OFFSHORE WIND SUCTION BUCKET ON AN INDUSTRIAL SCALE

FINAL REPORT

EUDP - 64015-0625

AALBORG UNIVERSITET

SIEMENS Gamesa RENEWABLE ENERGY

EUDP

Universal Foundation

IB ANDRESEN INDUSTRI

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1.1 Project details

Project title	Offshore wind suction bucket on an industrial scale
Project identification (program abbrev. and file)	64015-0625
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Siemens Gamesa Renewable Energy Borupvej 16, 7330 Brande, Denmark
Project partners	▪ Siemens Gamesa Renewable Energy ▪ Aalborg University, Depart of Civil Engineering ▪ Aalborg University, Institute for Mechanical and Manufacturing ▪ Universal Foundation ▪ Ib Andresen Industries
CVR (central business register)	76486212
Date for submission	2018-08-01

1.2 Short description of project objective and results

English

The project aims to develop a modular suction bucket design for various types of offshore wind foundations. Objectives are:

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 existing facility
4) Demonstration of assembly process of a full-scale bucket.

In the first part of the project, the design of the modular bucket was optimized for reduced skirt thickness and increased buckling strength to withstand seabed penetration. The optimized design resulted in a skirt thickness reduction from 40-50 mm to only 16 mm. The design included 16 skirt segments with several bucklings pr. skirt, 8 vertical stiffeners and installation of flushing panels at the bottom. In total, it was possible to reduce the weight of the new suction bucket with 25 tons compared to the reference bucket.

After design optimization, a prototype of the modular was produces in size 1x1 m. The production and assembly resembled full-scale conditions for verification of concept. The prototype was tested in the laboratory facilities at Aalborg University with data generation especially relevant for full-scale trial installation.

Important for the project was the possibility to produce the bucket components using existing local facilities. All the components, including lid, cylinder and skirts was produced at a local steel working factory and furthermore transported and assembled locally.

Based on extensive cost calculations, the cost of the new bucket was compared regarding assembly process, material, supply chain and logistics. It was found that the price could be reduced using fewer bucklings and bolts instead of welding. As a result of the comparison, the price of the modular bucket was reduced from EUR 238,000 (reference bucket) to EUR 160,000 on a mass production scale.

Danish
Projektet har til hensigt at udvikle et design for en modulær sugebøtte der kan anvendes til forskellige offshore vindmølle fundamenter. Målene er:

1) At fremstille en modulær sugebøtte hvor modulerne kan fremstilles på en eksisterende industriel produktionsfacilitet
2) Demonstrere installationsevne og kapaciteter af design i laboratoriemiljø
3) Producere sugebøtte-elementer på eksisterende anlæg
4) Demonstration af samleprocessen af en fuldskala sugebøtte

I den første del af projektet blev designet til den modulære bøtte optimeret for at reducere skørtetykkelsen og øge foldningsstyrken for at modstå modstanden i havbunden under installation. Det optimerede design resulterede i en tykkelsesreduktion fra 40-50 mm til kun 16 mm. Designet inkluderede 16 skørtesegmenter med flere foldning per segment, 8 vertikale afstivninger og installation af skyllepaneler i bunden. Totalt set, var det muligt at reducere vægten af den nye bøtte med 25 ton, sammenlignet med referencebøtten.

Efter designoptimeringen blev en 1x1 meter prototype produceret. Produktionen og samlingen af bøtten svarede til fuldskalaforhold for at verificere konceptet. Prototypen blev testet i Aalborg Universitets laboratoriefaciliteter med generering af data, der er speciel relevant for test-installationen af fuldskalabøtten.

En vigtig del af projektet var muligheden for at producere bøttekomponenterne ved brug af eksisterende, lokale faciliteter. Alle komponenterne, herunder låg, cylinder og skørtesegmenterne blev produceret af en lokal smedevirksomhed og desuden transporteret og samlet lokalt.

Baseret på omfattende omkostningsberegninger, blev prisen på den nye bøtte sammenlignet mht. samleprocesser, materialer, forsyningskæden og logistik. Resultaterne viste at prisen kunne reduceres ved at bruge færre foldninger og ved at bruge bolte i stedet for at svejse. Som et resultat af sammenligningen, kunne prisen for den modulære bøtte reduceres fra EUR 238.000 (referencebøtte) til EUR 160.000 på masseproduktionsniveau.

1.3 Executive summary
The project purpose was to develop a new design and prototype for modular suction bucket with the aim of material and cost reduction. A cooperation between Aalborg University and Ib

Andresen resulted in a range of suitable designs, that was analyzed regarding buckling resistance, imperfection tolerance and other important parameters. Simultaneous, Aalborg University performed cost analyses on the proposed design to ensure optimal cost savings. Based on the results, a 1x1 meter prototype was produced for scales tests at Aalborg University lab facilities.

To optimize cost reduction, production of the skirt modules should be possible for local steel working facilities. In production of the full-scale suction bucket, a local steel working company produced the skirt segments (~200 kg pr. segment) with satisfaction and the suction bucket was assembled at a local site in Frederikshavn.

The output of the project was a full-scale, strength and cost optimized prototype modular suction bucket to use with jacket structures. Furthermore, the project group looked further into the possibilities of producing a new design for the buckets to use with monopiles, "monobuckets". Here they came up with a new design (Mickey Mouse), that showed great results.

Structures of this sized, bearing even larger structures must be well validated for market penetration. Important for the future development and application of the modular buckets is the trial installation in different soil conditions. Consequently, the project group must perform several test installations to look further into the strength of the new design and to validate for market introduction.

The most commercial partner, Universal Foundation, has experienced high interest in the new suction bucket and more project developers are showing interest regarding future wind installation project. However, everybody is waiting for the results of the trial installation.

1.4 Project objectives

The overall goal motivating this project was to reduce the LCoE from offshore wind from the currently 14,5 EUR-cent per kWh to less than 10 EUR-cent per kWh. The perspective of the project was to move from specialized production methods to standardized components.

Steel should preferably be supplied as coil steel, which typically is around 15% cheaper than plate steel as a raw material, to existing mass-production facilities in Europe where the modules can be produced using automated processes.

Increasing the degree of automation in manufacturing of offshore wind structures raises the possibility for competitive production in Denmark/Europe compared to outsourcing, generating near-market manufacturing capacities maintaining short and logistical effective supply chains.

To reach the goal, is was necessary to reduce the thickness of the skirts from 40-50 mm to below 17 mm to accommodate the current production and treatment facilities of local steel working facilities. Furthermore, to reduce the skirt thickness, it was necessary to invent a new bucket design that could endure the large forced during installation and a modular approach that allowed for local production and assembly; and low transportation costs.

Below, you see an overview of the project work packages, the associated activities and milestones.

WP		Activities	Milestones
WP1	Design	▪ Reduce plate thickness on skirts (from currently 25-40mm to below 17mm) to be able to use IAI machinery – buckling calk. ▪ Develop skirt and lid modules that can be scaled for bucket dimensions from 7 to 24 m. ▪ Ensure that the bucket design minimizes the need for scour protection. Responsible AAU ▪ Secure that the bucket (with thin walls) can be installed efficiently and with a low risk profile (different soils, boulders). ▪ Design for cost efficient logistic. ▪ Design for cost efficient and quality focus assembly. ▪ Numerical flow analysis will be performed to determine the hydraulic gradients developing in response to applied suction.	M01 Design and manufacturing methods M02 Numerical flow analysis performed
WP2	Prototype	▪ Produce 1x1 m bucket for measurements in Aalborg University test facilities	M03 Production of 1x1 m prototype bucket
WP3	Scale tests	▪ Test installation, in place capacities and scour development on a scale model i.e. 1:10 of the design in AAU test laboratory.	M04 Installation tests in pressure tank M05 The in-placed capacity of the new Bucket geometries is tested in the pressure tank both for static and cyclic loads M06 Evaluate on prototype and decide if project is to proceed
WP4	Manufacturing	▪ Produce full-scale bucket	M07 Production of full-scale bucket
WP5	Logistic and Assembly	▪ Plan the assembly including tools, equipment. ▪ Perform assembly of the trial bucket	M08 Critical cost and quality parameters identified M09 Simulated effects on cost and timing M10 Quality control procedures are described M11 Full assembly and logistic plan M12 Full assembly and logistic plan for full-scale bucket
WP6	Project management and dissemination	▪ Daily project management and reporting to the EUDP, including Day-to-day coordination, Partner agreement, Kick off meeting, 6-monthly reporting, Project Group coordination and Final reporting ▪ Dissemination of relevant project results through channels described in section 4. ▪ Involvement of supply chain through an open seminar where project results are presented, and potential collaborative partners are invited to offer their services for further commercialization of the project.	M13 Presentation of results at offshore conference M14 Presentation of results towards the Danish supply chain M15 Seminar with involvement of supply chain

The project progressed using both end-to-end and adjacent activities to reach the goal. First order of business was designing the modular bucket to fit the new requirements. Simultaneous, optimizing the production process was an important activity to ensure cost reduction optimization. In the design phase, Aalborg University, in cooperation with Ib Andresen Industries, came up with a range of modular designs, varying in shape, number of segments, steel thickness and dimensions. These designs where then compared based on amount of material, production method, transport etc. for optimal cost reduction.

