Fehmarnbelt Fixed Link. Geotechnical Large Scale Testing

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ABSTRACT  
Femern A/S is tasked with designing and planning of a fixed link between Denmark and Germany, across the Fehmarnbelt. As part of the geotechnical soil investigations, Femern A/S has contracted Per Aarsleff A/S with GEO as a specialist subcontractor to carry out offshore Large Scale Testing in a test area situated in the Fehmarnbelt just north east of Puttgarden Ferry Port. The aim of the investigations is to reveal behaviours of soil and structural elements in the area, characterized by the presence of very high plasticity clay of Palaeogene origin. As a part of this investigation a number of different field tests were carried out, including trial excavations, pile and plate load tests, CPT and multi-beam surveys.  
The field work has been an exciting journey throughout 2 years, where new methods and equipment have been invented to meet the requirements of the project. This paper is a case story where we present the work performed and the individual purposes and some of the technical challenges that we had to overcome to move the project forward.  

Keywords: Full-scale tests, Field testing & monitoring, Offshore engineering.

1 INTRODUCTION  
Femern A/S is designing and planning a fixed link between Denmark and Germany, across the Fehmarnbelt. As part of the geotechnical soil investigations, Femern A/S has contracted Per Aarsleff A/S with GEO as a specialist subcontractor to carry out offshore Large Scale Testing in the test area situated in Fehmarnbelt just north east of Puttgarden Ferry Port. The aim of the investigations is to reveal behaviours of soil and structural elements in the area, characterized by the presence of very high plasticity clay of Palaeogene origin. As a part of this investigation a number of different field tests were carried out.  
The main part of the works consists of a 10 m deep trial excavation, performed in 3 phases.  
The excavation work and the behaviour of the excavation surface are documented by high precision multi-beam surveys. Furthermore, extenso-piezometers and surface targets were installed in the excavation, and CPT, block sampling and 3 different types of plate load tests were performed on the base of the excavation 20 m below sea level.  
In order to carry out the block sampling and to perform plate load testing 20 m below sea level, GEO has designed new equipment to meet the requirements of the project. Chapter 3 & 4 of this paper will focus on this new developed equipment.
Beyond the trial excavation, CPTs were performed, as well as pile load tests on driven steel tube piles and bored cast-in-place concrete piles. The pile load tests will be described in chapter 5 of this paper.

2 TRIAL EXCAVATION

The trial excavation was made in 3 phases: Phase I and II were excavated in 2010, and Phase III 8 months later in May 2011.

Phase I was an 8 m wide and 30 m long trench, in which 9 extenso-piezometers were installed to the depths of 3, 9 and 25 m below the excavations base. The extenso-piezometers developed by NGI for this purpose will be monitoring the swelling process in the palaeogene clay after the removal of 10 m of the overburden, simulating the required excavation for a tunnel or bridge construction. Right after the installation of the piezo-extensometers, the trial excavation was widened to 30 x 30 m forming the Phase II excavation. On the base of the Phase II excavation, 8 surface targets were placed in order to measure sedimentation and differential heave.

In 2011, the trial excavation was widened to its final extent of 30 x 70 m (Phase III). On the base of the Phase III excavation, CPTs were performed using a seabed CPT-rig. Furthermore, block sampling and 3 types of plate load tests were carried out.

3 BLOCK SAMPLING

Block samples with a diameter of 0.3 m had to be taken from 0.5 to minimum 0.8 m below the base level of the excavation. For this purpose, GEO has developed the seabed block sampler shown in Figure 1.

The block sampler consists of a housing frame for motor, casing and bore head, and a tilting device. The unit is controlled by hydraulics, and is lifted to the seabed using a crane. The main purpose of the tilting device is to get better access to the samples and to make it possible to handle them in horizontal position by means of a crane, as explained in more detail later in this paper.

Figure 1 Seabed block sampler with housing frame and tilting device.

When the block sampler is deployed and resting on the excavation base, the drilling can be initiated. The outer tube is equipped with cutting blades, which are cutting down into the formation (see Figure 2). As the outer tube is driven down into the formation, the inner tube is successively following and thus protecting the sample. When the target depth is reached, the rotation of the bore head is reversed, which automatically releases 4 knives cutting the bottom of the sample free from the formation.

Figure 2 Seabed block sampler.
Once the block sampler is recovered on deck of the support vessel, the housing frame is tilted and the sample can be released (see Figure 3 + 4).

The recovered block samples were of high quality, and to the full satisfaction of our client. The housing frame and motor was later refitted with a 1.5 m diameter bucket in order to level the seabed at the designed plate load test locations. The block sampler can thereby easily be adjusted to take even bigger samples than 0.3 m in diameter.

