Final report

1.1 Project details

Project title	Offshore wind suction bucket on an industrial scale part 2 Trial Installation
Project identification (program abbrev. and file)	64018-0066
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Siemens Gamesa Renewable Energy
Project partners	• Siemens Gamesa Renewable Energy • Universal Foundation • Fred Olsen Wind Carrier • Aalborg University
CVR **(central business register)**	76486212
Date for submission	03-2018

1.2 Short description of project objective and results

English version

The overall project objective was to test and demonstrate a modular bucket where modules can be produced in existing industrial manufacturing facility. The produced full-scale suction bucket was installed in the Kattegat Seabed 11 times during a 11-day campaign and the results showed that the design is feasible for installation in sand of different densities and that the design allows for an increase in diameter.

Danish version

Det overordnede projektmål var at teste og demonstrere en modulær sugebøtte, hvor moduler kan produceres i eksisterende industriproduktionsanlæg. Den producerede sugebøtte i fuld skala blev installeret i Kattegat-havbunden 11 gange i løbet af en 11-dages kampagne, og resultaterne viste, at designet er muligt til installation i sand med forskellig densitet, og at designet muliggør en forøgelse af diameteren.

1.3 Executive summary

The main purpose of this project was to prepare and install the previous constructed full-scale suction bucket in the seabed off the coast of Frederikshavn, followed by a comprehensive data analysis and comparison with lab experiments with a scaled model.

The test campaign, including 13 trial installations, indicate that the modular bucket model is a feasible solution for the installation in sand of different densities. The model allows for a significant increase in a diameter because it has a much better buckling performance during installation, which means that more suction under the bucket lid can be applied before reaching a structural failure. Additionally, in a full-scale, the model is more cost effective as it requires much less steel.

As such, the results of this project support the commercialisation strategy with evidence for a strong and enduring structure. Next step for the technology would be a full-scale demonstration of the suction bucket, jacket foundation and a spinning turbine. However, the related I4Offshore project is not likely to reach this demonstration phase, as it has been shut down. Hence, the future of the modular suction bucket is at this moment uncertain.

1.4 Project objectives

The overall project objectives were to 1) create a modular bucket where modules can be produced in existing industrial manufacturing facility, 2) demonstrate install-ability and in place capabilities of design in laboratory environment, 3) produce bucket elements at an existing facility and 4) demonstration of assembly process of a full-scale bucket.

During the project, the project group applied for two prolongations to complete the tasks. The first prolongation was cause by a requirement from the owner of the demonstration site to complete a seabed survey of unexploded ordinance (UXO). The survey showed no presence of UXO and the project was able to continue. This caused a 6-month delay. The second prolongation was caused by the COVID-19 situation. In the first half of 2020, the employees at AAU did not have access to the labs and the activities in WP6 could not be completed. Fortunately, the doors were open again from June and onwards and the activities could continue. This caused a 3-month delay.

Other then that, the project progressed close to the plan and the group was able to submerge the bucket into the seabed 13 times during a 11-day campaign.

1.5 Project results and dissemination of results

WP1 - Project Management and Coordination

The project was characterized by an intensive planning phase, short and very intensive demonstration phase and a relatively long data processing and validation phase. The project group coordinated on a regular basis and in the intensive periods, several days in a row. The project management was led by Siemens Gamesa, although much of the coordination was performed by the WP leads individually. The administration was carried out by Energy Cluster Denmark as was the case in the preceding project.

WP2 - Test setup and site assessment

During the preparation and planning of the test site, it became apparent that an examination of the seabed for unexploded ordinance (UXO) was necessary. As a requirement form the site owner (European Energy), the project group hired COWI to an independent assessment (Appendix 1) on the need for a detailed UXO investigation.

Their recommendation was: "*There is a significant risk of encountering UXO objects during the work in the area and a site-specific UXO-investigation should be performed for each test position. It is recommended that the UXO-investigation covers a box of 400 x 400 meters for each test position*".

This recommendation then triggered a hazard assessment (Appendix 2), for which Ordtek was hired. The recommendation of the assessment was to make a detailed Risk Assessment with Risk Mitigation Strategy (Appendix 3). Based on the latter, the project group could now navigate in the area and avoid high risk areas.

WP3 - Prepare prototype modular bucket for test installation

The bucket was equipped at the quay site in Frederikshavn with the measurement instrumentation and data acquisition equipment (SMS system) and the Click-on Unit (CoU - pump and installation control unit).