When the design was chosen, the prototype was produced by IB Andresen for validation of production process and for the scale tests in the lab at Aalborg University. However, Aalborg University was, for a substantial time, in the process of reconstruction- which included the lab. At the project start, the reconstruction timeline matched the project timeline, but due to delay in the reconstruction of the lab, the project was prolonged for a total of one year. Consequently, the scale tests of the prototype bucket were delayed as well. However, within the project period, Aalborg University managed to do several suction tests with the prototype, that are being analyzed during the composition of this report. Aalborg University will continue the suction tests of the prototype after the project end, gathering important data for the trial installation of the full-scale bucket.

Following design and production process selection, the skirt segments for the full-scale bucket was produced at a local steel working facility in Esbjerg and transported to Frederikshavn for assembly. The lid was produced by Nicon and likewise transported to the assembly site.

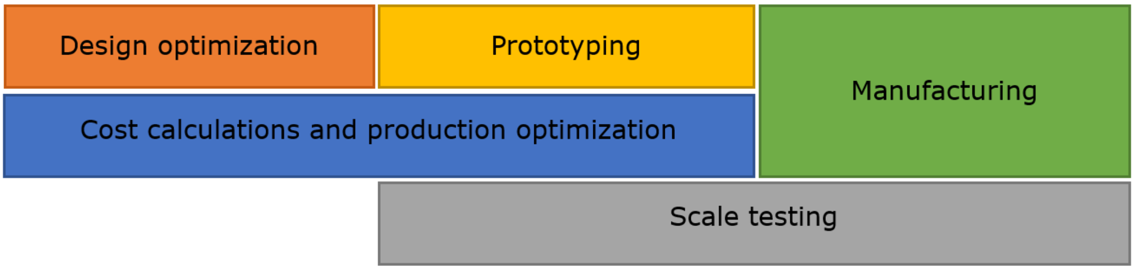


Figure 1 Project execution timeline

The above diagram shows how the project proceeded with several simultaneous activities and end-to-end activities for excellent project management.
The project management was divided into technical (Siemens Gamesa) and administrative (Offshoreenergy.dk) throughout the whole project. The cooperation has been demonstrated at a previous project and again, the cooperation was very fruitful.

In summary, besides the reconstruction of the lab facilities at Aalborg University, the projects progressed as planned with very good results both on the research side and the prototype side.

1.5 Project results and dissemination of results

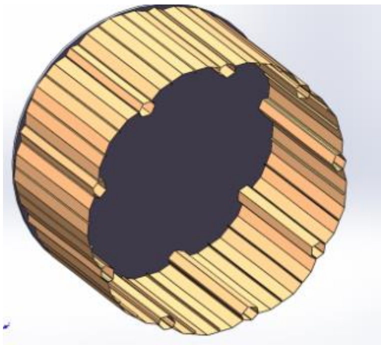
WP1 – Design

Based on the classical suction bucket concept, the first activity in the project was to optimize the design for modular production and reduce the steel thickness for cost optimization. Th "old" design was based on a perfectly cylindrical shape with a thickness of up to 40 mm. Based on new design suggestions and calculations, it was the aim to reduce the thickness to 17 mm or below.

In this WP, Ib Andresen Indutries (IAI) quickly came up with 3 design suggestions for the modular mono-bucket design and 6 suggestions for the modular jacket-buckets based on their knowledge on component design and construction.

The design descriptions and drawings were sent to Aalborg University – Department of Civil Engineering (AAU Civil) for further analysis. Every design was compared on several parameters, such as linear buckling pressure, critical buckling pressure, shell thickness and imperfection influence. The designs and results from the analysis is shown below.

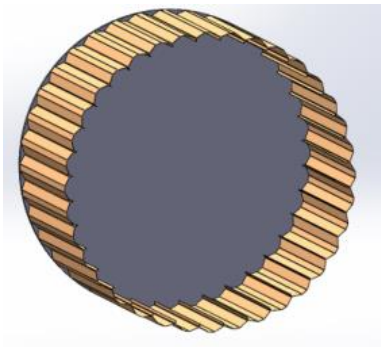
Suction buckets for monopiles



Type 1060

- ”Flower shape”

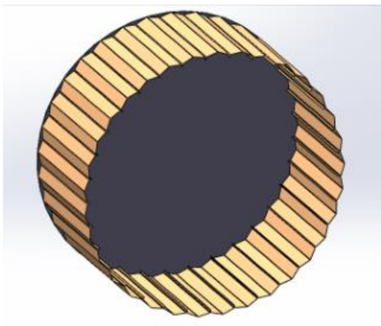
More resistant to buckling when the imperfect structure is considered.



Type 1055

- ”Cookie cutter”

Highly imperfection sensitive. However, the structure is still interesting regarding its behavior against buckling.



Type 1053

- ”Cookie cutter”

Less reliable because of its high imperfection sensitivity

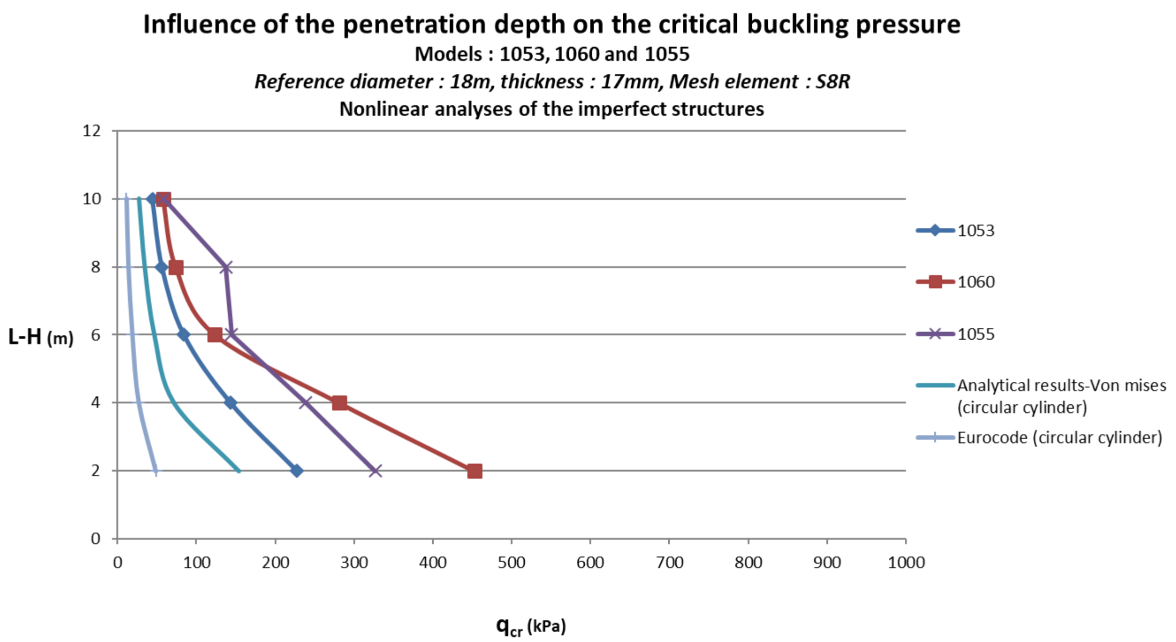
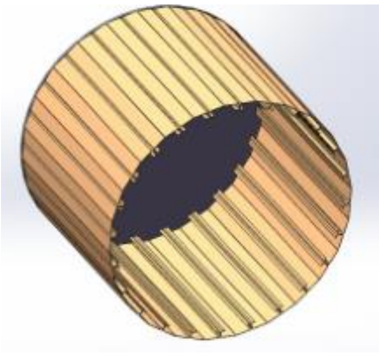


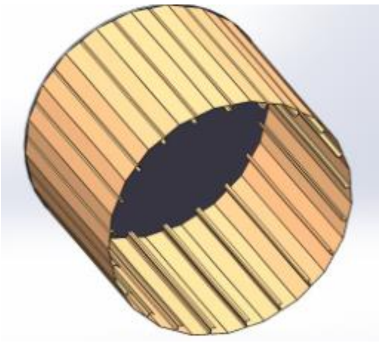
Figure 2 Critical buckling pressure calculation of monopile-buckets

