20: Benchmark leveling using RMD

As a possible second phase of the Large-scale tests program, the excavation will be expanded and lateral pile load test as well as large scale plate loading and lateral earth pressure tests are planned. The RMD will then be used to measure lateral deformations relative a fixed datum.

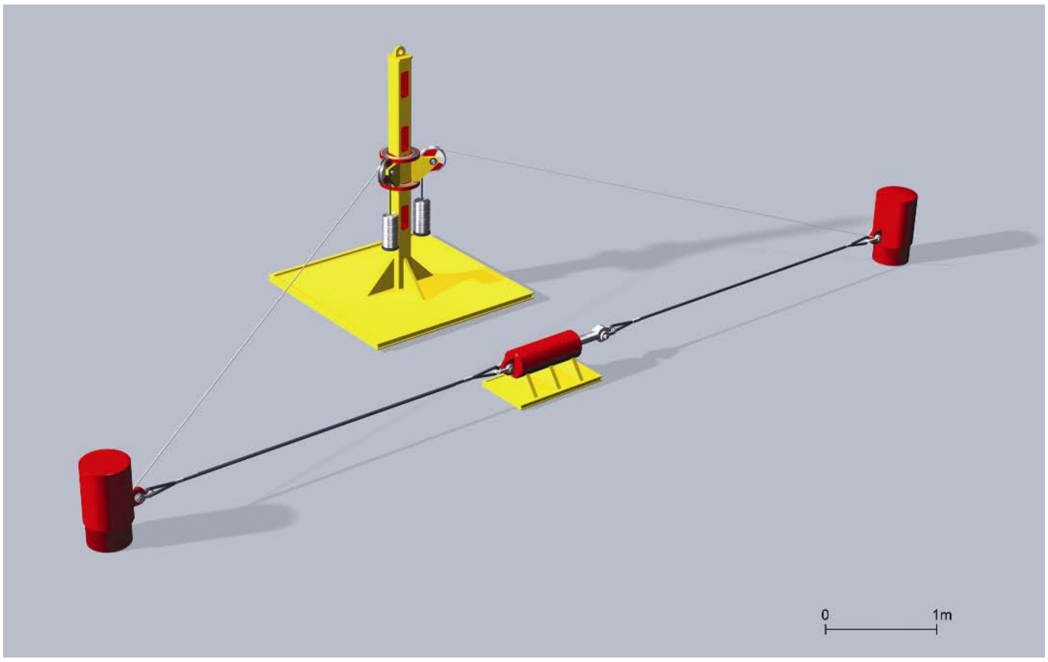

Figure 21: Set-up for lateral pile load testing using RMD to measure displacement