The following measurements were conducted by the instrumentation listed below:

- Steel stresses by strain gauges placed on the outside of the bucket skirt.
- Pore pressures measured placed on the bucket skirt at 3 levels outside and inside the bucket. The suction pressures during installation measured inside the bucket.
- Inclination measured in X/Y-directions during penetration.

The gained data can be used to calibrate finite element-models and correlate the stresses with those from the FE-model. The strain gauges are placed on the skirt in three levels to capture skirt deformation and buckling modes. These can be used to survey buckling and correlate pressure in the skirt with stresses. All strain gauges also function as root cause tool, if any unexpected incident should occur. The expected pressure on the bucket during installation is at most installation sites, much lower than the design pressure.

Figure 1 Installing the pump unit on top of the bucket

Figure 2 Connecting all the right cables to the pump unit

WP4 - Installation vessel

Initially, the plan was to use on of Fred. Olsen Wind Carrier's (FOWC) own installation vessels for the suction bucket demonstration. However, due to the changed time schedule cause by the UXO-investigation, the planned window for using the specific ship disappeared. As a result of FOWC's busy schedule, no ships were available for a long period and the project group had to go with plan B. This included search in the US of another ship for the demonstration. As the installation of the suction bucket into the seabed did not require high crane capabilities, a suitable ship (Jill) was located and transported to the test site. Jill is a drilling jack-up that is operated on a long-term charter and under commercial management by FOWC. The vessel is operating out of Europe carrying out O&M work in offshore wind and is capable of transporting WTG components up to 5 MW and can carry major components such as gear boxes, generators, transformers, blades and full drive trains for O&M jobs.

Figure 3 The Jill jack-up vessel used for the installation

WP5 - On-site installation test

The project Offshore Wind Suction Bucket on an Industrial Scale is a join development and demonstration project with support of the Danish "Energy Technology Development and Demonstration Program" (EUDP). Project partners are Siemens Gamesa Renewable Energy, Fred. Olsen Windcarrier, Aalborg University, Offshore Centre Denmark and Universal Foundation. The present Exclusive Summery Report is an extract of the part of the project that concerns the offshore trial installation campaign.

The project is a continuation of the EUDP-project "Offshore wind suction bucket on an industrial scale", in which a lightweight, coil steel-based suction bucket foundation was developed and lab-tested. The aim was to demonstrate a modular suction bucket design for various types of offshore wind turbine foundations such as the Siemens Gravity Suction Bucket Jacket concept and the Universal Foundation Mono Bucket. During the trial installation campaign, the Modular Bucket structure showed the ability to withstand 13 penetrations fulfilling the de-risk obligations identified in the project application (more information can be found in Appendix 4).

Seq. #	UF no.	Date	Loca-tion	Hea-ding	Ghost pos.	Pen. Depth	Position Northing	Easting	Remarks
1	7	21.05.19	B10	1	A	**2,5**	6371266	598310	Suction channel due to excess crane hook load
2	8	24.05.19	B10	1	B	**4**	6371259	598295	Unexpected hard layer in app. 4 m, skirt deflection
3	9	25.05.19	B10	1	C	**0,75**	6371267	598280	Ground faultier in suction pump connection
4	13	25.05.19	B10	1	D	**3**	6371278	598316	Unexpected hard layer in app 3 m, skirt deflection
5	10	26.05.19	B10	2	A	**3,4**	6371218	598317	Unexpected hard layer in app 3 m, skirt deflection
6	11	26.05.19	B10	2	B	**3,1**	6371233	598310	Unexpected hard layer in app 3 m, skirt deflection
7	12	27.05.19	B10	2	C	**3,50**	6371248	598318	Unexpected hard layer in app 3 m, skirt deflection
8	14	27.05.19	B10	2	D	**3,4**	6371213	598329	Unexpected hard layer in app 3 m, skirt deflection
9	2	29.05.19	B6	1	B	**6**	6368421	598383	First trial with active inclination control with nozzle
10	3	29.05.19	B6	1	C	**8**	6368407	598375	Full penetration, inclination < 0.1 degree
11	15	31.05.19	B6	2	D	**5**	6368396	598412	Maximum skirt strain
12	4	31.05.19	B6	2	A	**6**	6368400	598399	Excess inclination (boulder?)
13	5	31.05.19	B6	2	B	**6,5**	6368416	598393	Maximum skirt strain

Installation of the bucket in difficult soils.

