Final report

1.1 Project details

Project title	Kost effektive fundamenter og installation for bølge energi.
Project identification (program abbrev. and file)	Projekt nr. 2012-1-10796
Name of the programme which has funded the project	ForskEL - Bølger
Project managing company/institution (name and address)	Department of Civil Engineering, AAU Thomas Manns Vej 23 9220 Aalborg Ø
Project partners	Wavestar A/S Park alle 350A 2605 Broendby. Universal Foundations A/S Langerak 17, 1. sal, 9220 Aalborg Øst
CVR (central business register)	29102384
Date for submission	12 oktober 2016

1.2 Short description of project objective and results

- The project has focus on development of cost effective foundation and installation methods for Wave Energy Converters (WEC), by investigating and optimizing novel foundation systems recently developed for offshore wind turbines. The project has developed a new cost efficient solution for the foundation and installation of bottom fixed WECs. The project has explored structural and foundation ideas in combination. The research has developed solutions that reduce cost and speed up the installation of the WECs. The output has range from improvements in overall structural designs, development of installation processes and consideration of construction logistics. The work has included mathematical models of foundation response, based on laboratory testing, theoretical work to enable a new range of foundation and substructure designs methods to be developed.

- Projekt har fokuseret på at udvikle omkostningseffektive fundament og installation metoder til Wave Energy Converters (WEC), ved at undersøge og optimere fundament principper nylig udviklet til havvindmøller. Projektet har udviklet en ny omkostningseffektiv løsning til fundamentet og installation af WEC. Projektet har udforsket strukturelle og fundaments løsninger i kombination. Forskningen har udviklet løsninger, der reducerer omkostninger og reducere installationen tiden af WECS. Udgangen har spænder fra forbedringer i de overordnede strukturelle design, udvikling af installation processer og logistik. Arbejdet har omfattet matematiske modeller af fundament reaktion, baseret på laboratorietests og teoretiske arbejde hvorved nye designs metoder for fundamenter og underkonstruktion designs skal udvikles.

1.3 Executive summary

The main goal in this project has been to develop cost effective foundation and installation solutions in order for Wavestar C6 to become a competitive concept on the offshore renewable sector. A number of investigations are performed in order to come up with the most cost effective solutions in different fields. The studied areas are grouped in four main groups:

- Cost modelling of the foundation and installation method.
- Investigation on installation approach.
- Support structure, foundation and superstructure interaction.
- Foundation design.

A full scale prototype for Wavestar C6 was planned to be installed in the North Sea in the upcoming years. So this conceptual study pretends to be a reference for a more detail design phase. Therefore the design, cost studies and other documentation presented in the report is based on a concept level for this location.

Six innovative foundation solutions were investigated. A detail study focused on geotechnical and structural design was carried out for the 6 innovative foundation solutions in different soil conditions i.e. first site dominated by sandy soils, second site dominated by clayey soils and third one, a potential site were a Wavestar C6 prototype was presumably to be installed. The output from the study reflected that either 2- or 4- legged solutions were feasible solutions for all the concepts. However the loading conditions for the 4- legged cases leaded to a significant increase on the amount of steel or concrete for manufacturing. The results also reflected that the pile and bucket foundations were the most competitive concepts. The gravity based concept was discarded due to the logistics needed to transport the massive concrete blocks that were required to sustain WEC. A trend was observed for the three investigated soil scenarios; the amount of steel required to manufacture the bucket solution was significantly less than the steel needed to manufacture the piles under the same site conditions. The calculations indicated that the bucket solution saved 4% up to 30% the required steel compare to the pile solution depending on the soil scenario.

Another interesting finding was observed on the installation phase. The project initial phase did not cover in detail the different installation scenarios for all six concepts but it was noticed that the bucket solution was the only concept able to be assembled with the superstructure prior to installation. So this concept could be shipped to installation site together with the Wavestar C6 and install the entire system at once. The other concepts would require subcontractors to install the piles or the gravity based and afterwards the superstructure could be installed.

As the bucket foundations was found to be the most suitable and cost-effective solution for Wavestar C6 the research has focuses on the tensile axial response of bucket foundations in dense sand. The research addresses several critical design problems related to the tensile response. Among those are the soil-structure interface parameters, tensile loading under various displacement rates and tensile cyclic loading.

For the analysis of realistic soil-structure interactions, a physical model was designed. A new laboratory testing facility was built allowing model testing in scale of 1:10 prototype size. Furthermore, an overburden pressure was evenly applied on the sand surface for the simulation of different soil depths. Thus, higher soil stresses were created, diminishing scaling effects and providing more information about the interface parameters. Furthermore, the test set-up allowed examinations of long-term cyclic loading. Up to 40,000 harmonic load cycles were applied with constant mean loads and amplitudes. The test set-up provided high quality data about loads, displacement and pore pressure.

A different test set-up – a pressure tank – was employed for the displacement rate analysis. The pressure tank enabled the simulation of 20 m water depth, allowing for the generation of various pore pressure levels during the examinations.

The extensive testing campaign provides valuable data about bucket foundation behaviour under tensile loading. State of the art analytical methods are employed for the verification and analysis of the data. Back-calculation of the drained tensile capacity shows that the lateral earth coefficient decreases non-linearly with increasing soil depth. An interaction diagram is drawn for a summary of the cyclic loading test results. The diagram indicates the range of mean loads and amplitudes within which the foundation model remains in a stable condition. No excessive upward displacements are accumulated in the range. Finally, the displacement rate tests show that large tensile capacity is available.

1.4 Project objectives

The objective for the project has been to develop cost effective foundation and installation solutions in order for Wavestar C6-600 kW to become a competitive concept on the offshore renewable sector. Wavestar C6-600 kW is a wave energy converter (WEC) designed to deliver 600 kW of electrical power to the grid, see Figure 1. It can operate in up to 20 m water depth including storm surcharge. In order to deliver cost competitive solutions, Wave Energy Converters (WEC), must be optimized in several fields, e.g. transportation, installation, structure, machinery etc. Large expenses lie on the superstructure support, i.e. the offshore foundation.

The objective was to investigate a number of solutions in order to come up with the most cost effective solutions in different fields. The studied areas are grouped in four main groups:

- Cost modelling of the foundation and installation method.
- Investigation on installation approach.
- Support structure, foundation and superstructure interaction.
- Foundation design.

A full scale prototype for Wavestar C6 was planned to be installed in the North Sea in the upcoming years. Therefore the design, cost studies is based on this location.

The objective was to analysis and optimize of six possible foundation solutions for WEC. The analysis was performed for WEC superstructure supported by two or four foundations. This includes development of new design methods to satisfy both ultimate and serviceability limit state requirements. Especially the development of design methods for the serviceability limit state requires comprehensive experimental investigation of soil and foundation interaction.

Figure 1. Wavestar Wave Energy Converter (Wavestar.2011).

The objectives were implemented by subdivide the work into three works packages with specific task:

WP1: Installation technique and cost study

Objectives: The focus of the work packet was to develop cost effective foundation and installation systems for Wave Energy Converters (WEC), by investigating and optimizing the foundation systems.

Task 1.1: Cost modelling of foundation and installation method
A possibility to have the WECs becoming more economically feasible is to reduce the cost of the foundations and its installation. The aim for this task was to develop an innovative foundation system so the WEC can be self- installing without subcontractors.

Task 1.2: Suction Installation
Investigate and develop suction assisted penetration method the legs.

Task 1.3 Steel design of the Bucket foundation
One of the key requirements of the foundation and sub structure is its fatigue resistance. Especially in offshore conditions, the effect of wave can significantly increase fatigue loads. The attachment structures and other welded steel sub structures can possess reduced fatigue strength due to its manufacturing process. This task will focus on jointed sub structure topology optimization for minimum reduction in fatigue resistance as compared with a solid structure. The objective is to design a frame sub structure with minimal welded joints, but meeting all fatigue strength constraints.

WP2: Marine loads on WEC and foundation

Objectives: The objectives of WP1 are to establish the basis for an integrated offshore site specific design process. This involves the development of new specific methods and models for simulation of loads and structural response and integration of these into existing design tools to form integrated tools that incorporate a variety of new parameters.

Task 2.1: Foundation - WEC interaction. Concept studies
Concept studies of different integrated design solutions and the implications on stability, loading, damping and costs are conducted.

Task 2.2: Extreme and fatigue loads
Usage of second order nonlinear wave kinematic models will be made to determine the impact of the nonlinearities in the wave kinematics on the design of the support structure. The effect of fluid-structure interaction with second order water kinematics on the long term extreme and fatigue loads is evaluated.

WP3: Foundation Concept studies

Objectives: The primary objective is to deliver solutions for optimal designs and development of innovative, cost-efficient foundations and support structures. The dynamic loading from the waves plays a significant design issue and new design method for the soil/ water and structure interaction have to be developed, focusing on both short and long term effects. As the support structure is a major cost items, especially in deeper water, the optimization and development of new foundation systems is a powerful source of cost reduction.

Task 3.1: Concept studies.
For all tree foundation systems the extreme waves lead to very high loads with particularly large overturning components while the operation condition leads to vertical lift, which the structure and foundation must be able to resist. Two different ways of transferring the loads to the foundation, a two or four legs solution are studied.