4 PLATE LOAD TESTING

On the base of the Phase III excavation at a depth of 20 m below sea level, 3 different types of plate load tests were performed. In total, 4 vertical, 4 horizontal and 1 passive plate load test were carried out.

To reduce the divers down time to a minimum and to meet the quality requirements of the project, the setup presented in the following pages has been designed.

4.1 Vertical and Horizontal Plate Load Tests

The setup for the vertical and horizontal plate load tests (see Figure 5) consisted of a guide frame (orange+blue) to guide the two main frames (yellow + green) into position, and a cutter frame (yellow) used for support of the clay cutter when preparing the seabed at the designed positions for horizontal plate load testing.

After placing the different frames on the seabed, the seabed was prepared for the tests. At the four positions for vertical plate load testing, the clay cutter removed 0.3 – 0.5 m of the softened clay. Right after cutting, a fine layer of sand was distributed by a diver and the vertical plate (red) was placed by use of the placing tool (light blue).

Afterwards, the positions for the horizontal tests were prepared with the clay cutter resting on the cutter frame. For each horizontal test, three round cuts – with positions predefined on the cutter frame – had to be cut. After the preparation of each position, a 4 cm thick layer of sand was distributed by the divers using a levelling tool. On these sand pads, the horizontal test pads were placed using the placing tool (orange). On the test pads (see Figure 6) concrete kentledge beams were placed (grey) to ensure skirt penetration into the clay, and to provide vertical load during testing.

The preloaded test pads were left on the excavation bottom for 30 days before the testing was initiated, such that the loaded clay could reach its equilibrium. The consolidation settlements of the pads were measured using two mini-measuring bridges (yellow) with two vertical displacement transducers mounted on each.
During consolidation of the horizontal test pads, the vertical tests were carried out. For this purpose, the main frames were loaded with the required kentledge (black) to provide vertical reaction during the tests.

Thereafter the pressure unit and the main measuring bridge were lowered into position (see Figure 7).

The pressure unit was equipped with a contact plate. Three displacement transducers and two measuring devices delivered by the client were attached to the contact plate (see Figure 8).

On the deck of the support vessel, a predefined load scheme – different for each of the four locations for the vertical tests – was followed using the hydraulic steering unit.

After the 30 days consolidation period, the horizontal tests were initiated. The main measuring bridge with the attached transducer frame was lowered to the seabed, and the transducer frame (see Figure 9) was connected to the test pads.
Full-scale tests - Fehmarnbelt Fixed Link. Geotechnical Large Scale Testing

By means of the horizontal pressure unit (see Figure 10), the test pads were pulled horizontally over the seabed until the shear failure occurred. The movement of the test pads was monitored by 8 displacement transducers and the data logged for later 3D modelling of the movement.

Several units were designed modular and used for different purposes. The block sampler was modified into the clay cutter, the horizontal installation system was modified into the main measuring bridge used for both vertical and horizontal testing, and the vertical installation system was transformed into the vertical and later into the horizontal pressure unit.

The setup proved to be very efficient, and with the established know-how, similar setups for other purposes, e.g. vertical plate load testing for wind turbine foundations, can easily be mobilized.

4.2 Passive Plate Load Tests

Passive plate load testing was performed in a 2.5 m wide and 6 m long trench at the bottom of the phase III excavation. As the trench was dug by the dredger approx. 1 month prior to execution of the test, the passive plate load equipment was divided into two parts: An outer box (trench box) and an inner box (jacking unit) as shown in the following Figures 11 and 12.

After placing of the inner box into the trench box, the test was initiated, and the two plates of the trench box were pushed apart at a constant rate until a translation of 30 cm was reached.
5 PILE LOAD TESTING

Part of the Geotechnical Large Scale Testing program implies installation and tension load testing of 5 driven steel tube piles and 5 bored cast-in-place piles. All piles have been installed at the test site near the German coast at a water depth of approximately 10 metres. In the following, the pile installation, the test setup as well as the performance of the pile load tests will be described.

5.1 Pile Installation

The two types of test piles were installed in groups consisting of 9 piles each as illustrated in Figure 13.

Figure 13 3x3 pile configuration (bored piles).

The 4 corner piles in each pile group serve as reaction piles for the pile load tests to be performed on the remaining 5 piles in each group. The test piles (steel as well as concrete) were installed with their toe 25 m below seabed, while the reaction piles were installed to 22 m below seabed.