The soil conditions at the selected installation sites varied from very loose sand/silt to very hard clay. Some of the soil strength parameters was far beyond the conditions what the suction bucket was designed for, so full penetration depth could not be achieved with the available suction pressure. Full penetration was proven possible in one position as a result of the many different installation attempts, wear and tear on the foundation and equipment, soil conditions that was proven different from the predicted and a conscious decision of not going for full penetration.

Achieving verticality during installation in multi-layered soil profiles.

The inclination control was limited to use of the rim nozzle system divided into three sections. The system was only limited used on the first position, B10. But it was fully used during the last visited position, B6. The nozzle system would not work properly in the first position due to soil conditions, which resulted in a decision to use this position to collect data without 100% inclination control. During the installation on the second position, the inclination of the Bucket was controlled and kept within a satisfying tolerance. Verticality less than 0,1 degree and full penetration was achieved on installation site B6-8.

Capability to withstand large differential pressures without buckling.

The skirt did not show any signs of initial buckling deformation during the installation, where the largest differential pressures was used.

Damage to skirt during transportation and installation.

Skirt damage was encountered in installation sequence #2 due to unexpected rotation of the foundation encountering a hard clay layer. The installation campaign was continued with further 11 installations.

Figure 3. Observed skirt deflection.

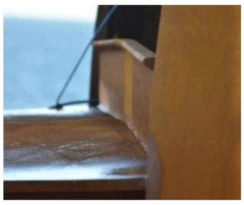

Figure 4. Observed lid stiffener deflection.

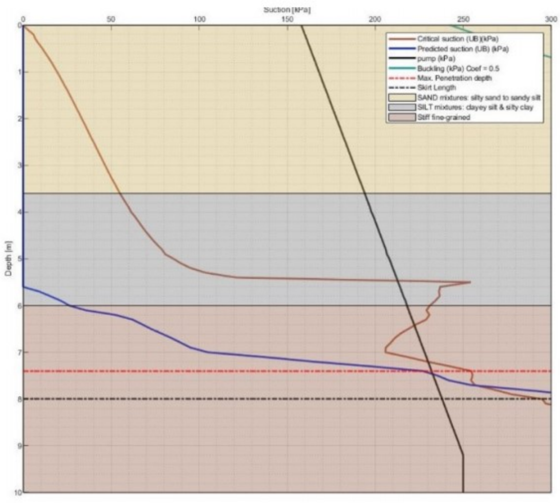

Figure 5. The penetration prediction based on CPT data. The hard layer is observed at 6 m.

An additional deflection was observed at each additional installation. The bucket proved the ability to be installed even though additional deflection was observed at each additional installation and the increasing deformation of the skirt. This proves the excellent robustness of the Modular Bucket concept.

The rotation of the bucket will be restricted by the stiff connection between the bucket and the jacket leg in Gravity Suction Bucket Jackets projects. This will prevent unexpected excess inclination. In the case where the modular concept is used for a Mono Bucket foundation, the inclination control in cohesive soils will be obtained with use of build-in clay chambers.