Task 3.2: Design methods for foundation concepts:
For these new foundation concepts more cost effective designs methods can be established with recent advances in geotechnical modelling. This will lead to more accurate design procedures resulting in cost effective designs, especially in problematic soil profiles.

Task 3.3: Experimental investigation of soil and structure interaction
The work will focus on investigations both the short and long term design issues in for vertical loading of bucket foundations. Experimental testing is essential to understand the mobilisation of the friction force and the long term degradation of it. The use of a recently developed finite volume based solution technique for the will be applied to the support structures and soil types investigated in this work package.

The project was initiated 1. July 2012 and ended 31 December 2015. A details time schedule was agree on at the beginning of the project and followed through the project. Numerous activities were planned to running in parallel as these were interrelated witch was a risks associated with the project. Good communication and compliance with milestones resulted in a good flow in the project and the objects in the projects was all reacted and reported as agreed.

A Ph.D project has been connected to the project and successfully defended at the 25 August 2016. The completion of the Ph.D thesis has been delayed due to pregnancy, witch has delayed this final report.

1.5 Project results and dissemination of results

The project initial phase consisted on a foundation concept study. The generated output would provide some light on which of the investigated solutions is the most favourable to sustain Wavestar C6 -600kW. Such task was developed in cooperation with all project partners i.e. Civil Engineering Department at Aalborg University, Wavestar and UFOAS. Therefore the first activity was aimed to investigate the performance of various foundation concepts extensively used on the offshore renewable sector and oil and gas. The investigated foundation concepts are:

- Pile foundation
- Gravity based foundation
- Universal Foundation prior called Bucket Foundation

Six innovative foundation solutions were investigated; those are presented in Figure 2. A detail study focused on geotechnical and structural design was carried out for the 6 innovative foundation solutions in different soil conditions i.e. first site dominated by sandy soils, second site dominated by clayey soils and third one, a potential site were a Wavestar C6 prototype was presumably to be installed.

The output from the study reflected that either 2- or 4- legged solutions were feasible solutions for all the concepts. However the loading conditions for the 4- legged cases leaded to a significant increase on the amount of steel or concrete for manufacturing.

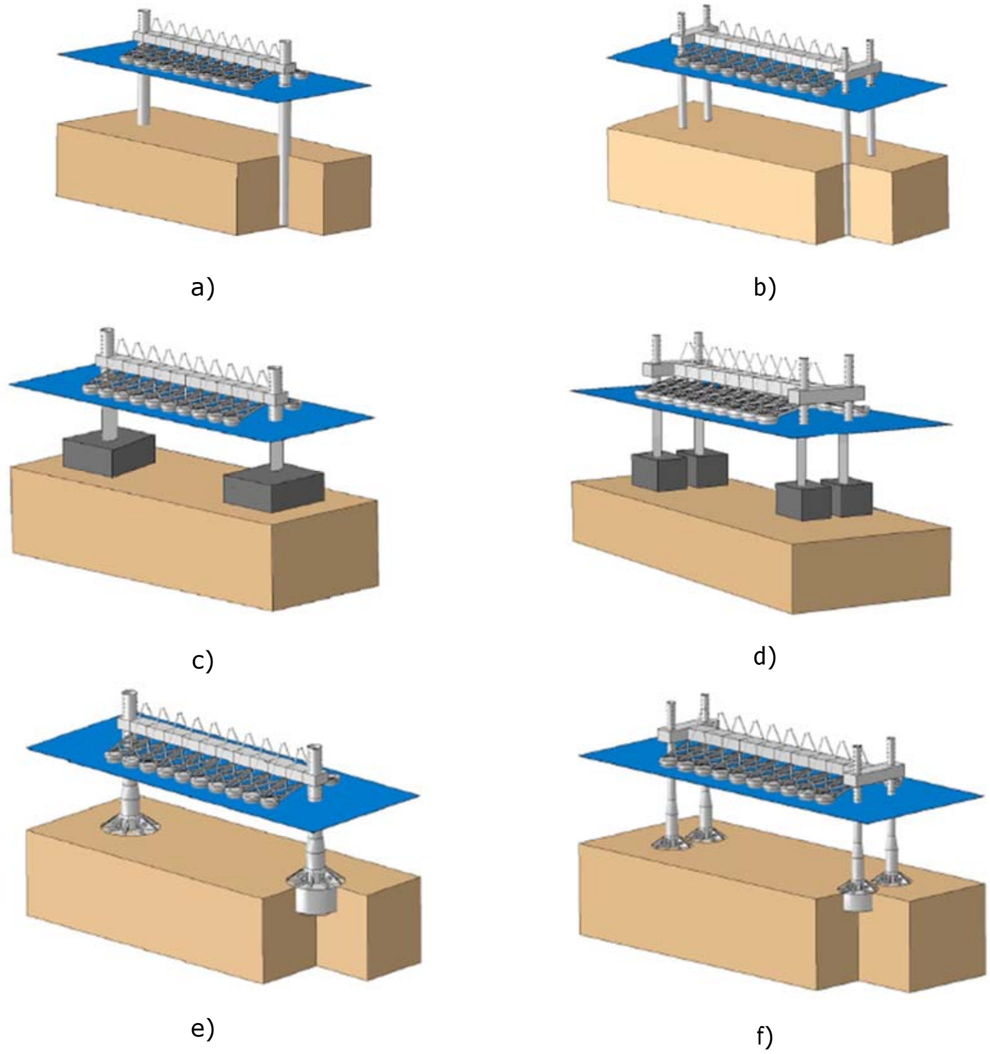


Figure 2. Analysed foundation solutions. a) 2 legged pile foundation. b) 4 legged pile foundation. c) 2 legged gravity based foundation. d) 4 legged gravity based foundation. e) 2 legged Bucket Foundation. f) 4 legged Bucket Foundation

The results also reflected that the pile and bucket foundations were the most competitive concepts. The gravity based concept was discarded due to the logistics needed to transport the massive concrete blocks that were required to sustain WEC. A trend was observed for the three investigated soil scenarios; the amount of steel required to manufacture the Universal Foundation was significantly less than the steel needed to manufacture the piles under the same site conditions. The calculations indicated that the Universal Foundation saved 4% up to 30% the required steel compare to the pile solution depending on the soil scenario.

Another interesting finding was observed on the installation phase. The project initial phase did not cover in detail the different installation scenarios for all six concepts but it was noticed that the Universal Foundation was the only concept able to be assembled with the superstructure prior to installation.

Monopile vs. Bucket Foundation

Nowadays the monopile concept is the preferable foundation solution for Offshore Wind Turbine OWT. Approximately 79% of the OWT are using such foundation concept. It is well-known on the offshore wind market that a monopile is a competitive solution until water depths around 25m. For bigger water depths this concept tends to become too large and also an expensive solution. Additionally OWT are increasing on dimensions day by day but also new offshore wind parks are projected in bigger water depths. Therefore other foundation concepts such as jacket structures and Universal Foundations are potential concepts in such circumstances. UFOAS developed an internal cost study for a major Offshore Wind Farm project on the North Sea. Two foundation concepts i.e. Monopile and Bucket Foundations were compared for a project containing 70 OWT units within water depths around 25m. The results proved that the Bucket Foundation is also a competitive foundation concept for water depths around 25m. The total weight for the monopile was up to 894t compared to the Bucket Foundation weight reaching the 720t. Therefore the cost-saving was up to 20% less amount of steel needed for manufacturing. Table 1.a). presents the unitary weight for all components considered on the Bucket Foundation concept together with price per tonnage and total cost. Table 1 b). presents the unitary weight for all components considered on the Monopile concept together with price per tonnage and total cost.

Table 1. Cost studies for North Sea projects. (a) Bucket Foundation study. (b) Monopile study.

Bucket Foundation Cost Study		
	Weight [t]	Cost [€/t]
Shaft	261	1,600
Lid arrangement	180	3,350
Skirt	171	3,350
Sec. Steel	97	6,134
Lift arrangement	11,3	2,247
Total cost per unit = 2,230,000m€		

(a)

Monopile Cost study		
	Weight [t]	Cost [€/t]
Monopile	529	1,653
Transition piece	350	3,930
Anode cage	15	-
Total cost per unit = 2,450,000m€		

(b)

However such study did not reflected other projects costs for example Installation, logistics, transportation and Engineering costs. One of the potential key elements on the Bucket Foundation concept is the installation approach. For offshore meteorological mast projects, UFOAS has proved that the installation times might be reduced considerably compared the current installation rate achieved by monopiles i.e. approximately one monopile installed per day. So the installation costs are reduced significantly if the installation times are also reduced.

The project initial phase and the monopile vs. Bucket Foundation study leaded to the decision that Bucket Foundation is the most cost efficient foundation concept for Wavestar C6-600kW no matter what are the load and soil conditions.

1.5.1 WP1: Installation technique and cost study

Objectives: The focus of the work packet was to develop cost effective foundation and installation systems for Wave Energy Converters (WEC), by investigating and optimizing the foundation systems.

All tasks involved in Work package 1 make reference to the foundation design, installation technique and project cost study. All tasks and results included in the work package are reported in one report [1] which can be read in it hole in Appendis A. The report is structured as listed below:

1. Support structure, foundation and superstructure interaction *(investigation on Task 1.3)*
2. Steel design for Universal Foundation. *(investigation on Task 1.4)*
3. Investigation on installation approach. *(investigation on Task 1.2)*
4. Cost modelling of foundation and installation method. *(investigation on Task 1.1)*

1.5.2 WP2: Marine loads on WEC and foundation

Objectives: The objectives of Work Package 2 are to establish the basis for an integrated offshore site specific design process. This involves the development of new specific methods and models for simulation of loads and structural response and integration of these into existing design tools to form integrated tools that incorporate a variety of new parameters.