Suction buckets for jacket structures

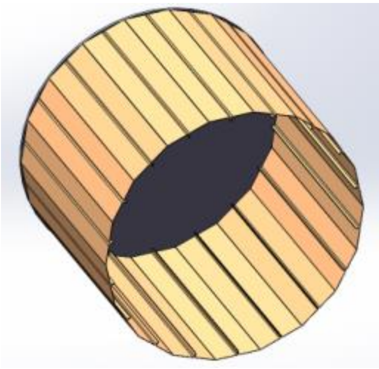


Type 50
- 24 segments
- Double buckling, 2 sides

Thanks to its low imperfection sensitivity, keeps a significant critical buckling pressure

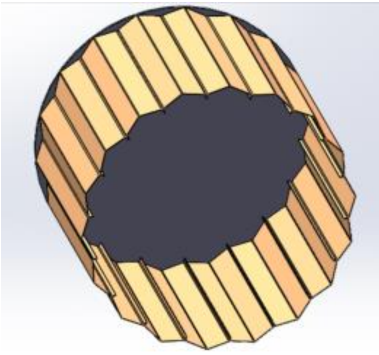


Type 51
- 21 segments
- Double buckling, 2 sides

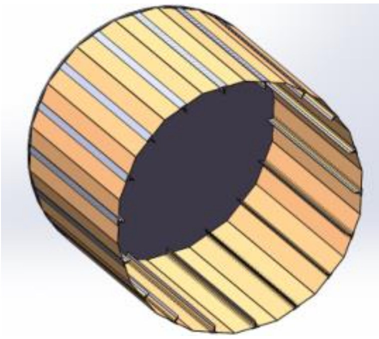


Type 52
- 18 segments
- No extra buckling

Less buckling resistant

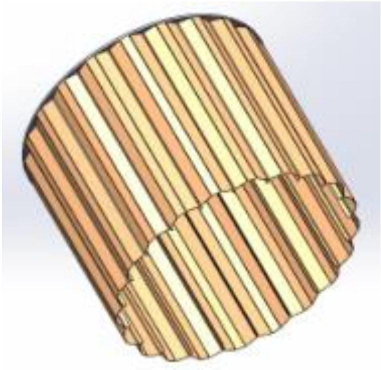


Type 53
- 18 segments
- ”Cookie cutter” design



Type 62
- 18 segments
- + 18 T-profils

Less buckling resistant



Type 55

- 21 segments
- " Cookie cutter" design

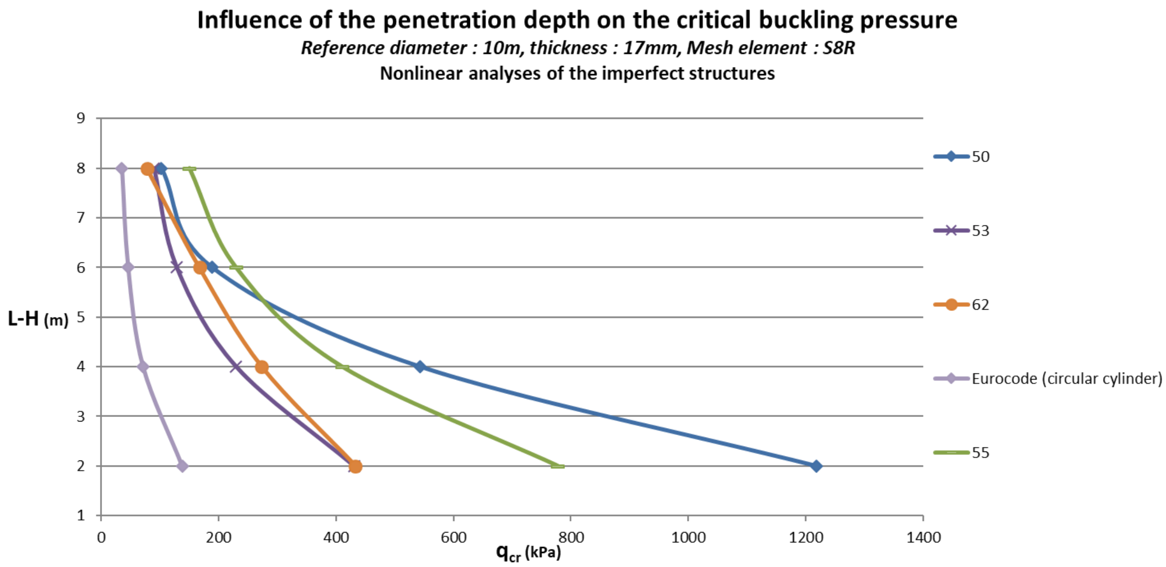


Figure 3 Critical buckling pressure calculation of jacket-buckets

This W was subject to an iterative process to optimize the design. Based on the first design calculations, the buckets with double buckling and a high number of segments had the best results regarding strength and imperfection influence. All calculations were performed with a skirt thickness of 17 mm as the target.
When looking at the cost optimization (WP5), the bucket types with lower bucklings showed lower costs and hence, the aim was to find a design with a lower number of skirt bucklings. In this case, the cookie cutter-design showed good results on the buckling pressure and a new type was designed (type 55). This design showed good results and the corresponding low cost fitted the project goals very well.

However, due to the low imperfection tolerance, other measures had to be taken. The double buckled types showed high imperfection tolerance because of the strengthened vertical structure between the segments. To keep the low-cost design and additional costs to a minimal, the project group came up with a solution, that could increase the imperfection tolerance and furthermore, increase the buckling load of the entire structure. Simply by introducing rib stiffeners between every skirt segment, calculations showed a buckling load increase of approx. 20%.

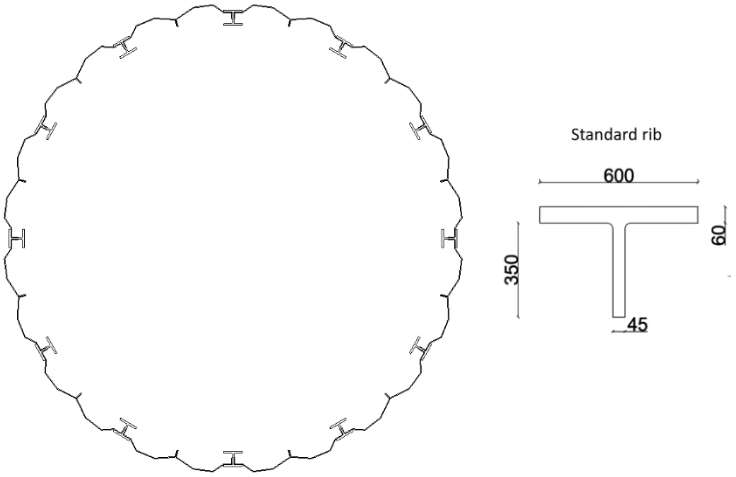


Figure 4 Calculations showed that installation of stiffeners between the skirt segments increased buckling load with 20%

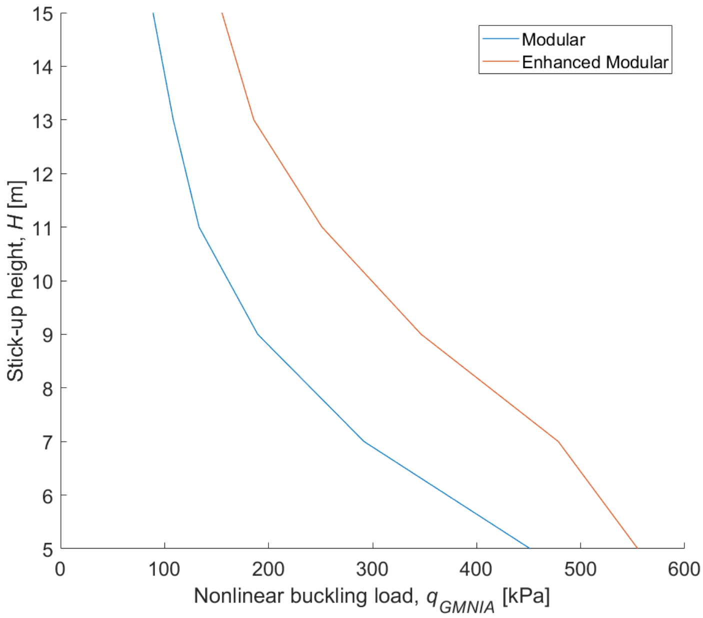


Figure 5 Calculation of buckling load with stiffeners. The enhanced modular bucket shows a higher buckling resistance

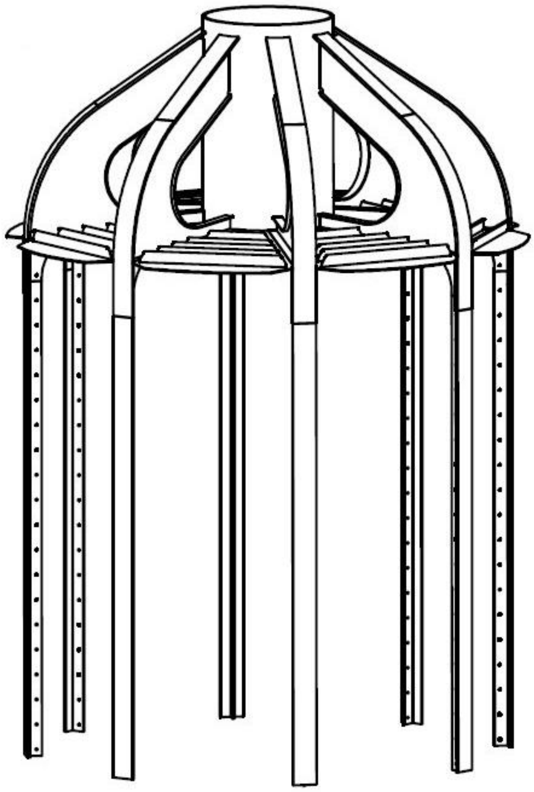


Figure 6 Lid web sections connected to stiffeners between skirt sections

Furthermore, to ensure stability and high strength of the entire structure, the stiffeners was connected to the lid segments, that were also integrated into the skirt segments as shown above.