Here is a series of pictures from the installation

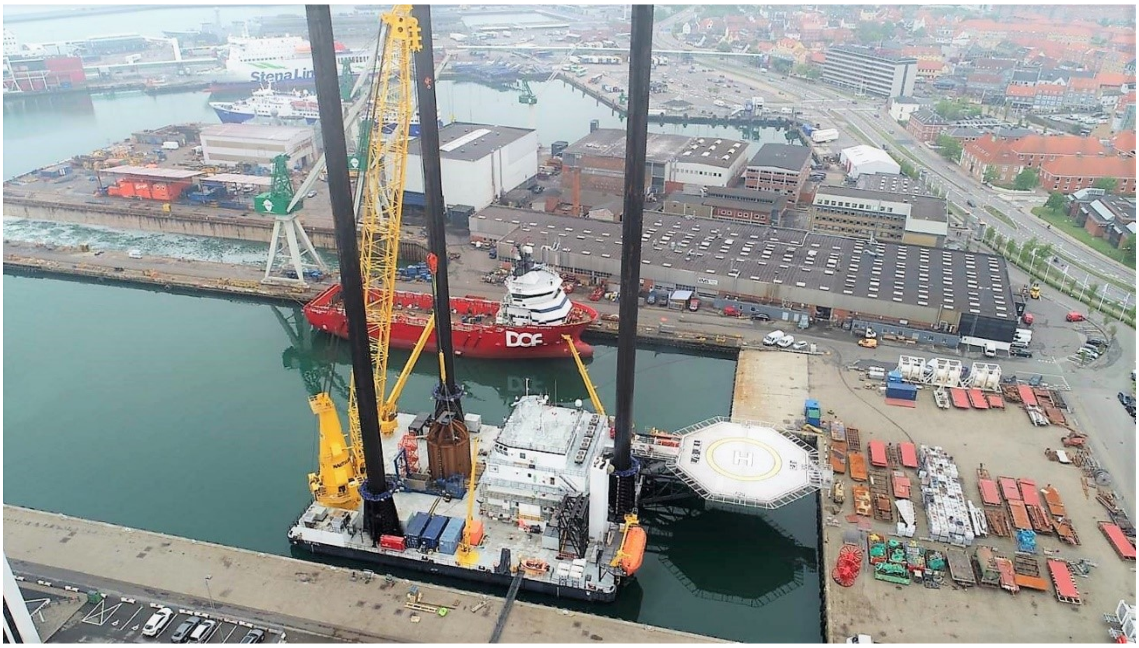

Figure 4 Jill vessel with the bucket ready for departure

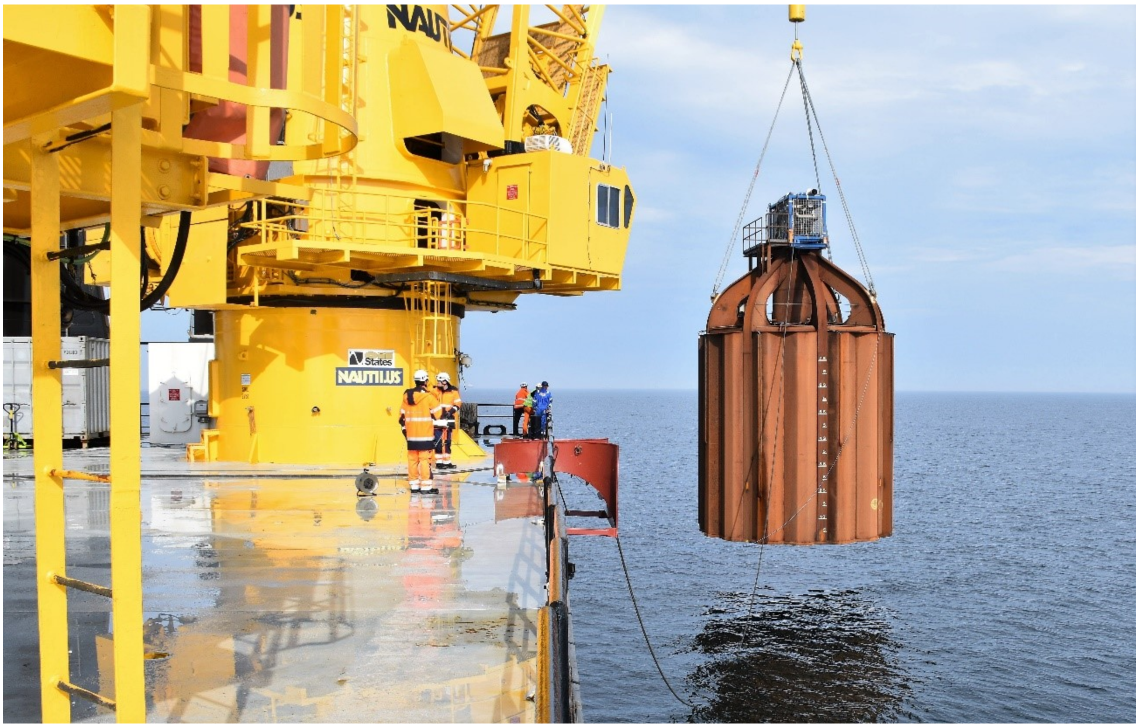