The works in the WP2 have been performed by Wavestar and has mainly focussed "Marine loads on WEC and foundation". The contribution involved the development of a complete simulation model for the 20 float system with 2 ledges substructures. In the model interactions between the floats was taken into account and the PTO dynamics and control strategies was simulated with great detail. The main contributions were summarised in 6 reports or Excel sheets, as described below. These documents are confidential and used by WP1.

Documents delivered to CEFIWE by Wavestar:

Task 2.1: Foundation - WEC interaction. Concept studies

Concept studies of different integrated design solutions and the implications on stability, loading, damping and costs are conducted.

- WS1 "Wavestar C6 structural loads for THV Mermaid"
  - The report describes in detail the simulation model and assumptions used to calculate the loads on the bearing attachments to the main structure

- WS2 "Loads on jacking system from floats in operation"
  - The report describes how the loads on the bearing attachments are transferred to the jacking sections (the loads needed for the foundation design).

Task 2.2: Extreme and fatigue loads

Usage of second order nonlinear wave kinematic models will be made to determine the impact of the nonlinearities in the wave kinematics on the design of the support structure. The effect of fluid-structure interaction with second order water kinematics on the long term extreme and fatigue loads is evaluated.

- WS3 "Environmental Conditions for Wavestar Design – Mermaid"
  - Excel sheets with wind and wave conditions which were used as design basis for the load calculations.

- WS6 "WS6 ULS-Production Max loads"
  - Excel sheet containing the max-loads for all the load combinations, and also the ULS design loads cases.

- WS7 "WS7 Comparison ULS-storm VS ULS-production"
  - An Excel sheet comparing previously established ULS loads with the new design loads established through the CEFIWE study.
  -
- WS4 "ULS-Storm loads from wind and waves"
  - Excel sheet with design wind and wave loads for storm protection

- WS5 "WS5 FLS loads on jacking system from waves"
  - Zip file containing 5 excel sheets with the FLS loads arising from the wave loads over a period of 20 years in production.

1.5.3 WP3: Foundation Concept studies

Objectives: The primary objective is to deliver solutions for optimal designs and development of innovative, cost-efficient foundations and support structures. The dynamic loading from the waves plays a significant design issue and new design method for the soil/ water and structure interaction have to be developed, focusing on both short and long term effects. As the support structure is a major cost items, especially in deeper water, the optimization and development of new foundation systems is a powerful source of cost reduction.

The works in the WP3 have been performed by AAU. The work has been integrated to the Ph.D dissertation connected to this project .The dissemination of the work in WP3 has been through the Ph.D thesis [2] and on five papers (that include three conference papers, two journal papers) and two technical reports. The papers cover the aims of the PhD project regarding the scientific analysis and the laboratory testing of bucket foundations in sand subjected to axial loading.

Task 3.1: Concept studies.
For all tree foundation systems the extreme waves lead to very high loads with particularly large overturning components while the operation condition leads to vertical lift, which the structure and foundation must be able to resist. Two different ways of transferring the loads to the foundation, a two or four legs solution are studied. The results of this task are reported in.

- [3] Vaitkunaite, E., Ibsen, L. B., Nielsen, B. N., and Devant Molina, S. (2013). Comparison of Foundation Systems for Wave Energy Converters Wavestar.

Task 3.2: Design methods for foundation concepts:
For these new foundation concepts more cost effective designs methods can be established with recent advances in geotechnical modelling. This will lead to more accurate design procedures resulting in cost effective designs, especially in problematic soil profiles. The results of this task are reported in.

- [4] Vaitkunaite, E., Nielsen, B. N., and Ibsen, L. B. (2015). Comparison of design methods for axially loaded buckets in sand.

Task 3.3: Experimental investigation of soil and structure interaction
The work will focus on investigations both the short and long term design issues in for vertical loading of bucket foundations. Experimental testing is essential to understand the mobilisation of the friction force and the long term degradation of it. The use of a recently developed finite volume based solution technique for the will be applied to the support structures and soil types investigated in this work package. The results of this task are reported in.

- [5] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. (2014). New Medium- Scale Laboratory Testing of Bucket Foundation Capacity in Sand.
- [6] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. (2016). Testing of Axially Loaded Bucket Foundation with Applied Overburden Pressure.
- [7] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. Bucket Foundation Model Testing under Tensile Axial Loading.
- [8] Vaitkunaite, E., Nielsen, B. N., and Ibsen, L. B. (2016) Bucket Foundation Response under Various Displacement Rates.
- [9] Vaitkunaite, E. (2015). Bucket Foundations under Axial Loading: Test Data Series 13.02.XX, 13.03.XX and 14.02.XX.

The project has succeeded in realising the objectives in this project. It has been shown that the bucket foundation can be integrated and used as foundation of Wave Energy Converters. The has been shown that this will reduce the cost and time regarding establishment of offshore installation and introduce industrialization by:

- Reducing the amount of steel used compared to piles, and use simple geometric welded steel structures. The structure is omnidirectional symmetrical with respect to the vertical axis.
- Few offshore operations, with utilizing smaller equipment/vessels during installation than is used in connection with other foundation types. No seabed preparation and no or reduces need of scour protection.
- Simple decommissioning.

By installing the foundation by suction, the following environmental benefits are achieved:

- No pile driving hammers or drill drives are used. Only the use of power packs generates noise, which in no way can be harmful to sea mammals.
- The seabed is kept intact to a large extent. The use of excess material for scour protection is reduced or not necessary.
- All steel materials can be retrieved from the seabed and recycled when the foundation is de-commissioned.
- By applying pressure to the bucket, the foundation can be retrieved from the seabed.

Did the project give answer to the problem stated in the project proposal which the funding has been based on? Did the project produce results not expected?

1.6 Utilization of project results

The plan was that the results from this project shut be used in very ambitious project of 1 MW in the North. The project has focus on this specific location in it design performed in WP1 and WP2. Despite a big bag of money from Horizon 2020 and not least the project's immediate success, throwing management in the towel the 1 of June 2016 due to lack of investors. Therefor these parts of this project will not be utilized at this current time.

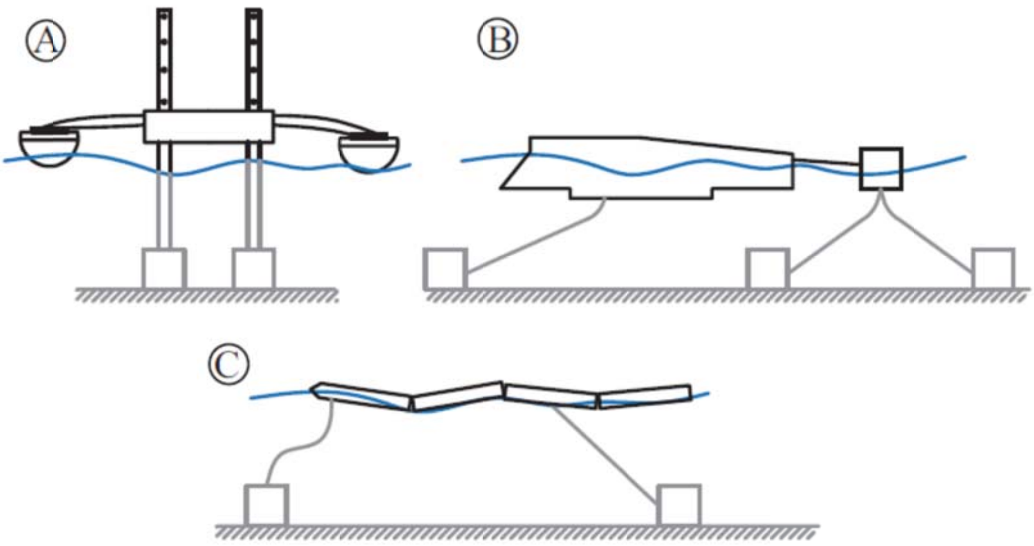


Figure 3. Wave energy converters: A) Wavestar B) Wave Dragon C) Pelamis.

The knowledge obtain by the research part of the project WP3 is still very valuable and can be used in design of foundation systems for other Wave energy converters as shown in Figure 3.

1.7 Project conclusion and perspective

The conclusion is split in two parts. One relating to WP1 and WP2 and one relating to the research part of the project WP3.

Conclusions relating to WP1 and WP2.

From an engineering cost point of view the difference on loading conditions between an OWT and a WEC structure demands that the foundation structure is investigated carefully from scratch. Therefore a site specific design has to be developed for any foundation concept consider suitable. This fact makes that to compare the engineering cost of a monopile and a bucket becomes a serious challenge. In such situation no benefits or drawbacks can be presented for any of the foundation concepts in terms of engineering costs

From a manufacturing point of view the main points that have an impact on the two analyzed structures i.e. circular and multishell concept, are the complexity and the vulnerability towards damages during manufacture due to large diameter of the bucket skirt. Conversely the difference in total weight from both structures does not have an impact on the manufacturing. Nonetheless the total foundation weight is affected by the steel price. An individual analysis is developed to point out pros and cons for the circular and multishell concept.

