CT Trial Installation-

UF Final Report

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Enterprise no.: 26046246

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1 Project details

Project title	Bucket foundation trial installation in multi-layered soil profiles (CT trial)
Project identification (program abbrev. and file)	64012-0214
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Nicolai Hallum / Universal Foundation
Project partners	Aalborg University, Statoil
CVR	26046246
Date for submission	30.09.2015

2 Short description of the project objective and results

Mono Bucket (MB) foundation is a next generation novel foundation concept that is capable of delivering significant cost reduction to offshore wind farms. The objective of the project is to gain confidence in the offshore installation and handling of the full scale MB in a variety of soil conditions including “impermeable” clays and dense sands.

Project aimed for a series of 5 trial installation with the same test bucket and realized in total 29 installations of two bucket type foundations. The diameter of the full size Universal Foundation, UF, MB foundation was 8 m with a skirt of 6 m, weighing 75t and sizes of Reference bucket were 6 m of skirt and 4 m in diameter with the weight of 25t. Campaign resulted in several measurements for each installation, including installation pressures, flows, inclination, vertical speed, geotechnical investigation and acoustic core analyzes. Installation data confirmed the robustness of the foundation concept, improved the design procedure and reduced the concept risk.

3 Executive summary

The trial installations took place in the North Sea and tested a wide range of different locations, all meticulously and individually selected by the developers due to their challenging soil properties. Soil characteristics within the three sites varied from soft clay, moraine clay, boulder bank clay- with sand spikes and layers, clay crust, sand and silt.

Within 24 days campaign, the sum of 29 installations were achieved between the two different bucket structures- Mono Bucket (the ‘UF’ bucket) and conventional ‘Reference’ Bucket, Figure 1 and Figure 2.

Figure 2 Trial installation Mono Bucket foundation

Figure 1 Reference bucket

The installations were carried out at the three offshore wind farm locations: Dogger Bank, Hornsea and Dudgeon in the UK North Sea. The tests were conducted from the jack-up vessel Brave Tern, Figure 3.

Figure 3 Brave Tern jack-up vessel

The campaign commenced with departure from Frederikshavn on the 5th of September and was finalized on the 4th of October, when the vessel arrived in Bremerhaven, Figure 4.