Figure 5 Preparing for suction at site B6

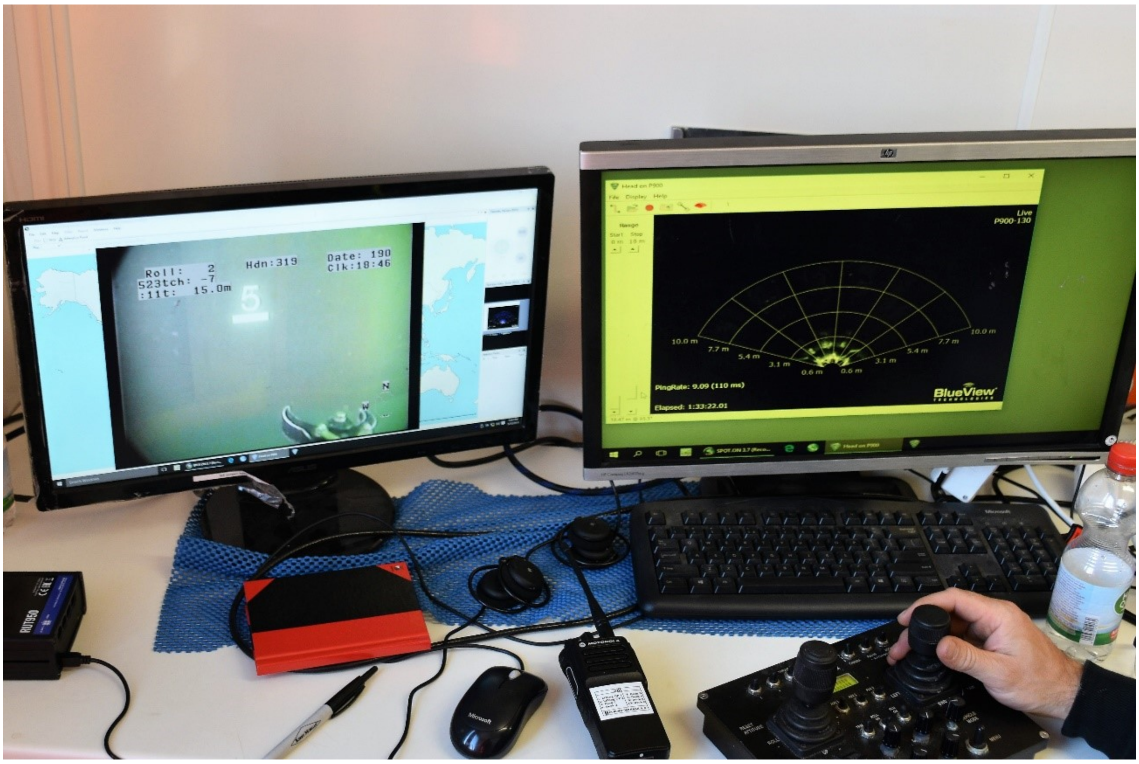

Figure 6 Controlling the ROV for closer inspection of the bucket during penetration