Universal Foundation circular bucket concept:

Pros:

- Skirt structure is easier to manufacture.
- Skirt structure faster to manufacture.
- Reduced risk for defects during manufacturing due to less complex structure.
- Less complex structure gives higher number of possible suppliers.

Cons:

- The weight of the pates composing the skirt structure is higher.
- The structure is more vulnerable for deformation of skirt during manufacturing, shipping and installation due to combination of large diameter and relative small plate thickness.

Universal Foundation multishell bucket concept:

Pros:

- Reduced material weight.
- More rigid concept is less vulnerable for deformation during manufacturing and shipping.

Cons:

- Skirt structure more complex to manufacture.
- More complex structure reduces number of possible suppliers.
- Longer manufacturing leads to longer time therefore higher costs.

From an installation point of view several uncertainties were aroused due to the nature and the maturity of the project. Since almost no experience is available installing a WEC in offshore conditions it is challenging to program a full installation campaign. However the installation approach presented in chapter 3 (in Appendix A) is a concept investigation that might be used as start point on a more detailed installation study. UFOAS is presenting here the pros and cons that were faced during the installation study developed for CEFIWE project.

Pros:

- Total installation costs since the installation expenses were the driving parameter.
- No subcontractors needed to perform the installation.
- No jack up vessel with massive crane required.

Cons:

- Complete new installation concept.
- Transportation for the total assembly i.e. Wavestar C6 and foundations due to final dimensions
- Synchronization for suction installation, Wavestar C6 floating state and barge positioning.

Conclusions relating to WP3.

A new laboratory testing facility was designed for the examination of long-term cyclic loading on a bucket foundation model. This allowed for the testing of a large bucket foundation model in laboratory conditions on a 1:10 scale model with a diameter of 1 m and a skirt length of 0.5 m. To the best knowledge of the author, this is the largest model foundation ever tested under laboratory conditions. The model skirt was naturally corroded and installed in fine dense sand providing realistic interface parameters.

The size of the sand container was maximally utilized testing mainly tensile loads and minor compressive loads. The boundaries of the sand container thus had no influence on the results. The application of suction under the membrane simulated an evenly distributed overburden pressure, which allowed for the examinations of friction responses at different soil depths. Overall, the design of the test set-up was successful in that it provided high-quality data and consistent results that were essential for the data analysis.

Monotonic displacement controlled tests were performed at various overburden pressure levels. With the slow displacement rate of 0.002 mm/s, drained responses were obtained. The tensile peak load was achieved within the first 10 mm of upward displacement, followed by an even reduction due to the diminishing area of the soil structure interface as well as soil softening. The higher the membrane pressure level that was applied, the higher peak resistance was measured, while the stiffness was similar for majority of the tests, at approximately 1 MN/m. The peak resistance values were used for the analysis of interface parameters. It was noticed that the unit skin friction increased non-linearly with the overburden pressure, which may be explained by a non-linear change in the lateral earth pressure. Back-calculation of the lateral earth coefficient K resulted in values from 3 for the low vertical stresses to 0.5 for the higher vertical stresses. The rapid change of K may be expected in the first five meters from the seabed surface. The tests results show that during static tensile loading, lateral earth pressure is higher than may be predicted with the conventional methods.

The next set of examinations involved cyclic load controlled tests at various overburden pressure levels. The mean cyclic loads and amplitudes were normalized with the measured drained tensile capacity. The bucket foundation model was subjected to long-term cyclic loading containing up to 40,000 cycles at a constant frequency of 0.05 or 0.1 Hz. Two-way (compression-tension) and one-way tensile loads were applied in the test programme. It was noticed that mean tensile loads of up to 50% of the tensile drained capacity could be allowed for the design without causing an excessive accumulated displacement during the 40,000 cycles. However, all testing with tensile mean loads resulted in an incremental upward displacement, even though it was as small as -10−4 mm. While the cyclic test resulted in very small accumulated displacements |wcyc|<0.01D, the model was exposed to gradual pull-out when peak loads reached the drained tensile capacity. Values for the cyclic loading and unloading stiffness were higher than those found for virgin loading stiffness. The magnitude depended on the loading amplitude and the mean cyclic load. Post-cyclic monotonic loading showed a stiffer response compared to the virgin loading. The post-cyclic peak tensile capacity was up to 25% lower than the virgin tensile capacity in tests with no membrane pressure. Relatively few post-cyclic tests were performed with membrane pressures pm>0 kPa; no indication of cyclic degradation was observed.

The final set of tests concerned tensile loadings in a pressure tank. The tank enabled the examination of very low negative pore pressures in a simulation of conditions at 20 m water depth. A bucket foundation model with a diameter of 0.5 m and a skirt length of 0.25 m was installed in dense sand. The smoothness of the model skirt (corrosion free) allowed a focus on the pore pressure distribution and the tensile capacity. The model was subjected to various pull-out rates. A rapid pull-out generated fully undrained behaviour, based on the measurements of the pore pressure transducers. The peak tensile resistance was found to increase with the pull-out rate, as did the upward displacement. The initial loading stiffness showed no clear dependency on the displacement rate. It was found that much larger than the drained tensile capacity is available, even when the limitations of the upward displacement are considered. To integrate this finding in design practise, a reliable method of negative pore pressure prediction in relation to loading intensity needs to be identified. Natural seabed conditions are extremely changeable, characterized by complex layering of soils and rich variation in their stiffness, strength parameters and various hydraulic conductivities. Furthermore, offshore loading conditions are complex, with their various loading regimes, amplitudes and mean loads. Model testing provides valuable information about soil and foundation behaviour. But large amounts of data and experimental analysis are still needed before all design aspects are clarified and standardized solutions can be proposed. The data provided in this thesis offer valuable information regarding the behaviour of bucket foundations under tensile cyclic loads in uniform dense sand.

1.8 References

[1] Molina S.D, Nielsen S.A (2014). Foundation Design, Installation Technique and Cost Study. *Universal Foundation. The report is in Appendix A of this report.*

[2] Vaitkunaite, E.,(2016). Physical Modelling of Bucket Foundations Subjected to Axial Loading. *Aalborg: Aalborg Universitetsforlag.*

[3] Vaitkunaite, E., Ibsen, L. B., Nielsen, B. N., and Devant Molina, S. (2013). Comparison of Foundation Systems for Wave Energy Converters Wavestar. *In 10th ewtec 2013 European Wave and Tidal Energy Conference Series: Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark. Technical Committee of the European Wave and Tidal Energy Conference. No. 10.*

[4] Vaitkunaite, E., Nielsen, B. N., and Ibsen, L. B. (2015). Comparison of design methods for axially loaded buckets in sand. *In Frontiers in Offshore Geotechnics III proceedings of the third international symposium on frontiers in offshore geotechnics (isfog 2015), Oslo, Norway, 10-12 June 2015. (Vol. 1, pp. 331-342). London: C R C Press LLC.*

[5] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. (2014). New Medium- Scale Laboratory Testing of Bucket Foundation Capacity in Sand. *In Proceedings of the Twenty-fourth (2014) International Ocean and Polar Engineering Conference, Busan, South Korea. (Vol. 2, pp. 514-520). International Society of Offshore and Polar Engineers.*

[6] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. (2016). Testing of Axially Loaded Bucket Foundation with Applied Overburden Pressure. Aalborg: Department of Civil Engineering, Aalborg University. DCE Technical Reports; No. 209.

[7] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. Bucket Foundation Model Testing under Tensile Axial Loading. *Canadian Geotechnical Journal. Submitted 14-10-2015 [cgj-2015-0497], Re-submitted 06-06-2016 [cgj-2016-0301].*

[8] Vaitkunaite, E., Nielsen, B. N., and Ibsen, L. B. (2016) Bucket Foundation Response under Various Displacement Rates. *International Journal of Offshore and Polar Engineering, 26(2), 116-124.*

[9] Vaitkunaite, E. (2015). Bucket Foundations under Axial Loading: Test Data Series 13.02.XX, 13.03.XX and 14.02.XX. *Aalborg: Department of Civil Engineering, Aalborg University. DCE Technical Reports; No. 199.*

Universal Foundation

Foundation Design, Installation Technique and Cost Study

Project:	Cost Effective Foundation and Installation of Wave Energy Converters CEFIWE
Document no.:	804-20-5201
Revision:	A
Date:	20.06.2014
Client doc. no.:	-

CHANGE LOG:

Rev.	Issue date:	Description:	Prep. by:	Check. by:	Appro. by:
A	20.06.2014	First release	SDM/LGC	MF/MJV	SAN
		Added buckling expl. And UR figures D=3,4,6m			

Summary

This report is presenting the work package 1 activities developed by Universal Foundation AS within the project Cost Effective Foundation and Installation of Wave Energy converters (CEFIWE).

The main goal for work package 1 is to develop cost effective foundation and installation solutions in order for Wavestar C6 to become a competitive concept on the offshore renewable sector. A number of investigations are performed in order to come up with the most cost effective solutions in different fields. The studied areas are grouped in four main groups:

- Cost modelling of the foundation and installation method.
- Investigation on installation approach.
- Support structure, foundation and superstructure interaction.
- Foundation design.