The final design

To fulfil the requirements and optimize the cost reduction, a design was chosen for further investigation, prototyping and manufacturing. Based on the calculations performed by AAU, the final design is an enhanced cookie cutter type with 16 segments.

The final design of the modular suction bucket includes:

- 1 top shaft section for connection to jacket (6721 kg)
- 8 lid web sections (1641 kg)
- 8 lid plates (830 kg)
- 8 double skirt section plates (3923 kg)
- 8 skirt beams / stiffeners (1147 kg)

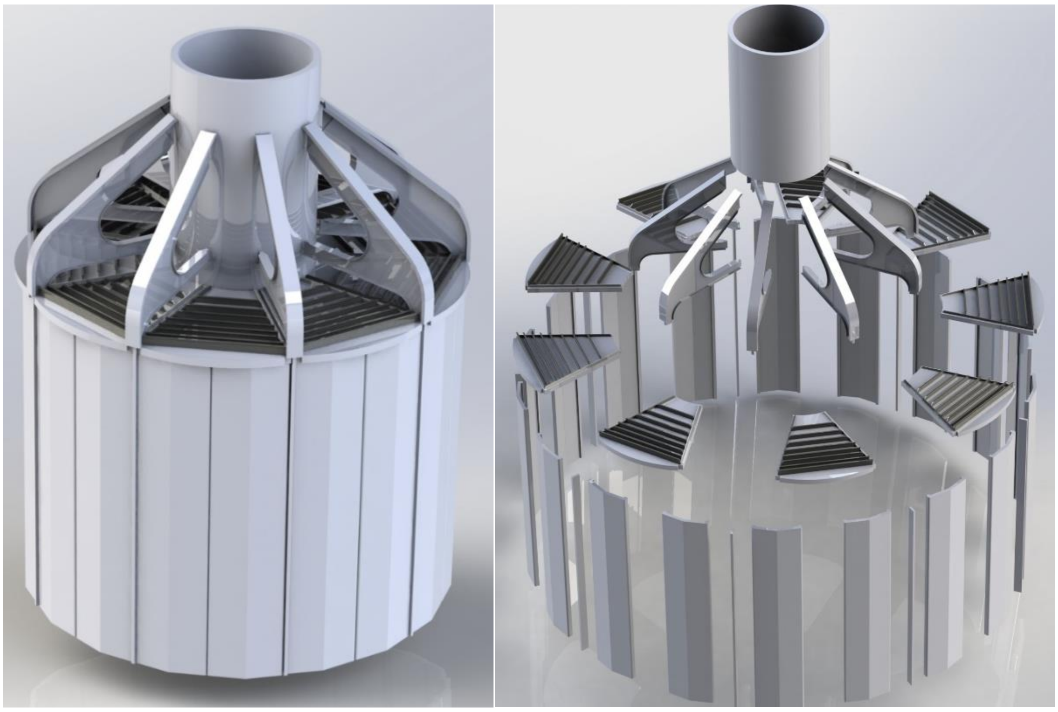


Figure 7 Final design of the modular suction bucket

The modular bucket has a diameter of 7,98 meters, skirt height of 8 meters and a total height of 11,34 meters. The net weight is 67,049 kg, that include all the above. Compared to the standard circular cylinder bucket with a weight of 92,000 kg, the new design has a weight saving of 28%.

The total weight of the bucket does not include the lowermost panels that are fitted below the skirt segments or the pipes, fitted from the top to the bottom. The purpose of these additional parts is the flush the sediment during installation. When installed in the seabed, the lower edge is exposed to great penetration resistance and to avoid edge buckling, the sediment is flushed, generating less damage to the material.

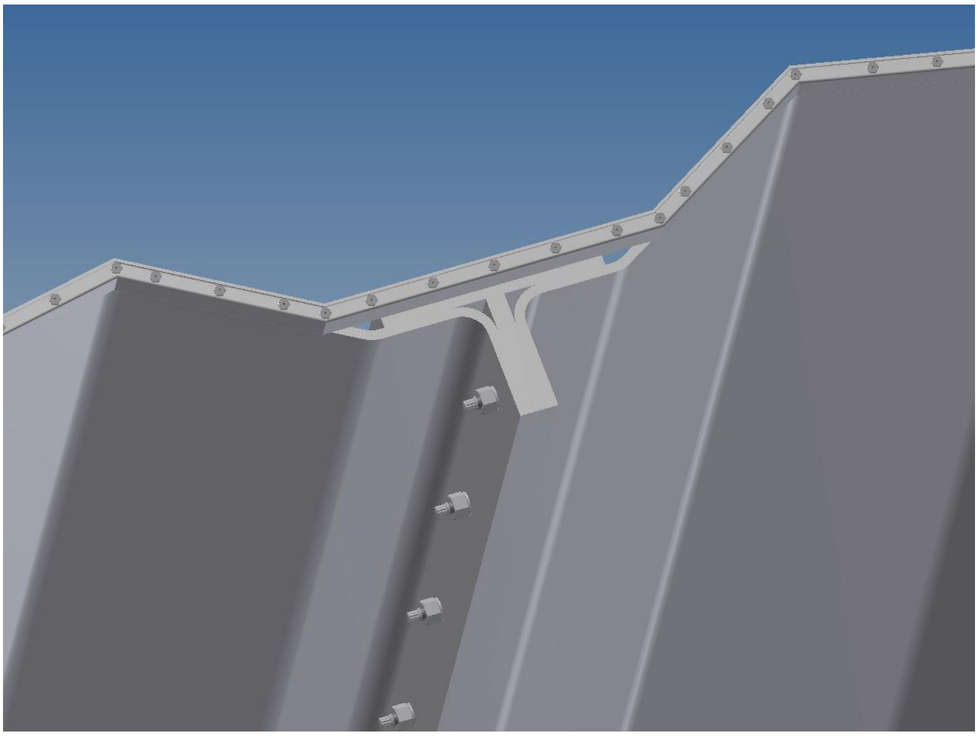


Figure 8 T-stiffener and flushing panels

Developing the modular bucket

The continuously growing need of creating offshore wind farms in greater depths lead the offshore industry to develop and introduce different types of foundations applicable for such a case. This idea would combine the advantages of the mono-bucket foundation and at the same time be able to be installed in greater depths. The Mickey Mouse bucket is meant to support future offshore wind turbines as large as +10 MW, which may be available in 2020.