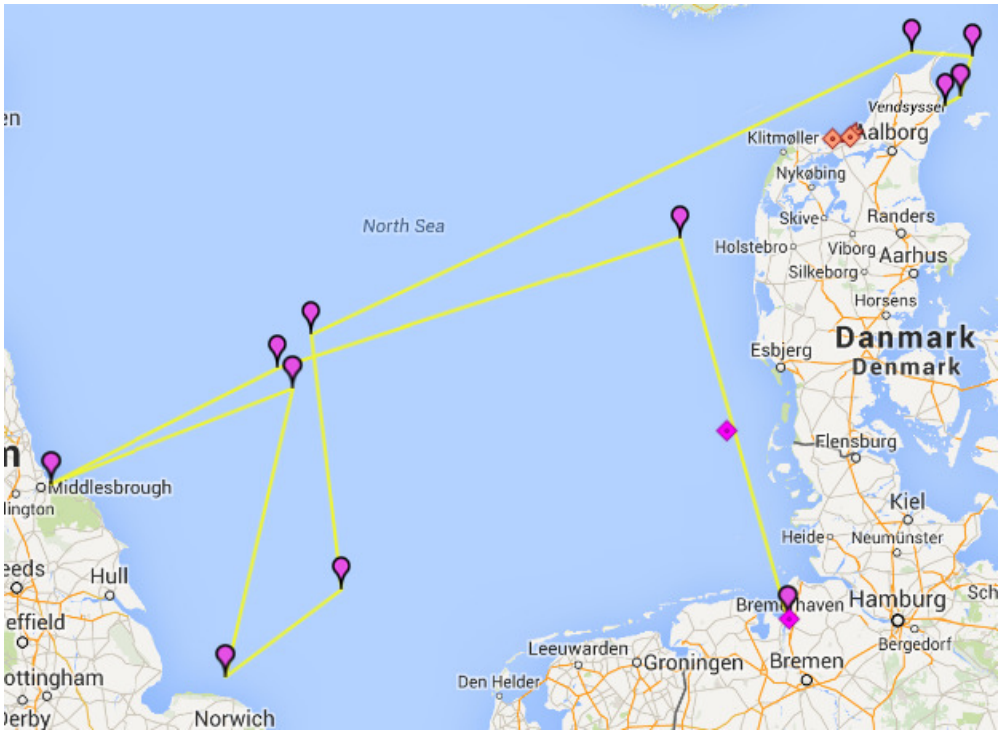

Figure 4 Installation route

The Trial Installation campaign demonstrated that the performance of the Mono Bucket exceeded the predictions and that the suitability of the concept goes beyond the expected limitations. With 24 days of a constant 'installation, retrieval and installation' cycles the Mono Bucket showed incredible robustness and flexibility in its performance. Even with very sticky to hard and stiff clay conditions as

well as combinations of layered soil profiles the vertical control of the Mono Bucket with the inclination below 0.1 degree across all installations confirmed the ability of the concept to stay below 0.25 degree limit.

The installation results were mainly used to calibrate and validate the CPT-Based Method for installation of MB foundation in layered soil profiles, developed by Universal Foundation (UF) and Aalborg University (AAU). In addition, obtained data developed a better understanding of the penetration ability of suction installed bucket foundation in layered soil conditions.

4 Project objectives

The overall objective was to gain confidence in the offshore installation and handling of the MB foundation in variety of soil conditions. Several measurements were collected during each installation, i.e. installation parameters like pressures, flows, inclination and vertical speed/position, geotechnical investigation and supplementary acoustic core analyzes.

4.1 Main challenges

Three main risks associated with the installation process were identified as:

- Installation of the bucket foundation in difficult soils (e.g. multi-layered soil profiles of sand, silt and clay), and when encountering boulders,
- Achieving verticality during installation in multi-layered soil profiles,
- Damage to skirt during transportation and installation.

It was generally considered complicated to install skirts/"buckets" in multi-layered soils including "impermeable" clays and dense sands. Verticality control for single compartment structures is not completely documented as well. Both this uncertainties are addressed through this project. The project also validated the offshore handling and the installation process of a single compartment MB foundation with the innovative design called the multi shell (a pre-buckled skirt).

4.2 Scope of the project

The project will:

- obtain design parameters for skirt penetration of a series of different soil profiles,
- Prove the offshore workability and installation of the single compartment MB foundation,
- De-risk the installation process and increase confidence to the structure.

The long series of installation data will significantly improve the robustness of the foundation concept and the experience gained will reduce the concept risk. The outcome will provide the partners with valuable data regarding installation of the skirted structure in different soil conditions, which also can be used for other skirted foundation designs.

4.3 Structure of the project

The project was divided into 4 work packages, each containing a number of tasks. Each work package had a work package leader responsible for the tasks in the work package and reporting to the project manager. WP 1 was describing the Task for the Project Management. The actual testing and data analysis was described in WP2. The main activities as the fabrication of the test bucket and the chartering of the installation vessel with the offshore equipment needed to do the actual installation were described at WP3 and WP4.

WP 1: Project management		Leader: Lars Kjuul Kristensen (UF)
Partners	Statoil; OWA Partners; Subcontractors	
Objective: This WP will manage the project		
Description of Work: Task 1.1: Project Management, CDM, HSEQ Task 1.2: Contracting Vessel charter, Fabrication Task 1.3: Document control Task 1.4: Engineering coordination Task 1.5: Control of Fabrication and Load-out		

WP 2: Test planning, execution and analysing		Leader: Lars Bo Ibsen (AAU)
Partners	UF; Statoil; OWA Partners	
Objective: This WP will measure and analyse the tests		
Description of Work: Task 2.1: Test Site identification Task 2.2: Stress in the foundation skirt during penetration Task 2.3: Prediction of penetration resistance Task 2.4: Test data processing and reporting		

Test Site identification: Following combinations were considered as the most challenging:

- A significant and continuous clay layer over dense sand

- Clay over sand where sand is variable (inhomogeneous)
- Clay over sand where sand is multi layered
- "Dirty sands", i.e. sands with significant fines content and uncertainty related to drained vs. undrained behavior.

Initially several sites within the Dogger Bank offshore wind farm zone have been identified as suitable for the installation and the 5 locations were chosen. However, during the installation campaign the project evolved to 3 offshore sites: Dogger Bank, Hornsea, and Dudgeon, where 12 locations were chosen for the installation.