A full scale prototype for Wavestar C6 is planned to be installed in the North Sea in the upcoming years. So this conceptual study pretends to be a reference for a more detail design phase. Therefore the design, cost studies and other documentation presented in the report is based on a concept level.

Table of contents

Acronyms and abbreviations

WEC	Wave Energy Converters
AAU	Aalborg University
UFOAS	Universal Foundation AS
OWT	Offshore Wind Turbines
CAPEX	Capital Expenditure
ULS	Ultimate Limit State
FLS	Fatigue Limit State

1. Project Introduction

The International Energy Agency (IEA) estimated that energy-related CO_2 emissions in 2010 were the highest in history. In terms of fuels, 20% of it came from natural gas, 36% from oil and 44% from coal according to IEA 2011. Wave energy wants to be an important player on the alternative energy source group to meet the target for CO_2 cuttings in 2020. The main advantage of wave energy is that it does not produce any harmful by-products or any other emission. However the wave energy sector is still not able to deliver cost competitive solutions for entire wave energy package.

1.1 Project description

The scope of work for all project partners is defined in [1].

1.1.1 Project definition

The focus for CEFIWE project is to develop cost effective foundation and installation systems for WEC, by investigating and optimizing novel foundation systems recently developed for offshore wind turbines.

1.1.2 Expected findings

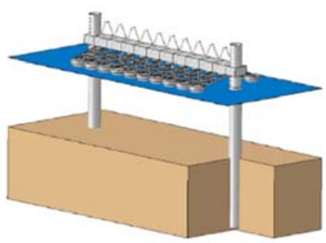
This project will explore structural and foundation ideas in combination. The research will deliver solutions that reduce cost and speed up the installation of the WEC. It will exploit, where possible, technology transfer from new innovative developments of offshore wind foundations, and address the unique problems facing marine renewable energy. The output will range from improvements in overall structural designs, development of installation processes and consideration of construction logistics.

1.2 Project initial phase and background on decisions

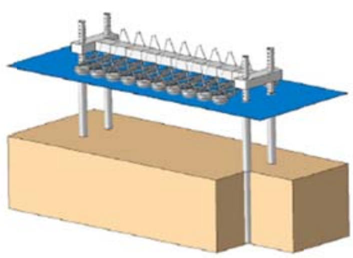
The project initial phase consisted on a foundation concept study. The generated output would provide some light on which of the investigated solutions is the most favourable to sustain Wavestar C6. Such task was developed in cooperation with all project partners i.e. Civil Engineering Department at Aalborg University, Wavestar and UFOAS. Therefore the first activity was aimed to investigate the performance of various foundation concepts extensively used on the offshore renewable sector and oil and gas. The investigated foundation concepts are:

- Pile foundation
- Gravity based foundation
- Universal Foundation prior called Bucket Foundation
-

Six innovative foundation solutions were investigated; those are presented on Figure 2.



a)



b)

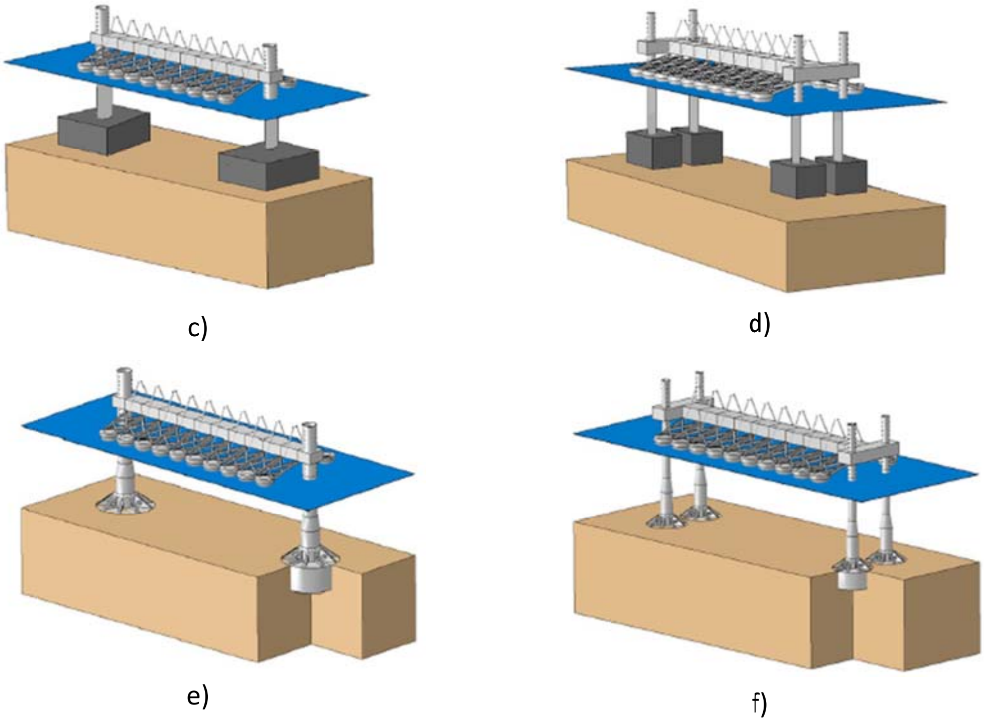


Figure 1.1. Analysed foundation solutions. 2 legged pile foundation. b) 4legged pile foundation. c) 2 legged gravity based foundation. d) 4 legged gravity based foundation. 2 legged Universal Foundation. f) 4 legged Universal Foundation

A detail study focused on geotechnical and structural design was carried out for the 6 innovative foundation solutions in different soil conditions i.e. first site dominated by sandy soils, second site dominated by clayey soils and third one, a potential site were a Wavestar C6 prototype was presumably to be installed. The output from the study reflected that either 2- or 4-legged solutions were feasible solutions for all the concepts. However the loading conditions for the 4- legged cases leaded to a significant increase on the amount of steel or concrete for manufacturing. The results also reflected that the pile and bucket foundations were the most competitive concepts. The gravity based concept was discarded due to the logistics needed to transport the massive concrete blocks that were required to sustain WEC. A trend was observed for the three investigated soil scenarios; the amount of steel required to manufacture the Universal Foundation was significantly less than the steel needed to manufacture the piles under the same site conditions. The calculations indicated that the Universal Foundation saved 4% up to 30% the required steel compare to the pile solution depending on the soil scenario.

Another interesting finding was observed on the installation phase. The project initial phase did not cover in detail the different installation scenarios for all six concepts but it was noticed that the Universal Foundation was the only concept able to be assembled with the superstructure prior to installation.

So this concept could be shipped to installation site together with the Wavestar C6 and install the entire system at once. The other concepts would require subcontractors to install the piles or the gravity based and afterwards the superstructure could be installed. The entire study can be found in [2].

1.2.1 Monopile vs. Universal Foundation

Nowadays the monopile concept is the preferable option to sustain OWT. Approximately 79% of the OWT are sustained by such foundation concept. It is well-known on the offshore wind market that a monopile is a competitive solution until water depths around 25m. For bigger water depths this concept tends to become too large and also an expensive solution. Additionally OWT are increasing on dimensions day by day but also new offshore wind parks are projected in bigger water depths. Therefore other foundation concepts such as jacket structures and Universal Foundations are potential concepts in such circumstances. UFOAS developed an internal cost study for a major Offshore Wind Farm project on the North Sea. Two foundation concepts i.e. Monopile and Universal Foundations were compared for a project containing 70 OWT units within water depths around 25m. The results proved that the Universal Foundation is also a competitive foundation concept for water depths around 25m. The total weight for the monopile was up to 894t compared to the Universal Foundation weight reaching the 720t. Therefore the cost-saving was up to 20% less amount of steel needed for manufacturing. Table 1 a. presents the unitary weight for all components considered on the Universal Foundation concept together with price per tonnage and total cost. Table 1 b. presents the unitary weight for all components considered on the Monopile concept together with price per tonnage and total cost.

Table 1.1 Cost studies for North Sea projects. (a) Universal Foundation study. (b) Monopile study.

Universal Foundation Cost Study		
	Weight [t]	Cost [€/t]
Shaft	261	1,600
Lid arrangement	180	3,350
Skirt	171	3,350
Sec. Steel	97	6,134
Lift arrangement	11,3	2,247
Total cost per unit = 2,230,000m€		

(a)

Monopile Cost study		
	Weight [t]	Cost [€/t]
Monopile	529	1,653
Transition piece	350	3,930
Anode cage	15	-
Total cost per unit = 2,450,000m€		

(b)

However such study did not reflected other projects costs for example Installation, logistics, transportation and Engineering costs. One of the potential key elements on the Universal Foundation concept is the installation approach. For offshore meteorological mast projects, UFOAS has proved that the installation times might be reduced considerably compared the current installation rate achieved by monopiles i.e. approximately one monopile installed per day. So the installation costs are reduced significantly if the installation times are also reduced.

The project initial phase and the monopile vs. Universal Foundation study leaded to the decision that Universal Foundation is the most cost efficient foundation concept to sustain Wavestar C6 no matter what are the load and soil conditions.

1.3 Universal Foundation concept

UFOAS is responsible for the overall design of the innovative offshore foundation concept and product brand THE UNIVERSAL FOUNDATION. After several years of research, the Universal Foundation has proved to be a potential concept for being the foundation solution for OWT and other energy sources such as WEC. This concept can significantly reduce the project costs due to significantly less amount of steel is required compare with other foundation solutions and the installation times are also reduced. Additionally heavy equipment such as driving hammers is also disregarded. Concerning to the installation process, a novel technique has been implemented to drive the foundation solution into the soil by applying controlled suction inside the Bucket caisson. Besides, the installation process proved to be respectful with the fauna and environment of the area.