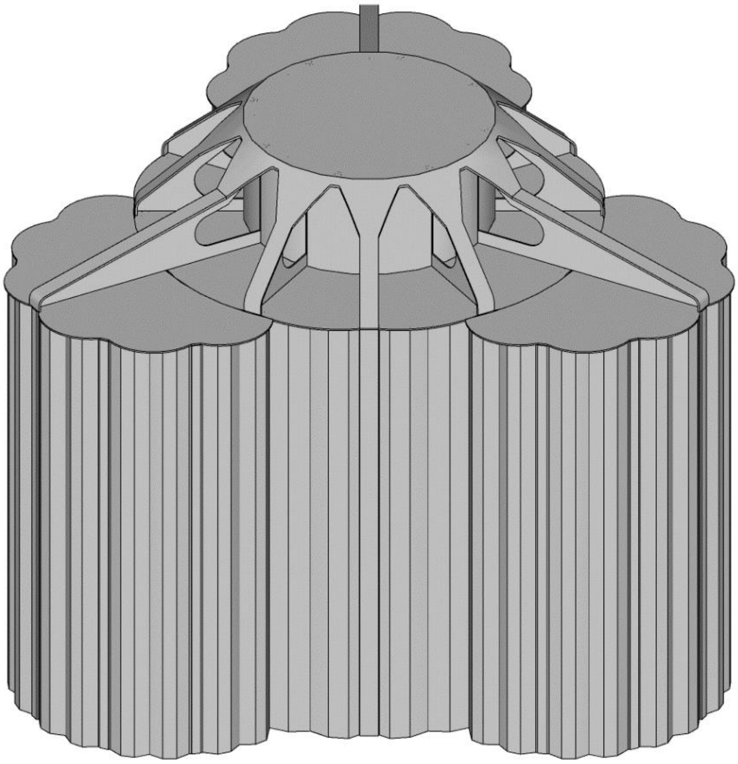


Figure 9 Suggestion for optimized suction bucket design

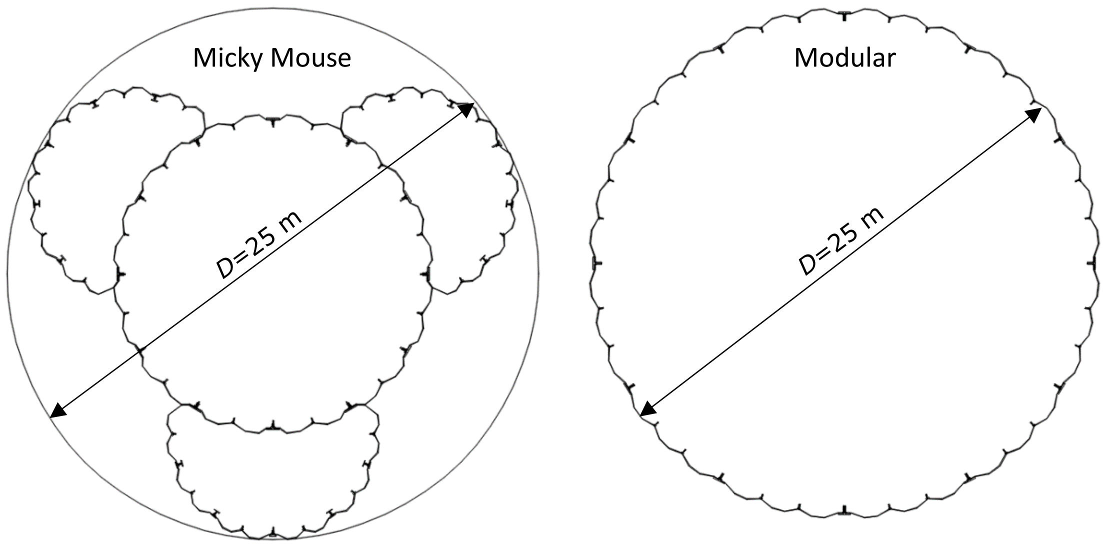


Figure 10 Design and dimensions of Mickey Mouse and modular suction buckets

A comparison of the new foundation concept and the mono-bucket has been made in terms seepage flow analysis. The model used for this comparison was created specifically for this foundation type and for that reason the model was evaluated before the comparison.
The Mickey Mouse foundation, in terms of seepage flow analysis, revealed some similarities with the mono-bucket foundation. More specifically, the behavior of the outer bucket of the

Mickey Mouse is behaving with the same manner as the mono-bucket while the inner bucket shows significant higher values. All these outcomes are observed both in the critical seepage length at the exit point at the lid but also in terms of excess pore pressure and seepage length at the tip of the foundation.

A study of the resistance of the soil was carried out as a comparison between two foundations: mono-bucket and Mickey Mouse. A set of variables were of interest in the study, geometrical properties of the bucket and application of the forces. In the case of the Mickey Mouse foundation, due to no axis-symmetry direction of the applied, forces were also studied. In terms of the variables, both buckets acted similarly under different loading and geometries. Results show a strong influence of the skirt length and the diameter, whereas the eccentricity does not impact significantly. By comparing suction buckets, a reduction of around 30% is found in the resistance of Mickey Mouse foundations compared to mono-buckets.

In comparison with a modular bucket of the same size, the Mickey Mouse shows more resistance against buckling. The influence of a few diameters was investigated. Based on the obtained linear results, it appears that a more comprehensive analysis is needed. This is because a direct correlation between diameter and buckling resistance was not found from the obtained results.

The assessment of various shapes of the mono-bucket has shown that improvements in terms of performance and cost is always a thing to aim for. The current design of the multi-shell has proven to be a valuable solution for the mono-bucket foundation. However, the modular promises lower costs due to its innovative design and higher buckling performance. The proposed design for larger wind turbines, referred to as Mickey Mouse, exceeds when compared with the same size modular, setting new ground for the future of offshore wind foundations.

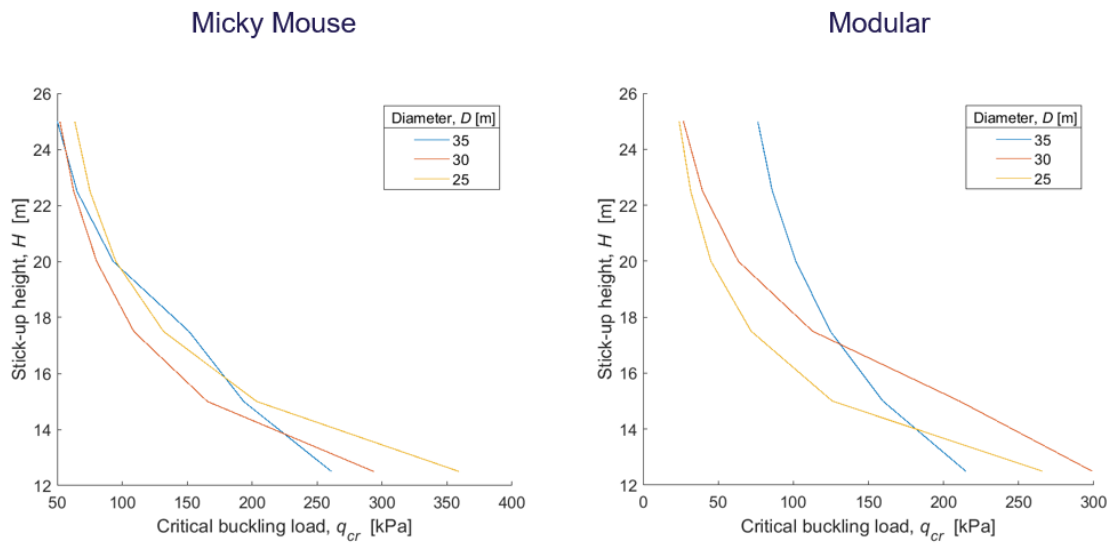


Figure 11 Critical buckling load calculations of Mickey Mouse and modular suction buckets

WP2 – Prototype

The observant reader might notice that the prototype design and the final design of the modular bucket are not entirely similar. Due to the prolonged design phase in WP1, the project group had to decide upon a design, not to interfere with the timeline of the project. At that time, the cookie cutter design with 21 segments showed the best results and hence, it was chosen for prototyping.

The purpose of the prototyping was to examine the production possibilities and to test the small bucket in the lab at Aalborg University. The bucket was produced according to the requirements of the lab facilities with at height and diameter of 1 m. Also, like the full-scale bucket, the small prototype was fitted with stiffeners to increase buckling resistance of the skirt. In the prototype, the stiffeners were fitted in every third section with a total of 7 ribs, compared to 8 ribs in the full-scale bucket.

The prototype was produced and assembled by Ib Andresen Industries.

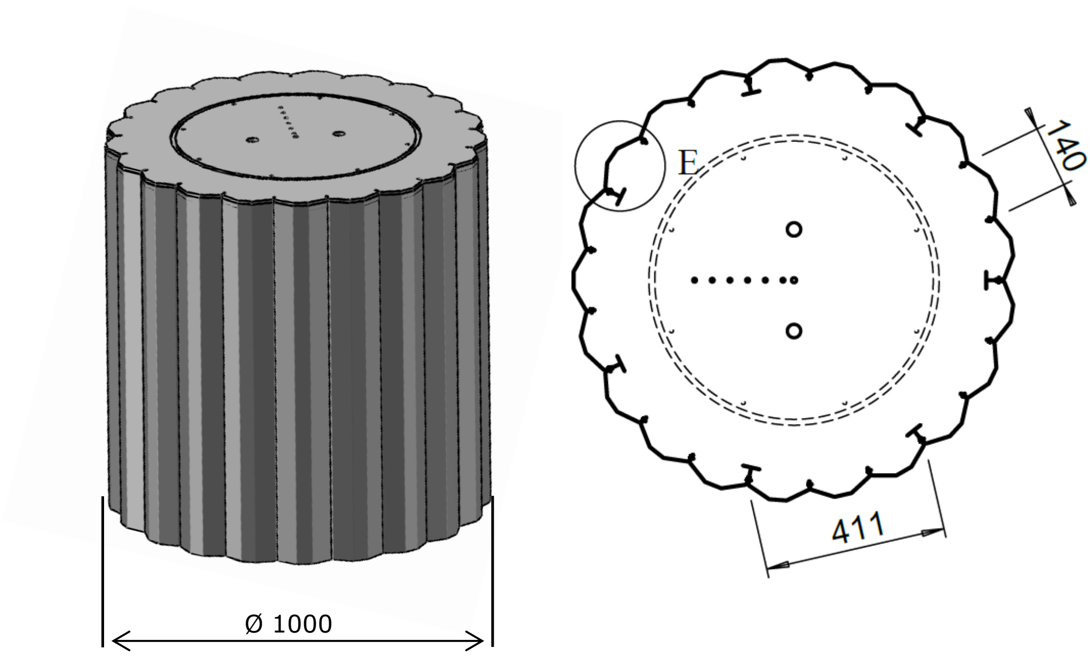


Figure 12 Fabrication drawing

Figure 13 Pieces for the 1m prototype. Upper left: T-stiffeners. Upper right: skirt pieces. Lower left: assembly of skirt. Lower right: fully assembled prototype.