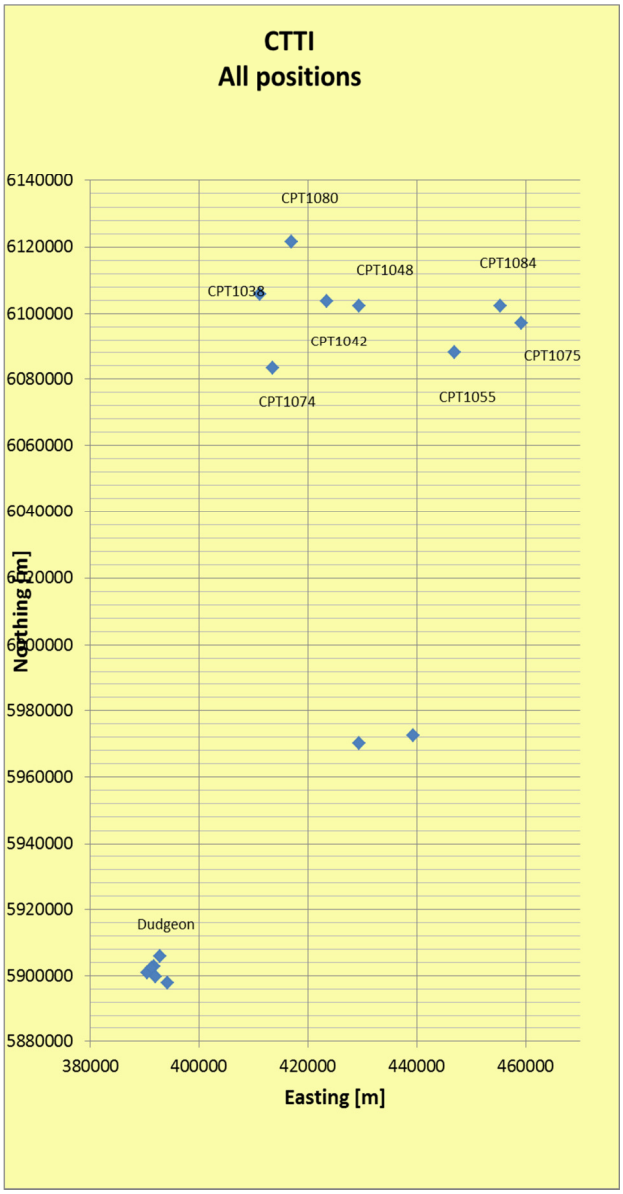

Figure 5 Trial Installation positions

WP 3: Engineering, design and fabrication of test Bucket	Leader: : Morten Fejerskov (UF)
Partners	Subcontractors: Steel manufacture
Objective: This WP will plane measure and analyse the tests	
Description of Work: Task 3.1: Detail design of the test bucket Task 3.2: Design of sea fastening etc. Task 3.3: Fabrication	

WP 4: Offshore operation and installations	Leader: Jens Sten Nielsen (UF)
Partners	Subcontractors: Vessel
Objective: This WP will plane measure and analyse the tests	
Description of Work: Task 4.1: Plane offshore operations Task 4.2: Offshore handling Task 4.3: Method statements Task 4.4: Installation tests	

Offshore handling: The project will test novel improvements of the handling of large structure:

- Use of Lifting yoke with guide system and automatic lock/release function to minimize manual handling and human interaction
- Avoid human interaction during lifting operations
- Bumper guides to be installed to protect and guide the foundation onto the sea fastening arrangement.

Use of Lifting yoke with a guided system and automatic locking/release function required to minimize manual handling, resolve access issues and to avoid human interaction with the foundation during lifting. Present solution, Figure 6, (shown to the left) will be upgraded to incorporate the remote functions similar to the yokes shown to the right.

Figure 6. Present solution (shown to the left) will be upgraded to incorporate the remote functions similar to the yokes shown to the right.

Bumper guides were installed on the seafastening to protect and guide the foundation during lifting operations, Figure 7. Only slight changes were required to facitilate easy retrieval and landing to seafastening arrangement which avoided offshore hot-work.