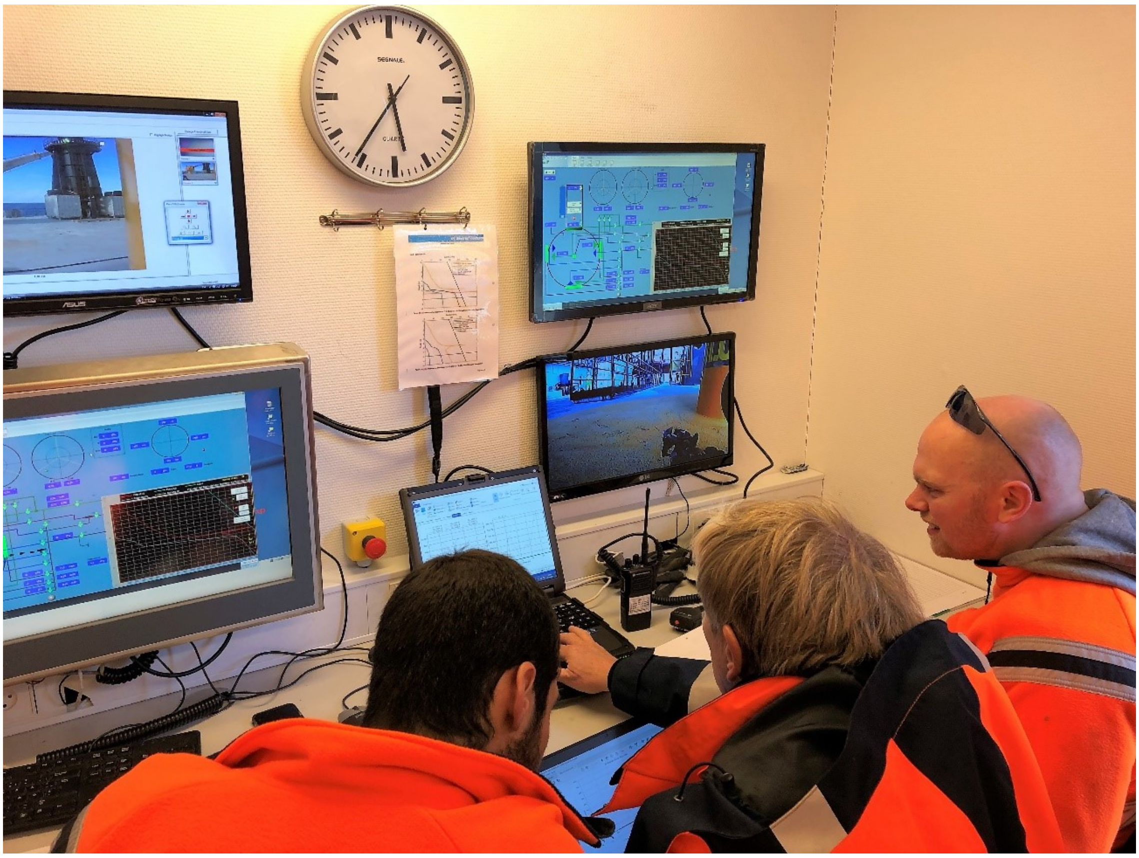

Figure 7 Installation of the bucket requires much information and many screens

1.6 WP6 - Data processing, evaluation and analysing

Introduction

The project "Offshore wind suction bucket on an industrial scale – Part 2 Trial Installation" is a continuation of the EUDP-project "Offshore wind suction bucket on an industrial scale", where a light-weight, coil steel-based suction bucket foundation was developed and lab-tested.

In the EUDP-project "Offshore wind suction bucket on an industrial scale" the aim was to develop and optimize the modular bucket, where a reduced skirt thickness and a higher buckling resistance was investigated. The model was first designed in a scale of 1 x 1 m, where both the production and assembling resembled the full-scale prototype. For the purpose of this report, the scaled-model was installed in the laboratory conditions to check and describe its install-ability. The results described in this report make a basis for the analysis of the in-situ test. The report includes the proposal of method for the design of the suction installation of bucket foundation, additionally accounting for the changed geometry.

The chosen modular bucket foundation has thinner skirt thickness what reduces the cost of the entire structure considerable. The modules that forms the modular bucket can be produced fast and in existing local facility. The structure due to modular shape has significantly higher buckling resistance against penetration allowing for higher suction pressure applied during installation prior to the structural failure. This fact is quite important considering the increase of wind turbine sizes and hence, the increase of offshore foundations

Description of work

In the AAU report (Appendix 5), the laboratory scale campaign is used for the proposal of a methodology correlating the installation requirements to currently used in-situ soil characterization known as a Cone Penetration Test (CPT). Two different models, a referenced bucket foundation and a modular bucket foundation are used in the campaign and their performance during installation in sand is described. As mentioned, the laboratory work focuses on installation in sandy soil as such conditions are more challenging. However, the methodology is suitable for all kind of soil conditions, though requires further validation with full-scale tests. The proposed method is later on applied on the site installation test results.

The suction installation of bucket foundation consists of two main phases. Firstly, the foundation penetrates into the soil under its own weight – self-weight installation. The penetration must be sufficient to provide an adequate hydraulic seal of the bucket skirt and soil, so that the suction can be applied under the bucket lid. The second phase is the suction installation, where the limit for the applied suction is given by the critical suction against piping. If the limit is significantly exceeded, the piping channel could form at the skirt wall, breaking the hydraulic seal and preventing the foundation from the further penetration. Therefore, the suction equal to the critical limit is often obtained and kept constant until the full penetration is achieved. In this manner, the suction installation is most effective.

The work package includes the data assimilation together with its processing, which is finalized by the proposed method for the suction installation of the bucket foundation. The analysis of test results confirms that the new design, the modular bucket foundation, is possible to be installed in sand, and the design does not requires additional suction pressure when compared to the installation of the round modular bucket that was used as a reference here.

Results

The test campaign with its results indicate that the modular bucket model is a feasible solution for the installation in sand of different densities. The model allows for a significant increase in a diameter because it has a much better buckling performance during installation, which means that more suction under the bucket lid can be applied before reaching a structural failure. Additionally, in a full-scale, the model is more cost effective as it requires much less steel. The increase in skirt frictional area improves the in-place performance of the bucket. At the same time, the results of this campaign prove that the installation ability of the modular bucket is very similar to the round model that was analysed in the test campaign as a reference.