The Universal Foundation combines the functionality of a Monopile together with a Gravity based foundation. When installed; mobilized earth pressures are developed along the skirt contributing for the moment and horizontal capacity. The soil encapsulated inside the Bucket contributes in the overall bearing capacity of the foundation. **Figure 1.2** presents all structural elements that configure the Universal Foundation.

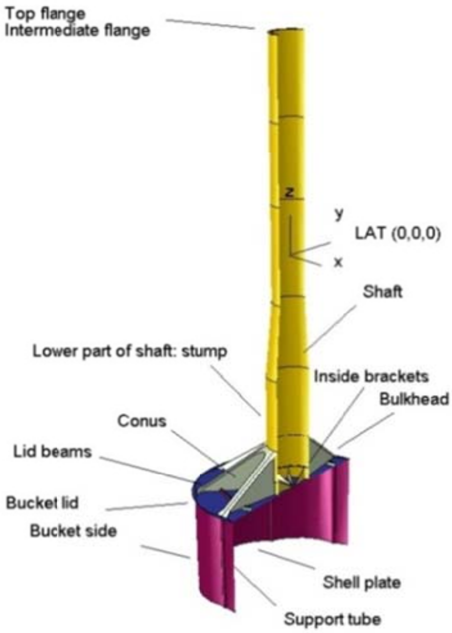


Figure 1.2. Structural elements assembling the Universal foundation.

1.4 Universal Foundation WP1

Universal Foundation scope of work is enclosed in Work Package 1 activities, see **Table 1.2**.

Table 1.2. Work Package 1 activities.

Work Package 1: Installation technique and Cost study.
Objectives: Develop cost effective foundation and installation systems for WEC, by investigating and optimizing the foundation systems.
Task 1.1: *Cost modelling of foundation and installation method.* The objective is to reduce the costs of the foundation system, so WEC can be self-installing without subcontractors **Task 1.2:** *Suction Installation.* Investigate and develop suction assisted penetration method for the foundation **Task 1.3:** *Support structure – tower interaction – concept studies.* Evaluation of 2- and 4- legged solutions. **Task 1.4:** *Steel design for the Universal Foundation.* Optimization for minimum reduction in fatigue resistance

All tasks involved in Work package 1 make reference to the foundation design, installation technique and project cost study. Therefore UFOAS established a working strategy to fulfil all tasks included in the work package. An order to follow was set to guarantee the working progress since some the actions needed input from the others. The actions are listed below:

1. Support structure, foundation and superstructure interaction *(investigation on Task 1.3)*
2. Steel design for Universal Foundation. *(investigation on Task 1.4)*
3. Investigation on installation approach. *(investigation on Task 1.2)*
4. Cost modelling of foundation and installation method. *(investigation on Task 1.1)*

1.4.1 Feasibility analysis

A feasibility analysis was performed prior to investigate in detail all the work package tasks. The following points where investigated:

1. Foundation design in a feasibility level.
2. Concept study on installation approaches.
3. Cost study for Manufacturing and Installation approaches.

The idea behind this first investigation was to see the areas where the foundation could be optimized if proper load input was to be provided. The foundation design was based on a preliminary foundation dimensioning process considering the loading conditions from project initial phase and a site specific soil conditions from an offshore wind farm in the North Sea Danish sector. In relation to the Installation approach, an Installation concept study was developed considering installation cost as driving parameter. This study was essential to define the final installation approach. Finally the cost study on installation was coordinated together with the previous exercise. Additionally the manufacturing cost started to provide some indicative price figures to define reference projects costs. Appendix A presents the developed concept drawing after this feasibility analysis.

1.4.2 Support structure, foundation and superstructure interaction

The first investigation performed was coordinated together between Wavestar and UFOAS. One of the important decisions that aroused from the beginning of the project was the decision on whether 2- legged or 4- legged foundation solutions was the optimum, see Figure 2. e and f. A number of analyses were developed to investigate on both configurations before finding out the most cost efficient option.

1.4.3 Steel design for Universal Foundation

After finalizing the concept studies and deciding on whether 2- or 4- legged foundation was the optimal solution, the overall foundation design in a concept level was begun. The first requirement to design the foundation was to have a proper load input. Especial attention was given on fatigue loads coming from the environment since was the main field to investigate in task 1.4. Therefore this task was coordinated between Wavestar, AAU and UFOAS looking at North Sea meteocean conditions. Next step was conducted entirely by UFOAS. The foundation structure was divided in three sections i.e. Shaft, Lid, Skirt as presented in

Figure 1.3. Then each of foundation sections was investigated individually in order to come up with an optimum design for each of the parts.

Figure 1.3. Universal Foundation configuration divided in three sections, Shaft, Lid and skirt.

1.4.4 Investigation on installation approach

One of the key elements on offshore projects is the installation phase. A good installation plan can lead to important savings on the total project costs. As presented in [1], The Carbon Trust Offshore Wind accelerator program found that around 50% of the CAPEX in offshore projects is invested on foundation and installation. Therefore a significant cost comes from installation phase. One of project goals is to optimize the installation approach in order to reduce project cost. Since limited experience on foundation installations for WECs is nowadays available, UFOAS started this assignment with a concept study on different installation approaches. Limited equipment is available on the market to perform such installation so total installation cost was again the driving parameter. Afterwards UFOAS developed an installation process description in a concept level. By describing the installation a number of installation challenges are faced and stated to be considered in future upgrades.

1.4.5 Cost modelling of foundation and installation method.

The last aspect to review deals with total project costs. The main goal of CEFIWE project is to create a more economically feasible concept i.e. foundation plus Wavestar C6. In this activity the different project cost are analysed individually. By analysing them it is expected to see the individual items that might be further optimized as well as seeing the challenges for the different project phases. Since a complete new concept is to be built, it is reasonable to believe that the entire system is far from being ready for a mass production. Furthermore unexpected issues might come up from all different project phases, see **Figure 1.4**. All unexpected items will be obstacles on the overall project progression. Therefore in this work package task it will be tried to align the different project phases to anticipate major challenges and avoid possible problems.

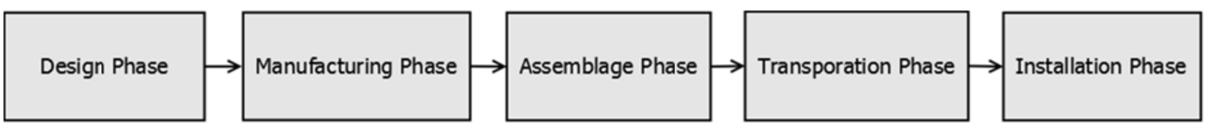


Figure 1.4. Typical project phases diagram.

2. Foundation design

This chapter is presenting the work package activities enclosed in Task 1.3 and Task 1.4. So first the interaction between superstructure and foundation is investigated in order to define the optimal foundation configuration for Wavestar C6. Subsequently the foundation design is portioned in three parts and investigated individually targeting for the optimal design.

2.1 Support structure, foundation and superstructure interaction

The conclusions presented after the project initial phase in [2] and subsequently proved in the feasibility analysis determined that Wavestar C6 could be sustained by either 2- or 4- legged foundations. Reasonable structures in terms of dimensions and total weights were obtained after the design phases. The principal difference between cases in terms of design came from the loading conditions affecting both configurations. For instance the 4-legged case is presented in Figure 2.1 where the foundation is dominated by vertical compression and tension loads on the legs. For the 2- legged case presented in Figure 2.2 the overturning moment is the dominated scenario. The project initial phase depicted that the final bucket caisson dimensions did not differ significantly when comparing the 2- and 4- legged cases. The loading conditions with especial remark on the tensile loads were the reason why the bucket dimensions for the 4-legged cases could not be smaller. The tendency reflected was that in 4- legged cases approximately 40% more steel was needed to manufacture the foundations compared to the equivalent 2- legged cases. The results for this investigation can be found in [3].

Since both legged configuration were suitable to sustain Wavestar C6, a new issue came up before choosing the final configuration. Presumably the jacking system to lift the structure to storm protection and also lower it to operational conditions would drive the decision on whether 2 or 4 legs were the optimal solution. Wavestar and UFOAS investigated all pros and cons on the jacking systems depending on the chosen foundation configuration. Additionally

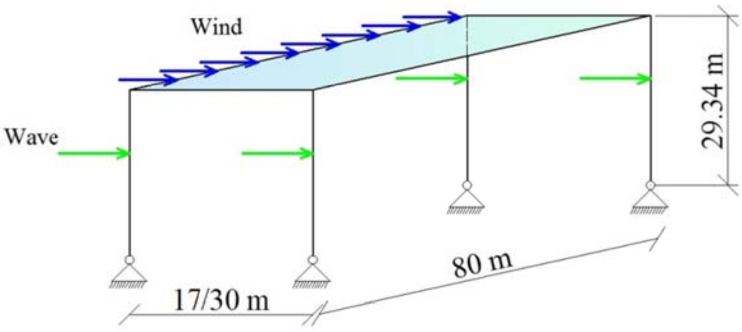


Figure 2.1. 4- legged configuration

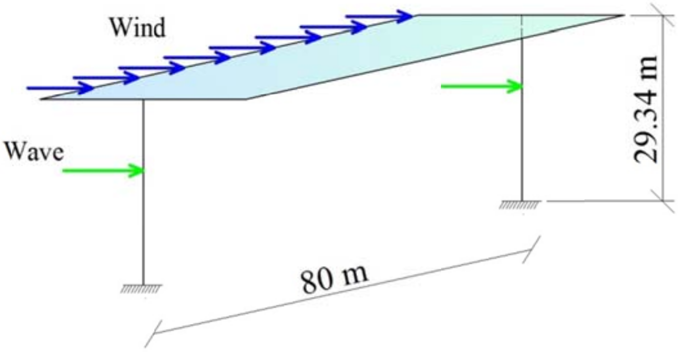


Figure 2.2. 2- legged configuration

the contribution from Semco Maritime investigating the performance of different jacking systems for Wavestar C6 sustained in 2- and 4- legged helped on the final decision. The conclusion from Semco Maritime was that a jacking system is not affected by the decision on 2- or 4- legged cases. So a jacking system could be installed on both cases and operate in safe conditions with any interference.