The bored cast-in-place piles were installed from a jack-up rig by a BG36 drilling rig, see Figure 14.

As test loads up to 6 MN were to be reinforced by 8 Ø36 mm SAS high strength steel bars.

The driven steel tube piles were installed from a jack-up rig by a crane-suspended IHC S90 hydrohammer. All piles were OD508 mm with steel thickness of 20-22.2 mm. At regular intervals during the pile installation, it was controlled whether plugging of the piles was tending to occur, as this would disturb the soil around the piles. Plugging was removed by percussive drilling down to pile toe before continuing the pile driving.

Figure 14 Installation of bored piles.

All piles were driven with additional length thus making it possible to keep the hammer above the water at all times. After installation to the required depth, the piles were then cut off at the desired levels.

As the installed position of the test piles and the reaction piles was crucial, installation frames (piling guides) were constructed and lowered to the seabed before starting the pile installation. By means of these piling guides, it was possible to reduce the off-set of the piles relative to the planned positions to less than 25 mm.

5.2 Reaction System

In order to transfer the load from the test piles to the reaction piles, two large reaction frames (piling guides) were constructed and lowered to the seabed before starting the pile installation. By means of these piling guides, it was possible to reduce the off-set of the piles relative to the planned positions to less than 25 mm.
reaction piles by a 130 tons mobile crane located on a jack-up rig. Figure 15 illustrates the installation of one of the two reaction frames.

Figure 15 Installation of reaction frame by mobile crane.

During the installation of the reaction frames, the optimum position of the frames (the position of the frame reducing the maximum off-set of the frame girders relative to the centre of the test piles) was found by divers simply measuring the off-sets by spirit level.

5.3 Loading Equipment and Instrumentation

The 2x5 test piles are to be tested 1 to 5 times. In this way, 30 pile load tests will be performed in total (of these 20 pile load tests have been performed by the end of 2011).

As all parts of the loading equipment and the instrumentation have to be installed by divers, great effort has been made in designing a test setup that is relatively easy to install and remove.

A test unit containing the hydraulic jacking unit as well as the load cell has been designed. The shape of the bottom plate of the test unit has been designed to allow for ±22.5° rotation of the test unit, which is necessary to ensure that the load transfer is in vertical direction, as 8 bars are used for connecting the test pile with the loading equipment. The test unit is illustrated in Figure 16 which shows a snapshot taken from the video recorded by the camera mounted on the diver’s helmet.

On top of the test unit, a yoke in the shape of a 150 mm thick steel plate with reinforcing plates is located.

After lowering the test unit on top of the reaction frame at the position of the test pile, 4 Ø57 mm SAS high strength steel bars are mounted to connect the upper yoke with a similar lower yoke mounted on top of the test pile, as illustrated in Figure 17 showing the entire test setup for driven steel tube piles. Hereafter, the verticality of the Ø57 mm bars is checked, the result being used to determine in which direction the test unit should be moved or rotated (if necessary) in order to obtain verticality of the bars within the specified limits.

The deformation of the pile during testing is registered by two displacement transducers of the LVDT type – the one acting as backup for the other. The displacement transducers are mounted temporarily on the side of the test unit during lowering of the test unit. In this way, all signal cables and hydraulic hoses are brought to the seabed in one run when lowering the test unit.
Apart from the instrumentation described above, a Reference Measuring Device (RMD) equipped with different measuring equipment is provided by the client. For the pile load tests two trim cubes (inclinometers) of the RMD are applied – one on the lower yoke as illustrated in Figure 18 and one on the lower flange of the reaction beam girder.

Furthermore, two elevation units of the RMD, which are measuring the elevation by means of a hydraulic system, are applied during the pile tests. In this way, the two elevation units are mounted in two brackets – one on each side of the lower yoke serving as an additional backup measurement of the vertical pile deformation, see Figure 18.

5.4 Reference System

In order to obtain reliable measurements of the pile deformation during testing, it is crucial that the displacement transducers are mounted on a reference system which is stable and which can be assumed to be isolated from the soil deformations induced by the test pile as well as the reaction piles.

During the design process it was found that an aluminum truss (alutruss) normally used for building concert stages is the optimum choice as the reference beam. This is due to the fact that this type of truss is quite stiff and easy to handle. Furthermore, the relatively small projected area of the tubes minimizes the forces induced by the sea current which can be quite intense at the site in Fehmarnbelt. Finally, standard brackets for mounting of different equipment on the truss are readily available. The alutruss used can be seen in Figure 17, but is more clearly illustrated in Figure 19.

The one end of the reference beam is mounted on one of the test piles not being tested at the moment thus providing a very stable end support of the truss.