The applied suction during the installation of the bucket foundation must create the downward force that resist the soil penetration resistance. Such resistance is rather high in sand, especially if sand is in its dense state. However, the suction applied during the installation induces the seepage flow around the bucket skirt that automatically reduces the soil penetration resistance. This has been proven in installation tests of both round and modular bucket models, by comparing the required force for the installation during jacking installation and during suction application in similar conditions and by analysing the CPT results and the soil relative density calculated based on the CPTs before and after each of the test. The drop in the relative soil density is visible after the suction installation in dense conditions and in some of the tests in medium dense sand. However, the direct comparison between the required forces between two different installations in similar soil conditions indicates that the seepage flow reduces the soil stresses in all soil conditions from loose to dense sand, and that this reduction is even higher that could be suggested by the comparison of CPT results. This proves that the soil penetration resistance in sand is always reduced by the seepage flow and that the soil regains some of its strength after a completion of the suction installation. Nevertheless, especially in dense sand, the change in the soil relative density is reduced to some extend permanently and this should be included in the in-place design of the bucket foundation.

It is important to mention that the suction installation has its limit, not only from the structural point of view, where the bucket model can start buckling as an effect of too high suction applied, but also due to a geotechnical failure that occurs due to a creation of piping channels. The critical suction against piping is suggested in this report. The suction applied during the installation of both round and modular bucket do not exceed this limit.

Moreover, in contrary to the jacking installation tests that indicate the significant increase in soil penetration resistance for the modular bucket compared to the round model, there is almost no difference in the pressure applied during the suction installation of both. The increase in the jacking installation does not come only from the increased frictional area of the skirt, but also there is an additional increase in the stresses between inside stiffeners and modular shaped parts of the skirt. The seepage flow induced around the skirt during the suction installation removes this additional stress increase, leaving almost the same soil penetration resistance during the suction installation of both models. The small increase in the modular bucket might indeed be only related to the increased skirt area. Nevertheless, the additional increase in stress during the jacking installation might not be present in full-scale tests and also that increase is not very significant during the first stage of the installation which is the self-weight penetration. To be on the safe side, the shape factors proposed in the report for the jacking installation of the modular bucket should be used during the design of the self-weight penetration stage, but it still requires validation with tests of the full-scale.

Based on the overall observation, the possible heave should be included in the design, as it prevents from reaching the full penetration. Around 10% of skirt length heave should be included in the in- place design of the bucket foundation, and additional skirt length should be added to the design if needed. Finally, when it comes to the installation design of the bucket foundation, the CPT-based method is proposed in the report. Firstly, the method includes the empirical coefficients k_p and k_f to relate the measured cone resistance during the CPT to the soil penetration resistance of the bucket skirt. Then the β-factors are used in order to account for the reduction in soil penetration resistance as an effect of seepage flow. The method with chosen coefficients and parameters proposes a required suction for the installation in different sand densities that is seen as a reasonable solution that is, in most cases, not exceeded by the applied suction during the installation tests.

The proposed method is applied to the in-situ installation tests and the results are further reported in "Offshore Wind Suction Bucket on an Industrial Scale: Analysing test results from the offshore trial installation".

WP7 - Dissemination

Given the late TRL stages of this project, dissemination was an important part of efficient knowledge sharing and industry approach. In this work package, the partner group was obligated to present results at an offshore conference, towards the Danish supply chain in general and to host a seminar with involvement of supply chain.

Starting with the presentation at an offshore conference, the suction bucket concept was presented at the Foundation Ex 2019 in Bristol. The presentation included the new modular suction bucket, along with the additional concepts from Universal Foundation. In the same period, Universal Foundation attended a Danish export expedition on the American east coast, coordinated by the Danish ministry of foreign affairs.