After both analyses, UFOAS and Wavestar concluded that the preferable option to sustain Wavestar C6 at the current state was 2- legged case due to cost-savings on material.

2.2 Steel design for Universal Foundation

The overall foundation design is presented in this chapter. As mentioned on the introduction the Universal Foundation is split in three sections and investigated each of them individually. The idea behind such approach is to investigate in detail each section and involve specialist from geotechnical and structural departments to come up with the optimal foundation structure. The three sections are:

1. Shaft design
2. Bucket Skirt design.
3. Lid configuration design.

However to start the conceptual design a proper loading input was required. Remarkably fatigue effects from the environmental loads were the focus of the attention for task 1.4. As presented in Section 2.2.4, the current status is that the first Wavestar prototype is about to be installed in 2017 in the North Sea in the Belgium sector. Therefore UFOAS and Wavestar developed together a working plan to generate a relevant loading input for the foundation design. The working plan is numbered below:

1. Analysis for North Sea meteocean conditions on Belgium sector.
2. Developing the following loading cases affecting foundation and superstructure:
    a. ULS loads on operational conditions.
    b. ULS loads on storm protection.
    c. FLS load conditions.
3. Evaluation and definition for design loading conditions.

As soon as the design load cases were available the foundation design was begun. Since the shaft is the main foundation section interacting with the environmental loads, it was the first item to design and investigate.

2.2.1 Shaft design

The shaft is dimensioned considering the loads provided by Wavestar in [4], [5], [6] and [7]. The loads considered are related to ULS and FLS.

2.2.1.1 ULS Loading Conditions

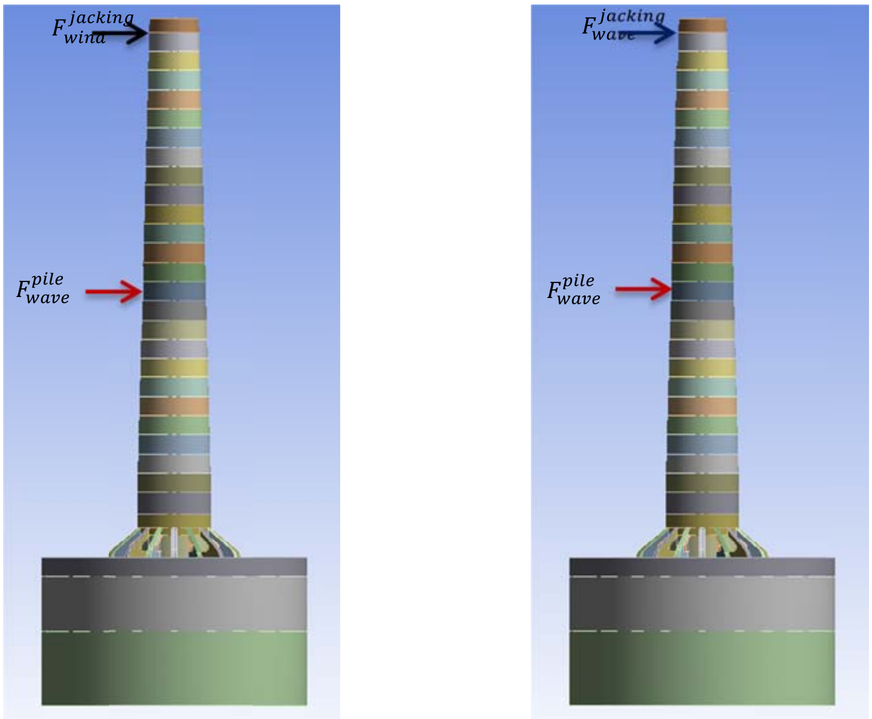
The load cases are found in [7] for a pile diameter D = 5 m and are shown in Table 2.1 and Table 2.2. Each load is applied in the structure as depicted in Figure 2.3.

Table 2.1. Production characteristic loads [7]

F_y [MN]	Pile	Jacking
Wind	0	0
Wave	0.51	3.78

Table 2.2. Storm protection characteristic loads [7]

F_y [MN]	Pile	Jacking
Wind	0	1.05
Wave	3.69	0



(a) Storm *(b) Production*

Figure 2.3. Load cases.

The top of the shaft is taken at 40.33 m above mudline as stated in [8]. The load combination from wind and wave is a quadratic proportion between loads based on [9].

2.2.1.2 ULS Production

The design input loads are given in **Table 2.3**. The conditions assumed in the load calculations are the outlined in [4]. A safety factor of 1.35 [9] is used for the design load calculation.

Table 2.3 ULS maximum design input loads in production from jacking (fixed support) and pile

	F_x [MN]	F_y [MN]	F_z [MN]	M_x [MNm]	M_y [MNm]	M_z [MNm]
FS_jacking	$7.23 \cdot 10^{-4}$	5.11	0.56	14.24	-9.09	74.21
Pile	-0.15	0.68	0	4.60	0.82	0

The resultant loads at mudline used to dimension the foundation are shown in **Table 2.4**.

Table 2.4. ULS maximum design loads in production at mudline - fixed support

	$F_{y,wind+wave}$ [MN]	$F_{z,self-weight}$ [MN]	$M_{x,wind+wave}$ [MNm]
Mudline load	5.79	6.90	232.81

2.2.1.3 ULS Storm protection

Table 2.5. presents the design input loads in storm protection related to the ULS 2 in [6]. The resultant loads at mudline using a load factor of 1.35 are depicted in **Table 2.6**.

Table 2.5. ULS maximum design input loads in storm protection from jacking (fixed support) and pile [3]

	F_y [MN]	M_x [MNm]
ULS2_pile	4.99	114.01
Jacking	0.00	0.00

Table 2.6. ULS maximum design loads in production at mudline - fixed support

	$F_{y,wind+wave}$ [MN]	$F_{z,self-weight}$ [MN]	$M_{x,wind+wave}$ [MNm]
Mudline load	5.54	7.43	137.13

The results show that ULS-operational loads have a greater contribution than storm conditions at mudline and will determine the design of the foundation.

2.2.1.4 FLS loading conditions

The main conclusions found in [8] are stated:

- Pile loads are generally significant smaller than jacking loads.
- Jacking loads are presumably dominating the foundation design.
- The moment contribution from the jacking loads in the foundation is small compared to the contribution of the moment from the horizontal forces. Hence the jacking support system is not relevant, i.e. the system of transferring moments to the foundations is of minor importance.
- Operating conditions are more severe than storm conditions.

- Hence the following considerations are taken in FLS load calculations:
- Wave contribution on piles is disregarded since they haven't been provided.
- Only maximum operational jacking loads (loads transferred to jacking system) from dynamic wave forces are considered.
- HAT-LAT = 4 m assumed and used only for corrosion allowance and additional secondary steel calculation.

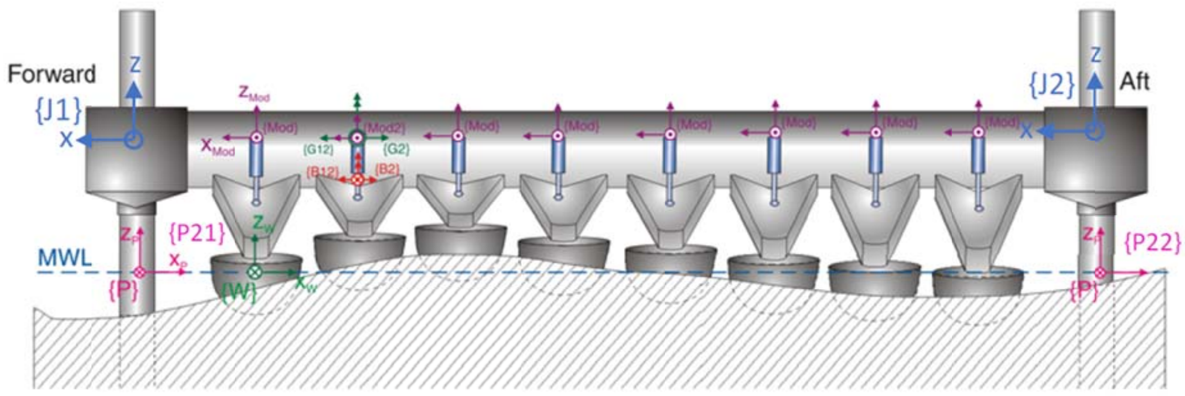


Figure 2.4. Wavestar C6 with jacking system configuration.