The other end of the reference beam is mounted on a $1 \times 1 \text{ m}^2$ seabed support frame which is placed on the seabed approx. 4.5 m from the test pile after removing any thin layer of soft sediment and replacing this with a gravel pad. The seabed support frame is equipped with a small skirt in order to provide horizontal stability. Therefore, the diver must use his body weight to press the skirt into the gravel before ballasting the bottom plate of the frame by sand bags. The seabed support frame can be seen at the lower right corner in Figure 17.

The mounting brackets at each end of the reference beam allows for vertical adjustment as well as rotation of the beam. In this way, the reference beam can be leveled perfectly which is necessary in order to ensure that the displacement transducers measure the deformations in vertical direction. Figure 19 illustrates the two displacement transducers mounted on the reference beam as well as the reference plate mounted on the pile.

In order to optimise the test setup process, a trial setup comprising the loading equipment as well as the reference system was performed on land before starting the test program. This made it possible to make small adjustments to improve the equipment before bringing it offshore. Furthermore, check lists with detailed instructions and illustrations...
have been elaborated. During each test setup, the check list is followed and checked by the diving supervisor who is constantly in contact with the diver(s) by radio and camera. This has proved it possible to reduce time consuming errors and misunderstandings during the test setup to a minimum.

Generally, it has been strived to achieve a high degree of flexibility when designing the different parts of the test equipment. During the execution of the work, this has turned out to be a key parameter as regards overcoming unforeseen challenges encountered especially when testing new piles for the first time.

5.5 Execution of Tension Load Tests

After finalization of the test setup at a given test pile, a steadiness test is performed with the purpose of verifying that the reference system as well as the instrumentation is performing as expected. In this way, the system is left untouched for minimum 5 minutes while the measured deformations are followed on the monitor of the data logging equipment on the deck of the support vessel.

Generally, it has been observed that the measured deformations during these initial steadiness tests have been very limited thus proving the efficiency of the designed reference system.

All pile tension load tests follow the same incremental loading procedure as presented in Table 1. Each load increment is applied in 30 seconds.

<table>
<thead>
<tr>
<th>Load step</th>
<th>Total load (load increment)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Datum load 100 kN</td>
<td>Hold point</td>
</tr>
<tr>
<td>1</td>
<td>400 (300) kN</td>
<td>6 min</td>
</tr>
<tr>
<td>2</td>
<td>800 (400) kN</td>
<td>6 min</td>
</tr>
<tr>
<td>3</td>
<td>1200 (400) kN</td>
<td>6 min</td>
</tr>
<tr>
<td>4</td>
<td>1400 (200) kN</td>
<td>4 min</td>
</tr>
<tr>
<td>5</td>
<td>1600 (200) kN</td>
<td>4 min</td>
</tr>
<tr>
<td>6</td>
<td>1800 (200) kN</td>
<td>4 min</td>
</tr>
<tr>
<td>Thereafter</td>
<td>Xxxx (100) kN</td>
<td>3 min</td>
</tr>
</tbody>
</table>

As previously mentioned, the 2x5 test piles are subjected to 30 pile tension load tests in total. In this way, the piles in each pile group are generally tested at multiple ages after pile installation as follows:

- 5 tests on one pile (1, 3, 6, 12, 24 months)
- 4 tests on one pile (3, 6, 12, 24 months)
- 3 tests on one pile (6, 12, 24 months)
- 2 tests on one pile (12, 24 months)
- 1 test on one pile (24 months)

This extensive test program provides a perfect opportunity to study the effect of multiple testing, but also the effect of ageing is well illuminated.

The final test campaign (24 months) is yet to be performed. It is expected that these final 10 pile tests will be performed in the summer of 2012.

Therefore, it is still too early to draw final conclusions on the results of the performed pile load tests, but until now the test results have shown to be very consistent. In this way it is judged that the results of the performed tests will provide valuable information about the effect of multiple testing and ageing of piles installed in paleogene clay.

6 CONCLUSIONS

In order to meet the technical challenges entailed by working at a water depth of 10-20 metres, different types of new testing equipment have been developed. Great effort in designing very flexible equipment combined with a detailed planning process including onshore trial setups has proven to be beneficial as regards to ensuring test results of the required high quality as well as minimizing the down time of the divers.

With the established know-how, similar setups for other purposes can easily be mobilized.

This paper does not include information about the actual test results achieved during the testing campaign. However, more information and publications on the geotechnical campaigns for the Fehmarnbelt Fixed Link can be found on the Femern A/S homepage, www.femern.com.