WP3 – Scale tests

The purpose of this WP was to perform installation tests of scale models in the AAU test laboratory, using a pressure tank. The buckets were tested for both static and cyclic loads to perform several linear and nonlinear numerical buckling analyses of the bucket foundations.

A suction caisson, here called a bucket foundation, is installed through suction applied under the bucket lid. By this means, it can be installed faster and easier, as this method eliminates the use of heavy and expensive driving devices. Nevertheless, the design for the installation process is not straightforward. Firstly, the suction applied to create a driving force has its limitation that need to be preserved. Secondly, while dealing with permeable soil, there is a flow of groundwater around the whole bucket skirt, resulting from the suction. This seepage flow changes the pore pressure, hence the soil stress state. Therefore, the seepage flow requires an analysis, as it influences the soil resistance against the penetration.

The main part of the WP contained a numerical analysis of seepage development around the bucket foundation during its installation in permeable layer. Different soil combinations were considered with impermeable layer introduced in the soil profiles.

First aim of this WP was to evaluate a pore pressure factor. The factor describes the ratio between the excess pore pressure generated on the bucket tip and the applied suction under the bucket lid. The pore pressure factor could then be used for prediction of excess pore pressure at the tip or along bucket skirt with known soil condition, bucket geometry and applied suction.

The second aim of the WP was to evaluate expressions for normalized seepage length for different soil combinations and penetration depths. The seepage length was then used to make a prediction of critical pressure that would create piping channels at exit, which was near to seabed and to the caisson wall, along bucket wall and at the tip. That was how the limits for suction installation could be assumed.

Finally, the critical suction was used for predicting the reduction of penetration resistance and the method describing this approach was presented with its assumptions. The method is called AAU CPT-based method and it is a great step in the development of practical design tool for bucket foundation installation process.

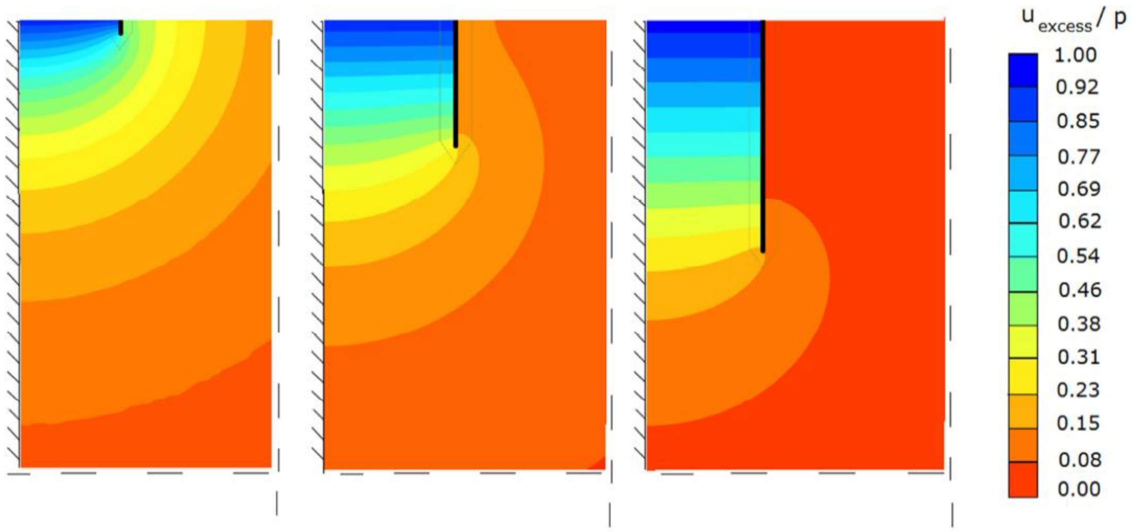


Figure 14 Results of ratio between excess pore pressure and applied suction under the bucket lid

Conclusions

Concluding on results, the seepage flow inside the permeable layer behaves differently if there is impermeable soil layer in close surroundings. Presence of impermeable layer above sandy soil, as well as presence of impermeable layer below, increases the normalized seepage length value and the pore pressure factor. Exception from this are the results of normalized seepage length for tip gradient for the case when penetrating skirt approaches the impermeable layer, case. In this case the values are decreasing towards 0, indicating almost full reduction in tip resistance in short time and for relatively small values of applied suction.

The results prove that the critical gradient due to applied suction under the bucket lead occurs first at the tip, then along the inside wall and finally at the exit, inside the bucket. According to numerical results, it is the soil resistance at the tip, which is reduced the most. It might seem logical then, that the failure of soil could happen in the same time. However, it is predicted that the soil material in surroundings densifies the area around the tip and therefore, it is the exit seepage results that should be controlling the allowable suction to avoid complete loosening of sand, resulting in piping channels.

The proposed solution getting us closer to the full design of installation of bucket foundation in permeable soil, where also impermeable soil layer is present in soil profiles.

Test of prototype

Due to the late completion of the suction tank in the lab at Aalborg University, the modular prototype bucket was only tested a handful time at the end of the project. The suction tests are used for general data collection on installation of suction buckets in different soil types, but moreover, the data collection from the prototype suction tests is important for trial installations of the full-scale bucket. Data collected during the full-scale trial installation are compares to the prototype tests for further analysis on structural behavior.

During the summer and early autumn 2018, Aalborg University will carry out more tests on the prototype for further and sufficient data collection.

Figure 15 Scale test with prototype modular bucket in pressure tank

WP4 – Manufacturing

The purpose of this WP was to prove, that the designed parts of the new, modular bucket could be produced at local steel working facilities. By producing the segments locally and by companies with limited capacity, more companies are able to bid for the production and price of the elements will go down. Furthermore, increased production facilities mean higher availability and higher total production capacity, which is a necessity with the increasing size of the future wind farms.

Production facilities for the skirt was examined thoroughly and three companies was chosen for bidding on the assignment. A local steel working company in Esbjerg (Nicon) won the bid and was hired for the skirt segment production. All 16 segments were produced in a few days and shipped to Frederikshavn for assembly.

The lid was produced based on a conventional design, fitted to the 16 segments. The lid was designed by Universal Foundation and produced by Nicon Industries together with the skirt segments.

For the assembly, a special blot was used. To ensure right bolt tightness, HRC bolts was used for the assembly of the skirt. This special bolt has an additional section in the thread end (spigot). The installation of the HRC bolt was done with an electric screwdriver and when sufficient torque was reached, the grooved spigot at the end of the screw ruptured. There is no possibility of over-tightening because the sizing of the shear section is calibrated.

Figure 16 HRC bolts was used for the assembly of the skirt

Here follows a series of pictures from the production of the elements and the assembly process.

Figure 17 T-stiffeners and flushing pipes

Figure 18 Lid web section

Figure 19 Shaft section

Figure 20 Assembly of the skirt sections

Figure 21 Fully assembled suction bucket

Figure 22 Flushing pipes and panels

Figure 23 T-stiffener section

Figure 24 Fully assembled suction bucket

WP5 – Logistic and Assembly

The purpose of this WP was to look into the production process, logistics and assembly to optimize cost reduction on the new design. The WP was led by Aalborg University, Institute for Mechanical and Manufacturing who examined every stage of the supply chain to reduce cost as much as possible. The two AAU departments worked closely together to find the best design, but also the adjusting and aligning the design to production, logistic and assembly.