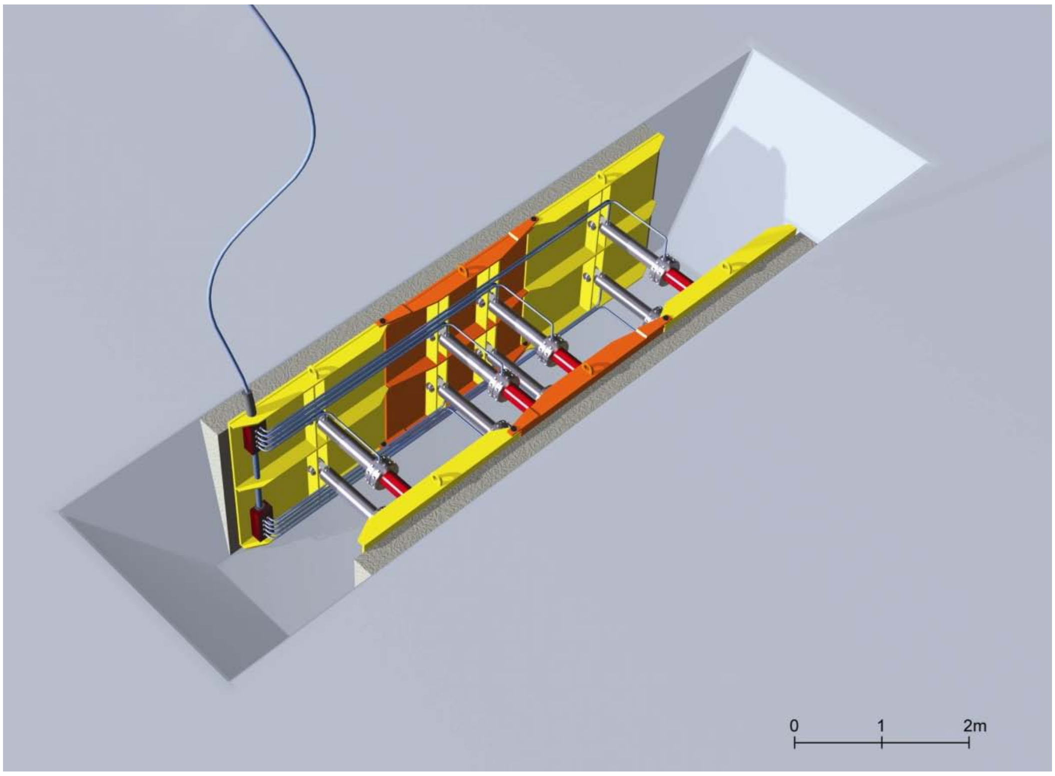

Figure 22: Set-up for lateral earth pressure testing using a special trench (illustrations Femern A/S)

6 Initial operation and results

The data from the Extenso-piezometer array and pile piezometers is downloaded at regular intervals (~2-3 months) in conjunction with commencing pile load tests. The instrumentation has worked well so far although the logger indicated a minor leakage through a subsea connector and was replaced by a back-up unit. Also one instrument head for the Extenso-piezometer has been replaced by a back-up unit after being hit, probably in conjunction with ongoing excavation works.

As the re-sedimentation occurred quickly in the excavation some of the extensometer pedestals may not be placed as firmly as expected on the exposed stiff clay and the measured heave could initially have been reduced by settlement of the pedestal. Therefore the relative elevation of all pedestals is measured by the RMD to detect and compensate for possible settlement of the seabed reference, also some of instrument heads are outfitted with inclinometers. After the first six months of operation a maximum heave of 27mm was recorded by the instruments with deep anchors, while the shallow instruments recorded an average heave of about 10mm.

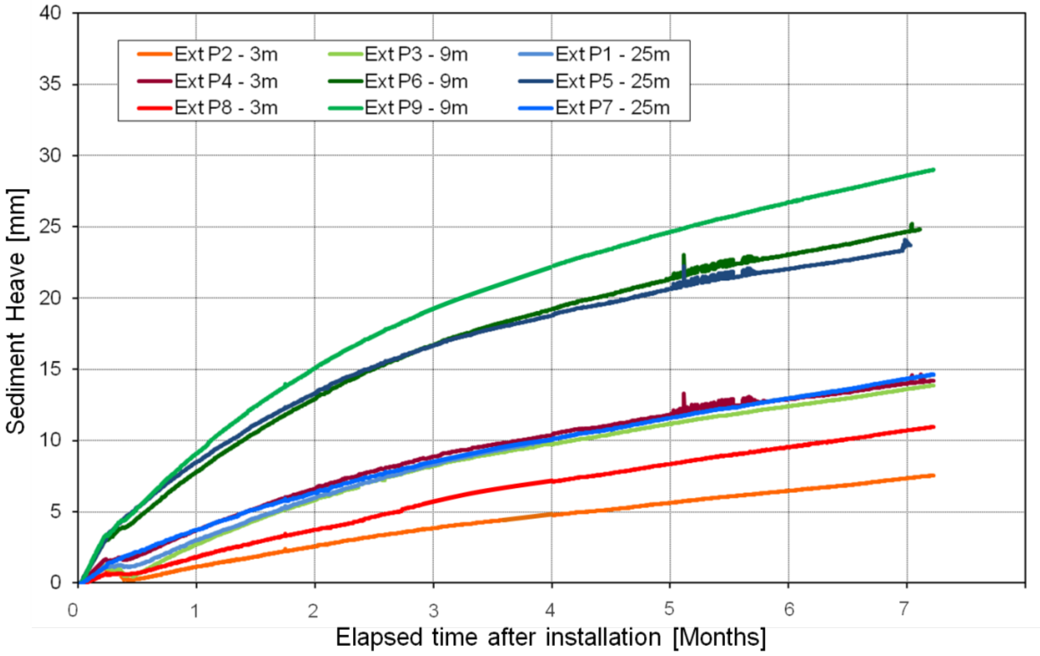

Figure 23: Heave (swelling) recorded by the Extenso-piezometers

The recorded pore pressures are directly compensated for hydrostatic pressure. However, although the piezometer standpipes were open during push-in, the excess pore pressure in the disturbed clay around the filter had not dissipated for some piezometers when the bypass valve was closed and monitoring was started. Thus, for some of the piezometers the magnitude of negative pore pressures may still be affected by the installation in the impervious clay. However, the trend is as expected with the piezometers recording stationary negative pore pressures when the heave is stabilizing at constant rates. The transient drops in pore pressures initially recorded with the shallow piezometers followed the excavating steps when the excavation was enlarged to full size (30x30m bottom footprint).