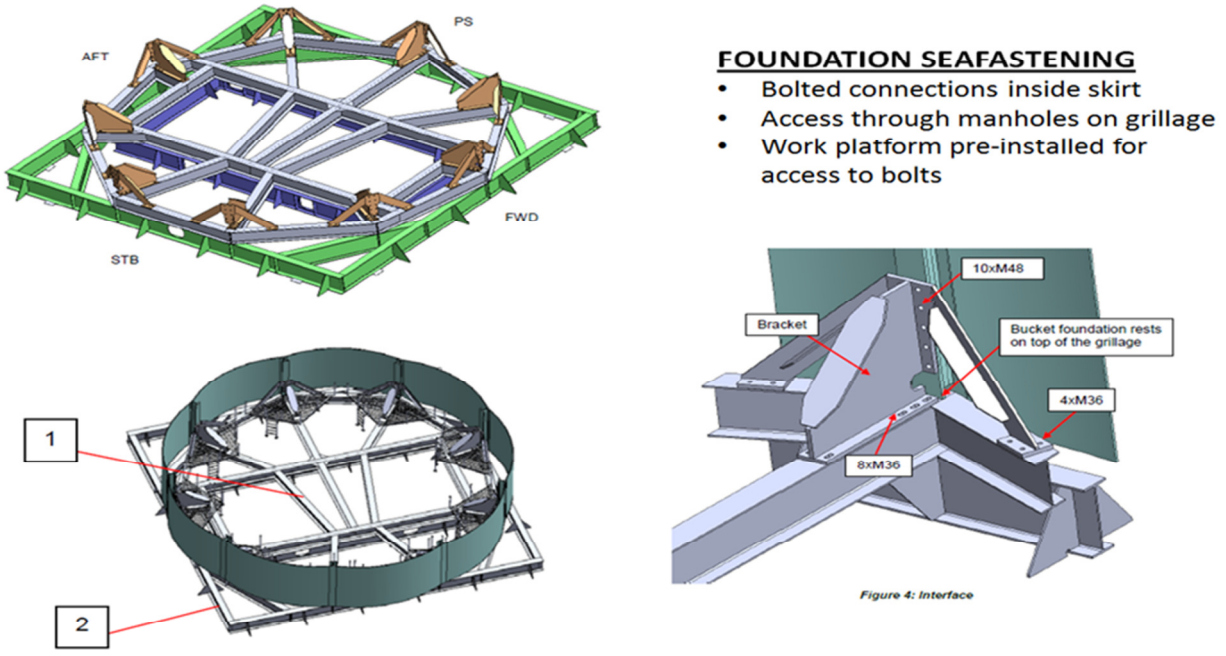

Figure 7. Improved seafastening.

5 Project results and dissemination of results

5.1 Universal Foundation deliverables

Universal Foundation delivered the results from each installation as well as all gathered sets of data. The complete data packages were delivered in different terms:

- Trial reports for each installation (SIR report signed off by UF installation Manager) - Appendix A,
- First deliverable in one month after demobilization - Appendix A.

5.1.1 Delivered content

The following issues are presented on each of the technical SIR notes:

- General status / summary of events
- Jacking / summary of events
- UF Trial Installation / summary of events
- From Click-on-Unit, CoU, control system, screenshot from control system final penetration

First deliverable in one month after demobilization contained:

- CoU installation results
- Remotely operated underwater vehicle, ROV, survey prior and after installations
- Soil conditions and Penetration analysis

Following plots were presented for each installation (CoU installation results):

- Pressure applied on the center, penetration prediction and suction limits respect to penetration depth.
- Pressure applied individually in each of the clay chambers respect to penetration depth.
- Driving pressure respect to penetration depth.
- Rotations North-South and East-West respect to penetration depth.
- Angle of rotation respect to Z-axis respect to penetration depth.
- Penetration respect to time.
- Driving pressure respect to time.
- Accumulated water flow on flushing system respect to time.
- Rotations North-South and East-West respect to time.
- Angle of rotation respect Z-axis respect to time

ROV survey contained a number of photos illustrating the seabed conditions prior and after installations. The soil conditions and penetration analysis were performed based on CPT data using in-house UF software, with the output of:

- Soil stratigraphy,
- Tip resistance, sleeve friction,
- Pore water pressure,
- Strength parameters of the soil.

Additionally, Universal Foundation delivered on separate hard disk:

- CoU filtered data.
- ROV video files.