Based on the proposed designs in WP, the following parameters was examined regarding optimal cost reduction, while maintaining structural properties:

Materials	Processes	Resources
Steel Concrete Cast steel Filler material	Transport Handling Inspection Assembly	Workers Cranes Equipment

Based on these parameters, AAU build a model to calculate the cost of each combination, using standard values for the cost of steel transport welding, workforce etc. The results of the cost calculation were then compared to the most obvious solutions and to the reference bucket, produced by a well-known suction bucket developer (not Universal Foundation).

The diagram below shows an overview of the steps and parameters in the cost model.

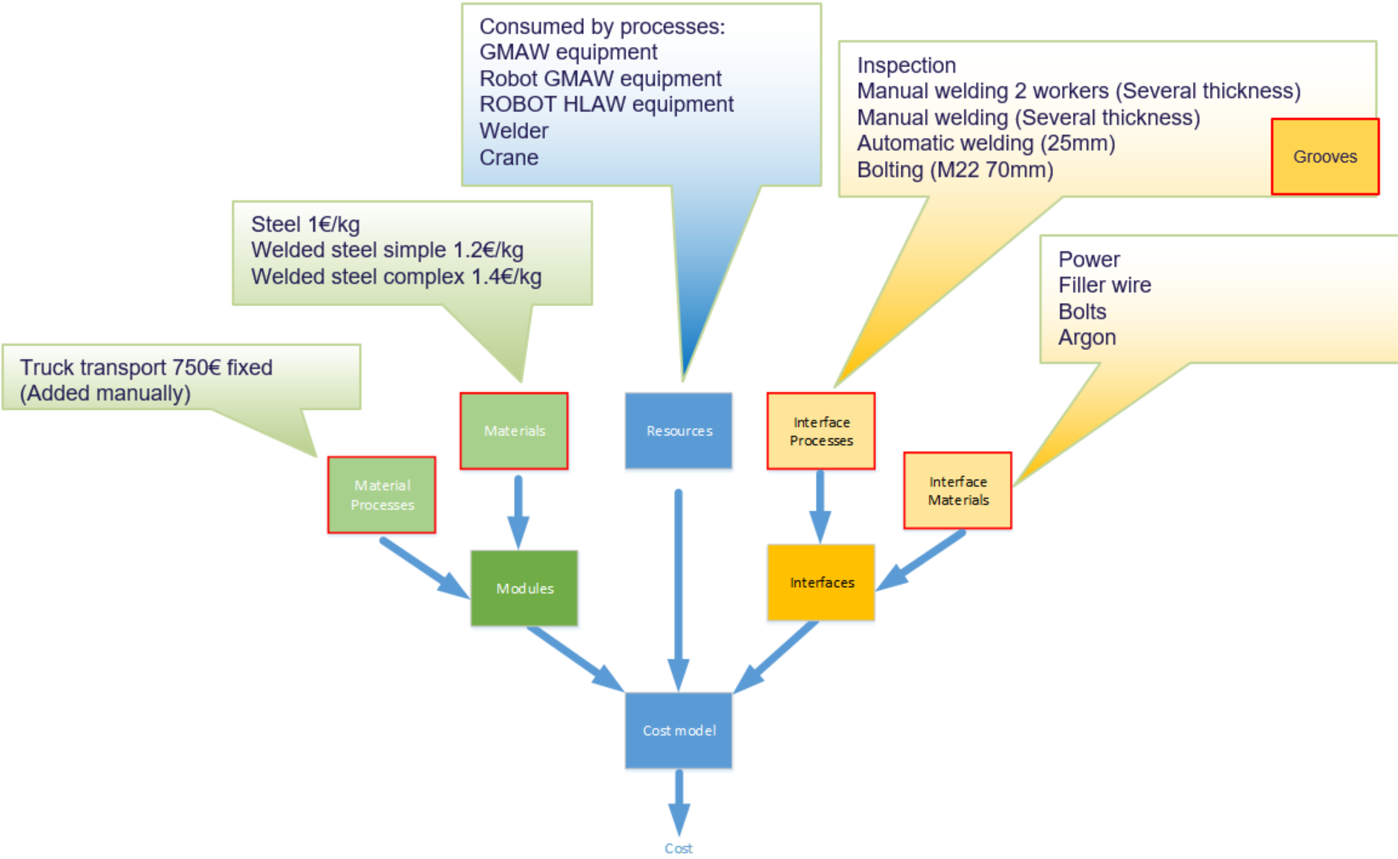


Figure 25 Overview of the build model for cost comparison

Calculating cost distribution

A calculation of the cost distribution between assembly, inspection and transportation revealed the fact that 90% of the costs linked to the production of the lid and skirt and 76% of costs linked to cost of material itself. This distribution emphasizes the importance of the project goal concerning material thickness reduction.

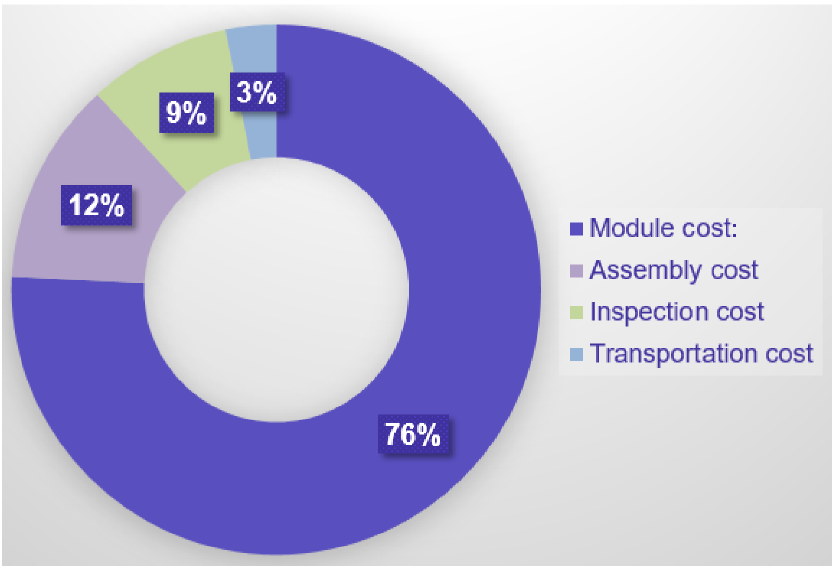


Figure 26 Distribution of costs

Also funding in the analysis, was the correlation between the cost and the number of segments in the skirt. The fewer segment, the lower price. Ultimately, this correlation was use for the final design selection of the skirt, as the best design went from 21 segments to 16 due to the cost/buckling resistance ratio.

Bolting vs. welding

One of the most crucial aspects of the production and assembly process was the choice between bolting, manual welding and automatic welding. Bolting and manual welding would require only minimal investment, whether as automatic welding would require substantial initial investment of equipment and production facilities. AAU estimate a required investment of approx. EUR 200,000 plus tool for the robot welding setup, while bolting and manual welding could have as low an investment as EUR 7,000.

Several methods of welding were considered for the assembly process: manual, automated and 2 different hybrid laser arc welding methods. The cost analysis showed that the HLAW was by far the cheapest. However, this method requires access from both sides and a quite complex setup to succeed.

	Manual (2 Welders)	Automated (1 operator)	HLAW (1 operator)	SP HLAW (1 operator)
Skirt->Skirt	14661€	8235€	2123€	2292€
Skirt->Web	7413€	4158€	1061€	1146€
Skirt->lid	5226€	2268€	1891€	1935€
Lid->Web	11572€	6690€	2045€	2171€
Lid->Cylinder	2043€	1474€	932€	946€
Web->Cylinder	3621€	3621€	3621 € (Manual)	3621€ (Manual)
Total	44538€	27698€	11673€	12114€

Further analysis of the costs revealed a rather large price difference between bolting and welding. Bolting has a price of 2.16 EUR/m, while both manual and robot welding has a price of 7.8 EUR/m for the material. The price of welding took another hit when the inspection cost was calculated. When welding large, bearing structures, inspection of the welding is a requirement. It is often performed by a neutral third-party and have a heavy cost. AAU estimated a welding inspection cost of approx. 25 EUR/m. The inspection is often done twice – after 2 hours and after 48 hours, meaning a double cost and a total cost that by far exceed the cost of the operation itself.

Conclusion

The new-build model was able to compare all parameters of the production, transport, assembly, material type etc. into total prices of the modular bucket. All scenarios were compared to the reference bucket with a wall thickness of 40 mm and a weight of 92 T. The purpose of this project was to reduce weight, modulize for smaller production facilities and examine assembly method. In the presentation of the final results, production of the full-scale bucket is included for comparison.

Compared to the reference bucket, the full-scale bucket ended with a weight reduction of 25 T. This is mainly because of the skirt thickness, where the project group managed a reduction from 40 mm to 17 mm. The project group choose a bolted solution due to the welding prices. However, installation of a vertical rubber sealer was necessary to ensure proper sealing in the joints during the lifetime of the bucket. When looking at the prices, the full-scale bucket ended at EUR 259,000, which is more expensive than the reference bucket. However, when looking at the mass production estimates, the bolted modular bucket has a cost saving of approx. 78,000 EUR/bucket or a cost reduction of 32%. Even at mass production level, the welded solution is more expensive than the bolted solution, but still has a lower price than the reference bucket.