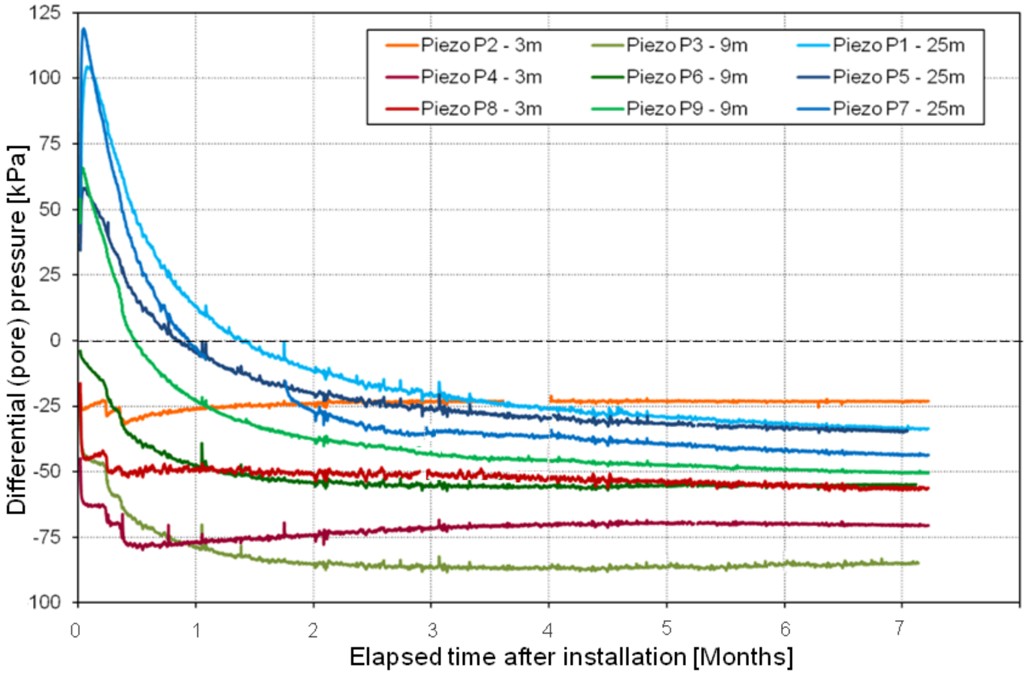

Figure 24: Negative pore pressures recorded by the Extenso-piezometers

The pile piezometers show the dissipation of pore pressures after driving, still with significant excess pressures remaining around the pile wall 6 months after driving.