Looking at the result presentation towards the general Danish supply chain, several activities has been completed. First of all, the partners used their individual press platforms for dissemination, such as LinkedIN and press releases in their websites:

- https://universal-foundation.com/universal-foundation-partner-with-siemens-gamesa-to-perform-test-installation-on-industrialised-suction-bucket-concept/
- https://universal-foundation.com/industrialising-a-game-changer/

Additionally, Energy Innovation Cluster (now Energy Cluster Denmark) wrote and article in their yearbook about development and the latest results. The article is available here:
https://eicluster.dk/sites/default/files/publications/yearbook_2019.pdf (page 8)

For the purpose of better dissemination, especially after the offshore demonstration, Universal Foundation made a very nice video from the ship, including key persons and industry effects. The video is available here: https://vimeo.com/343447767

1.7 Utilization of project results

The final target group of the project is the electricity clients that are aiming at the offshore wind market utilizing bottom fixed offshore structures. Focus is cheaper renewable energy to replace fossil fuels in the needed energy mix. The on-going R&D effort have in the past couples of years encouraged government to have a larger focus on offshore wind as a source of renewable energy. This have made market visible for bottom fixed offshore wind foundation in numbers of +15.000 in the next decade.

The target group are offshore wind park developers, national and international. The big offshore wind developing companies like Ørsted, Vattenfall and RWE are constantly looking for more cost-effective solutions.

All parts of the value chain that can contribute to more financially viable offshore wind projects are subject to big interest from these companies. The value chain is therefor subject to investigation these years to lower Levelized Cost of Energy – it is the theme in the R&D sector, the private sector and not least politically both national and international.

The project has shown results that can contribute to both cheaper production of foundations but also cheaper transport and more lean and simplified assembly logistics e.g. assembly of the bucket structure on quay site. In other words, the cost-savings that this project can lead to are substantial on one of the main elements of deploying offshore wind parks and is therefore by default subject to interest from the developing companies.

Further, other target groups are the different supply chain sectors related to foundations that are involved in jacket structures: Sourcing, manufacturing, logistics, shore-based transport links, port and staging facilities, vessels, lifting equipment, operation management.
Since the wind industry is highly fragmented with many independent participating companies a major emphasis will be on modeling the entire chain in order to identify interconnections between the sequential steps that might generate waste according to the lean principles.

The modular suction bucket solution with bolted skirt sections and a lid demonstrated a case that can affect major parts of the existing value chain. By designing the bucket in modules based upon coiled sheet steel. Coiled steel is significantly cheaper than flat plates of steel. The initial logistic costs of handling coils compared to steel plates are lower. The handling cost of the individual modules are lower compared to handling the whole suction bucket because ordinary trucks can transport the individual modules. Furthermore, the design with bended/folded bucket section have shown to be very robust during the installation operation.
The modular design enables the involvement of new types of suppliers. Suppliers that are more cost competitive because they normally operate in more matured industries where competition is fiercer.

The many potential cost-saving elements can only be realized if the full value chain is reconfigured based on future full-scale demonstration offshore. Instead of producing the suction bucket in one place, today it is produced in a series of processes by specialized independent companies. The final stage is the assembly of suction bucket at a port and the attachment to the jacket. This final step requires specific facilities at the harbor in terms of assembly process equipment, handling equipment, storage facilities etc. The modeling of the full value chain will identify the potential cost reductions and will also identify the new process steps that are necessary to realize the changed setup.

Since the networks of interconnected activities are complex it is not trivial to estimate the potential consequences and the potential performance improvement in terms of cost reductions and quality improvements. The road ahead is to market the solution to potential innovative offshore developers e.g. like demonstration projects and the holds of the intellectual properties will issue licenses worldwide also to new markets like USA, Japan and Taiwan.

1.8 Project conclusion and perspective

State the conclusions made in the project. Try to put into perspective how the project results may influence future development.

The test campaign with its results indicate that the modular bucket model is a feasible solution for the installation in sand of different densities. The model allows for a significant increase in a diameter because it has a much better buckling performance during installation, which means that more suction under the bucket lid can be applied before reaching a structural failure. Additionally, in a full-scale, the model is more cost effective as it requires much less steel.
As such, the results of this project support the commercialisation strategy with evidence for a strong and enduring structure. Next step for the technology would be a full-scale demonstration of the suction bucket, jacket foundation and a spinning turbine. However, the related I4Offshore project is not likely to meet this demonstration phase, as it has been shut down. Hence, the future of the modular suction bucket is at this moment uncertain.

Annex

Appendix 1: UXO study of the coast of Frederikshavn
Appendix 2: UXO Hazard Assessment
Appendix 3: UXO Risk Assessment and Risk Mitigation Strategy
Appendix 4: Universal Executive Summary Report
Appendix 5: AAU report on scale tests and data validation