	Reference Suction Bucket	Suction Bucket Prototype (Nicon)	Suction Bucket Series Production	Suction Bucket Series Production
Weight	92 T	67 T	67 T	67 T
Required # Units	300 Units	1 Unit	50 Units	50 Units
Assembly type	Welded	Partly bolted	Automated Welded	Partly bolted
Cost	238,000 €	259,000 €	205,000 €	160,000 €

WP6 – Project Management and dissemination

Project management was divided between Siemens Gamesa (SGRE) as technical project lead and Offshoreenergy.dk (OEDK) as administrative project lead. SGRE was responsible for the progression of the project regarding technical development and the production phases, in co-operation with WP leaders. OEDK was responsible for project economy, financial disbursement, reporting, project documents and general guidance on EUDP rules and possibilities to the project partners. This cooperation was implemented and adjusted at previous EUDP projects (64015-0042 and 64014-0537) and carry general project management satisfaction from all partners. As a result of this cooperation, the project partners are able to focus on their core competences, technical development.

On average, the project group had coordinating meetings every 3 month, not including internal meetings and focused sessions for project development.

Dissemination

Throughout the project, the partners have carried out dissemination of the project and the aims. Before and during the project, there has been only limited dissemination due to patenting and uncertainty about the results. However, at the end of the project, there has been quite the attention about the results. Several high-rated news media brought the news of the modular suction bucket after assembly and publication of the full-scale bucket pictures. This was well timed with the news from EUDP about supporting the trial installation project, making the news even more consistent support and development of this technology.

Here we bring a list of articles about the project and results. Active links have been added to the headlines.

<u>Before and during the project</u>

- Energy-Supply: Vindprojekt i Frederikshavn skal pushe sugebøtte-fundament
- Offshoreenergy.dk's Yearbook 2017 (p. 52)
- Fyens.dk: Dansk gennembrud gør vindkraft billigere
- B.dk: Dansk opfindelse kan revolutionere vindkraften

<u>Dissemination on results and trial installation funding news</u>

- Energy-Supply, Metal-Supply og Electronic Supply: EUDP uddeler 191 millioner ud: Her er de heldige kartofler
- Windpoweroffshore.com: Thinner suction bucket concept awarded grant

- Windpowerengineering.com: Wind consortium to test industrialized suction-bucket foundation foundation for offshore wind
- Rechargenews.com: Universal Foundation sucktion bucket gets Danish boost
  Renews.biz: Danes decide bucket list
- Breakbulk.com: Consortium tests coil steel foundation design
- Windtech-international.com: Universal Foundation partner with Siemens Gamesa to perform test installation on industrialised suction bucket concept
- https://www.offshorewind.biz/2018/07/03/new-project-eyes-cutting-foundation-related-costs-by-40/
- Renewablesnow.com: Universal Foundation team gets funds for suction bucket prototype installation
- Owjonline.com: Industry partners to industrialize cost-saving suction bucket
- Safety4sea.com: New technology aims to cut offshore wind costs
- Randers Amts Avis: Dansk gennembrud gør vindkraft billigere
- Aarhus Stifttidende: Dansk gennembrud gør vindkraft billigere
- Flensborg Avis: Dansk gennembrud gør vindkraft billigere
- Nordjyske: Gennembrud: Nordjysk projekt sænker prisen på havvindmøller
- AAU: innovativt design af fundamenter til havvindmøller kan næsten halvere prisen

1.6 Utilization of project results

For the project partners, working with the general suction bucket concept was not something new. However, the scope of the project was to create a new, modular approach that would cut costs and generate a new market or accelerate an already emerging market. The results of the project will be used in many ways, but ultimately, it all depends on the next phase of the project.

So far, the project parts have been able to prove a new design, production method corresponding cost savings, but without comprehensive evidence regarding installation capacity and durability, there will be no market. The foundations are a vital part of the offshore wind turbine with an expected lifetime of 25 years. For investment, the project developers need to be sure about the technology and the durability.

The project group has shown that even though the wind industry is under pressure and the competition is high, companies are still motivated to cooperate to achieve common goals. For the project group, part of the motivation derives from the goal of reinforce jacket structure's competitiveness in the wind industry as the technology is suitable for most sites in Europe and in addition also new markets, such as USA and Asia. However, Universal Foundation is also looking further into the mono-bucket design due to the well-developed production facilities of monopiles. Jacket structures are still more expensive than monopiles, but with the future projects and further development of the jackets, price is coming down, making this foundation type more competitive.

Commercialization

It is the expectation of all the industrial partners to use the results commercially. As stated above, it really and ultimately depends on the test installation of the full-scale bucket. If results are good, the project partners expect an extensive increase in industry interest. The project and the results have already drawn a lot of attention and project developers are looking more into the suction bucket technology. With the new, improved design, it is possible to cut costs further and save time on foundation installation.

In a typical project, the costs of foundations and installation constitute 20% of CAPEX. On the bucket itself, Universal Foundation expect 25% savings compared to conventional foundations making 0.5 to 1.0 mill. EUR savings pr. turbine. On the installation, UF expects a cost reduction of 40%, adding up to a total saving of approx. 1.5 mill. EUR pr. installed turbine. Also, it is estimated that suction buckets could be use on approx. 60% of the future European project and assuming a steady 4GW new installed offshore wind capacity every year, the market potential is huge. Furthermore, the suction buckets have a very high potential and benefits when it comes to deeper water projects and the increasing wind turbine size.

With the results of this project, the main commercial partner (UF) has adjusted their business plan. UF was already in the process of changing or adjusting their company strategy, but with the results of the project, modular buckets became a part of the new strategy. There are still some loose ends regarding site applicability and precise installation capabilities.

Along with the great results of this project came dissemination of the project achievements. At the IKPC conference in Bremen in June (Offshore Foundations), UF presented the results to the attendees with great response. Furthermore, with the completion of the full-scale bucket and the press release from EUDP regarding funding for the trial installation, the new bucket has received massive attention from the industry.

1.7 Project conclusion and perspective

The project purpose was to develop a new design and prototype for modular suction bucket with the aim of material and cost reduction. A cooperation between Aalborg University and Ib Andresen resulted in a range of suitable designs, that was analyzed regarding buckling resistance, imperfection tolerance and other important parameters. Simultaneous, Aalborg University performed cost analyses on the proposed design to ensure optimal cost savings. Based on the results, a 1x1 meter prototype was produced for scales tests at Aalborg University lab facilities.

To optimize cost reduction, production of the skirt modules should be possible for local steel working facilities. In production of the full-scale suction bucket, a local steel working company produced the skirt segments (~200 kg pr. segment) with satisfaction and the suction bucket was assembled at a local site in Frederikshavn.

The output of the project was a full-scale, strength and cost optimized prototype modular suction bucket to use with jacket structures. Furthermore, the project group looked further into the possibilities of producing a new design for the buckets to use with monopiles, "mono-buckets". Here they came up with a new design (Mickey Mouse), that showed great results.

Structures of this sized, bearing even larger structures must be well validated for market penetration. Important for the future development and application of the modular buckets is the trial installation in different soil conditions. Consequently, the project group must perform several test installations to look further into the strength of the new design and to validate for market introduction.

The most commercial partner, Universal Foundation, has experienced high interest in the new suction bucket and more project developers are showing interest regarding future wind installation project. However, everybody is waiting for the results of the trial installation.

Annex

ARTICLES, REPORTS ETC.

1	Buckling analysis for EUDP offshore wind suction bucket
2	Buckling Assessment of Modular Suction Buckets
3	Canadian Geotechnical Journal Medium-scale Laboratory: Mono-bucket
4	Conclusions on Buckling
5	ICPMG: Reduction in Soil penetration resistance
6	ISOPE: Seepage study for suction installation of bucket foundation
7	Numerical analysis of Modular Suction Buckets
8	Analysis of Laboratory Installation of Suction Bucket Foundation in Sand
9	Set-up and Test Procedure for Suction
10	Application of Hybrid Laser Arc Welding for the Joining of Large Offshore Steel Foundations

PRESENTATION OF RESULTS

11	Presentation Buckling of Modular Bucket
12	Presentation of Micky Mouse
13	Results of Work WP1 & WP3
14	Suction Installation of bucket foundation
15	Results of Work in WP5

TECHNICAL DRAWINGS

16	Design types
17	Rubber vertical sealer
18	Suction Bucket Prototype
19	Full-scale bucket

OTHER

20	DNV GL Comments
21	Patent application