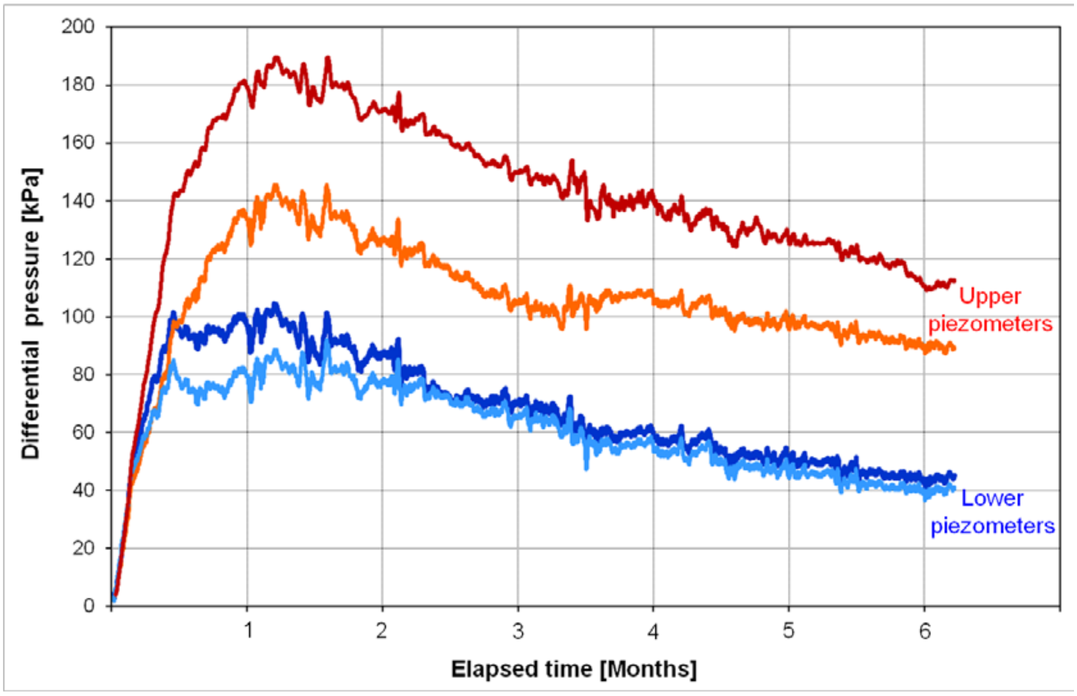

Figure 25: Dissipating pore pressures recorded by the Pile piezometers

The reference measurements (RMD) taken during pile load testing confirmed that the reaction frame did not move during testing and confirmed that the direct LVDT measurements were correct and not subjected to false deformations.

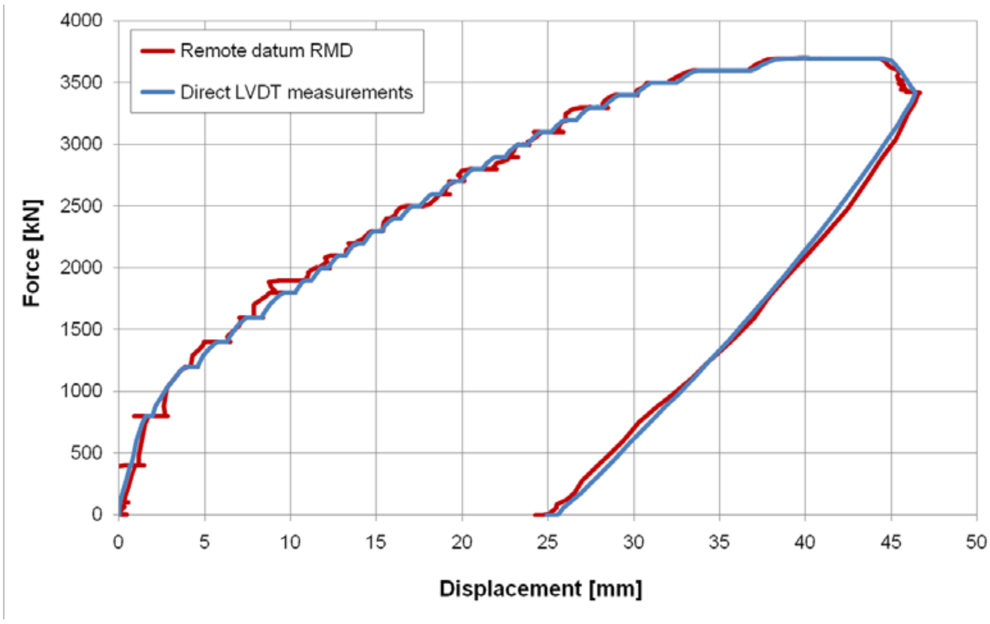

Figure 26: Example of Load displacement plots for a concrete pile pull-out test showing recorded data from both displacement monitoring systems

7 Conclusion

At the time for writing this paper, it appears as the instrumentation has worked as expected and minor problems have been solved during visits for data downloading . The monitoring program is planned to continue for at least three years, all data will be available in the public domain and can be used by potential contractors as input to design and bid preparation for the construction of the crossing.

8 Acknowledgements

Femern A/S is acknowledged for giving NGI the opportunity to participate in this exciting project and for showing their confidence in the proposed instrumentation concepts. Rambøll/Arup JV, Aarsleff A/S and Geo are acknowledged for excellent cooperation during installation and operation of the monitoring systems.

Finally, the project team at NGI with John Løvholt as project manager is acknowledged for extraordinary efforts making the system development and supply possible within a tight schedule. Especially to be mentioned is Stephen Hayes for excellent and fast track 3D design, Yme Kvistedal for getting the electronics in place, Ra Cleave for supervision and problem solving during field installation and Lloyd Tunbridge for field operation and data recovery.

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