- SMS raw installation data.

5.2 Project outcome

The trial installation campaign illustrated that it is possible to install the Mono Bucket foundation in all soil conditions considered previously as challenging. The installation time varied with a mean value of 4.16h and standard deviation of 1.56h for all the trial installation campaign results.

For the inclination at the seabed, MB foundation performed within assumed expectations, reaching values far below typical 0.25 degree limits without using heavy installation equipment.

Novel structure handling improvements and various equipment used during and before the installation performed very well, i.e. Figure 8.

Figure 8 Skirt nozzle test

The quality of the measurements was verified using real time ROV surveys, confirming the exact moment of the touchdown and full penetration of the foundation, Figure 9.

Figure 9 ROV photo – full penetration

Minor issues were encountered with CoU and SMS instrument box which were repaired during the installation campaign on the deck of the vessel.

Unique in offshore wind foundation industry 29 noise-free installation-decommissioning cycles proved general idea and high durability of the MB concept. During last installations, minor deflections at NE/NW clay chamber were encountered due to high number of installation cycles and

high pressures applied, however not affecting overall installation-decommissioning capabilities of the foundation.

In overall, as described above, the trial installation campaign ended in sound success, fully realizing established objectives, in many cases exceeding the settled goals and expectations concerning the performance of the MB structure. Collected installation outcome not only helped to improve and calibrate existing design methods, resulting in even more optimized design, but also established a significant degree of confidence towards MB foundation in the offshore wind industry.

Installation campaign opened vast possibilities for future commercial projects in various, previously considered as challenging, soil conditions, where conventional offshore foundations are not considered to be installed. Project illustrated that after years of development created technology is mature and robust enough to enter the commercial market, ready to compete with standard and proven offshore foundations.

6 Utilization of project results

Trial Installation results can be grouped into several categories:

- Measurements of CoU and SM systems,
- Experience with installation equipment, structure and technologies used in extreme installation conditions,
- Practice in handling and organization of complex and extensive offshore operation

The CoU and SMS measurements were used to calibrate and validate the CPT-Based Method for installation of bucket foundation in layered soil profiles, developed by UF and AAU. Following method has been used to predict the installation resistance for the Mono Buckets installed in Frederikshavn 2002, Horns Rev 2009, and the two met mast at Dogger Bank in 2013 with success. Obtained results were used to evaluate the k_p and k_f empirical factors for very dense sand and stiff clays, back calculated from all 29 installation tests, which significantly enhanced existing analysis methods incorporated in in-house geotechnical software, Figure 10.

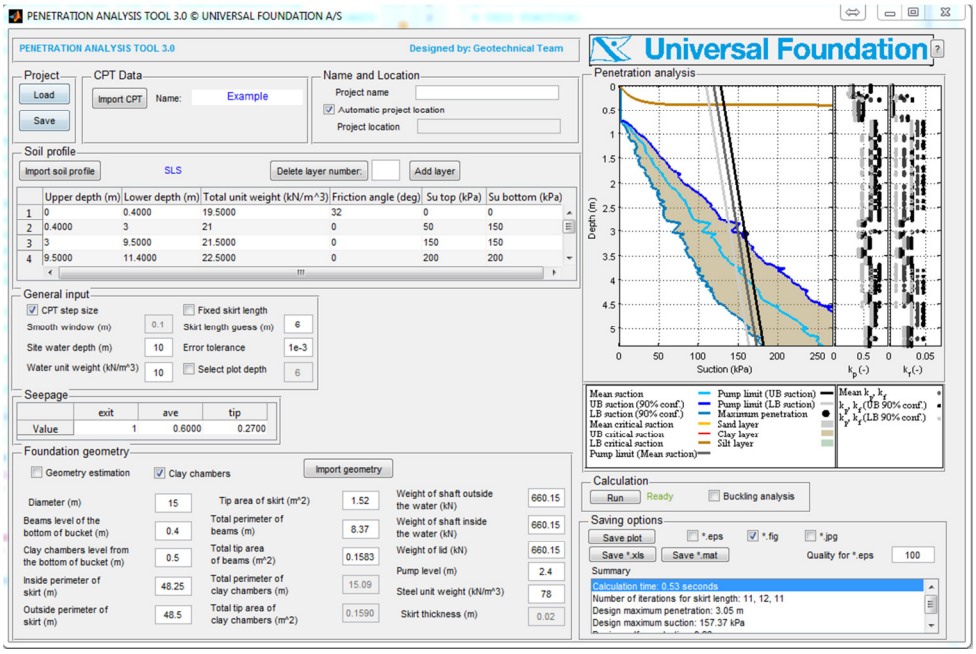

Figure 10 UF Penetration Analysis tool updated by CTTI results

Experiences gained with the installation equipment and novel technological improvements used during trial installation campaign would benefit in general know-how during the installation of future offshore foundations and help in creating company procedures in case of malfunction/damage of any equipment/structure.

The 24 days of installation-decommissioning cycles set a new standards in offshore foundation industry and established higher goals for the company – i.e. remote MB installation technology. The success of the campaign opened new possibilities towards the installation of the Danish offshore support concept on the new sites with challenging soil conditions where the installation of conventional offshore foundations surpasses ecological regulations and economic reasons.

The major part of trial installation results were analysed by the cooperation of UF and AAU, what resulted in creating the geotechnical design charts with empirical k_p and k_f factors for the North Sea, Figure 11.

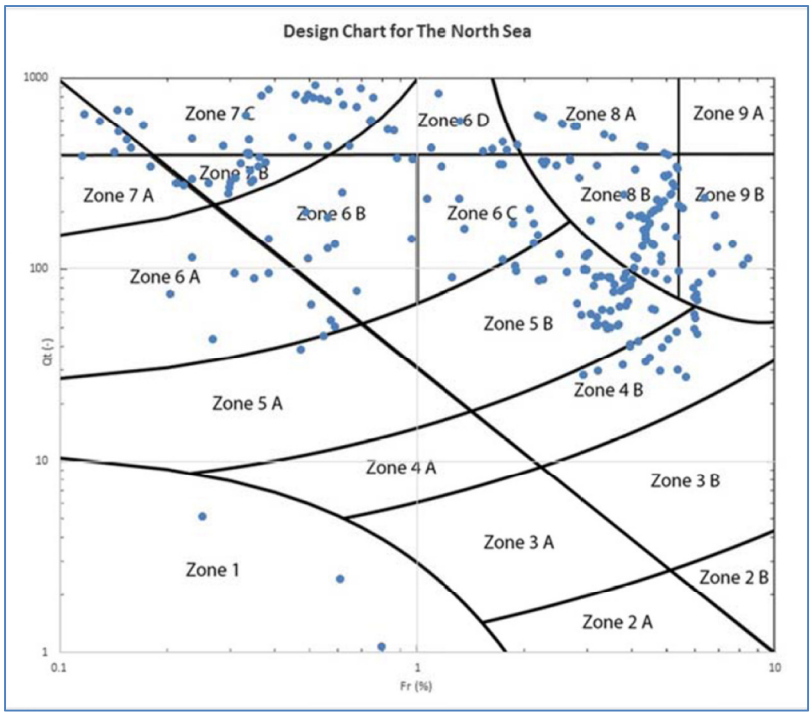

Figure 11 Design charts for North Sea

Following data, updated by the numerical investigations, formed a basis for a PhD study at AAU concerning MB foundation, treating a positive benefits of cyclic penetration in clay and tip pulsing in dense sand under a clay boundary. That could provide a better understanding and future enhancements of MB foundation soil penetration process.

7 Project conclusion and perspective

Carbon Trust Trial Installation project is concluded as a significant accomplishment for Universal Foundation and a major step towards the complete commercialization of MB foundation. Trial installation campaign de-risked MB foundation concept from the uncertainties identified by the OWA partners (installation of the foundation in difficult soils, achieving verticality after installation in multi-layered soils, damage to skirt during transportation and installation) and acquired wide recognition with significant degree of confidence towards MB foundation in the offshore wind industry. Project fulfilled all assigned objectives and illustrated that after years of development MB offshore foundation solution is mature and robust enough to compete with standard and proven offshore foundations on all the levels.

From a broader perspective, trial installation project created a new standards to the offshore wind turbine foundation industry regarding the versatility of offshore support, as well as established new perspectives for further development of the MB support- remote installation concept, improved CoU technology. The trial campaign broaden the business strategy of the company and opened a vast number of offshore sites with difficult soil conditions towards the installation of MB foundation.