In order to calculate the equivalent fatigue loads, the 20 year load distribution in [5] is used. The calculations are assessed at node {J2} since FLS loads are found to have larger moment contribution than at node {J1}. See Figure 2.4.

The equivalent fatigue loads are presented in **Table 2.7** and are calculated according to Palmgren-Minor sum, Equation 2.1.

$$F_{eq,y} = \left(\frac{\sum N_i F_{y,bin\_i}{}^m}{N_{eq}} \right)^{1/m} \tag{2.1}$$

Table 2.7. FLS equivalent fatigue loads in production at node {J2}

	F_x [MN]	F_y [MN]	F_z [MN]	M_x [MNm]	M_y [MNm]	M_z [MNm]
J2_jacking	0.125	0.810	1.226	6.6	17.21	11.680

The equivalent fatigue loads at mudline are shown in **Table 2.8**. for the load scenario F_y and M_x.

Table 2.8.FLS equivalent fatigue loads in production at mudline

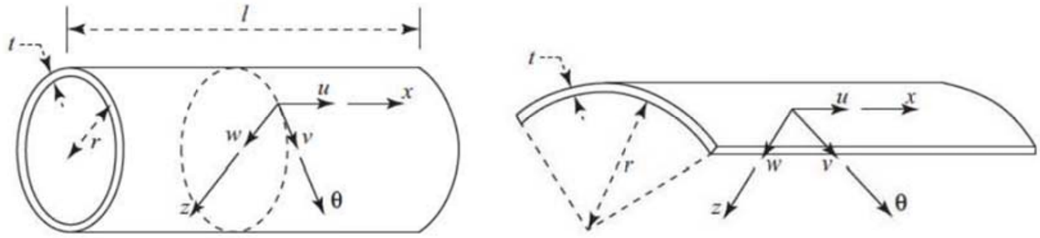
	F_y [MN]	F_z [MN]	M_x [MNm]
Mudline load	-1.226	0.810	42.33

The fatigue on the shaft is assessed by considering the SN curves in seawater with cathodic protection according to DNV-RP-C203 [11] The stress limit at 10^7 cycles is that related to an SN curve C1 for transverse butt welds (from both sides).

2.2.1.5 Buckling

Structures with very small wall thickness compared to radius are prone to suffer from buckling which can in turn control its failure criteria, therefore being necessary to study the buckling limit state where the structure suddenly loses stability and large deformations happen.

The buckling verification is done for each strake or panel length in which the shaft is discretized. Each panel is considered as an unstiffened circular cylinder and is subjected to axial compression force, bending moment and horizontal force coming from environmental loads in the superstructure and the shaft. These loads result in membrane stresses in the shell: longitudinal membrane stresses, circumferential membrane stresses and membrane shear stresses.



Under these loads, the structure may experience local and/or global deformation and in order to obtain greatest resistance against stability failure, the material changes its shape from a straight cylinder to waveforms and can occur in different modes, globally or locally.

Imperfections in the structure can have a big influence on how the structure will buckle and at which load and therefore it is difficult to predict the exact buckling load and shape.

The buckling strength of the shaft is verified according to [9]. The methods considered are semi-empirical and are based on an assumed level of imperfection which considers nonlinearities in material and geometry with imperfections.

The stability requirement for a shell-column subjected to the above actions is given in [9] as

$$\sigma_{j,Sd} \leq f_{ksd}$$

Where $\sigma_{j,Sd}$ is the design equivalent Von Mises stress resultant from external loads and f_{ksd} is the design shell buckling strength which depends on the elastic buckling strength of circular cylindrical shells and the influence of the stresses in the shell used in $\sigma_{j,Sd}$, i.e. the design stress applied to the cylinder.

In the present case the buckling modes to be verified are shell buckling and column buckling.

The shell buckling strength for unstiffened circular cylindrical shells is given by

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2$$

Where C refers to the reduced buckling coefficient which depends on the radius, thickness and length of the shell and Poisson's ratio, ν, E Young's Modulus, t shell thickness and l length of cylinder.

Column buckling may occur for long and/or slender cylinders and the buckling strength is only assessed if:

$$\left(\frac{kL_c}{i_c}\right)^2 \geq 2.5\frac{E}{f_y}$$

Which represents Euler's column buckling.

2.2.1.6 Results

Figure 2.5 depicts the results from the optimum design. It can be seen that the upper parts of the shaft are more prone to suffer from buckling due to small thicknesses and the lower parts are driven by ULS-operational loads reaching the ultimate limit capacity.

The influence of the thickness in the shaft is assessed in a second study case where a pre-set thickness of 29 mm is considered in the upper levels. As can be seen in **Figure 2.6** there is an increase in the buckling capacity, i.e. lower utility ratio or reserve strength. Even though this geometry is not the optimum, it could be seen as a solution when arranging the pinholes at the connection with the jacking system in order to handle high concentrations of stresses.

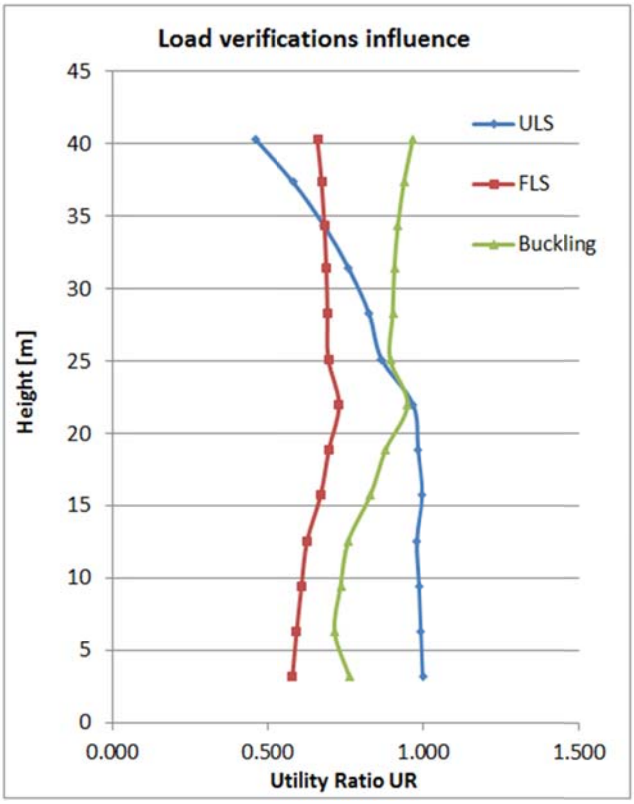


Figure 2.5. Load case influence. Diameter 5 m. Total weight 177 T.

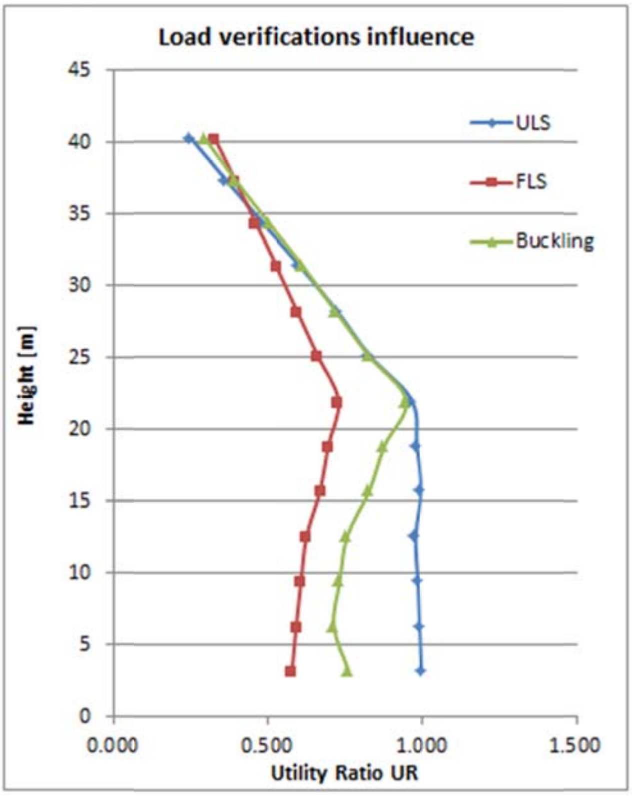


Figure 2.6. Load case influence. Diameter 5 m. Total weight 193 T.

2.2.2 Sensitivity analysis, Influence on pile diameter

A sensitivity analysis is conducted to determine whether a different diameter than D = 5 m may be a benefit. Hence the same calculations previously introduced are carried out for a diameter D = 3 m, 4 m and 6 m in production conditions.

Wind loads on pile are disregarded due to the small importance and ULS-wave operational loads are calculated by scaling the loads from a pile D = 5 m. This ratio is established between pile diameters considering that wave loads are proportional to the square of diameter.

Table 2.9. shows the ULS resultant loads at mudline for different pile diameters. As expected a decrease in diameter implies lower loads in the structure, however a decrease of 40% in diameter reduces the moment 3.4%. On the other hand large diameters allow a reduction in thickness as can be noticed in the total weight calculation, **Table 2.10**.

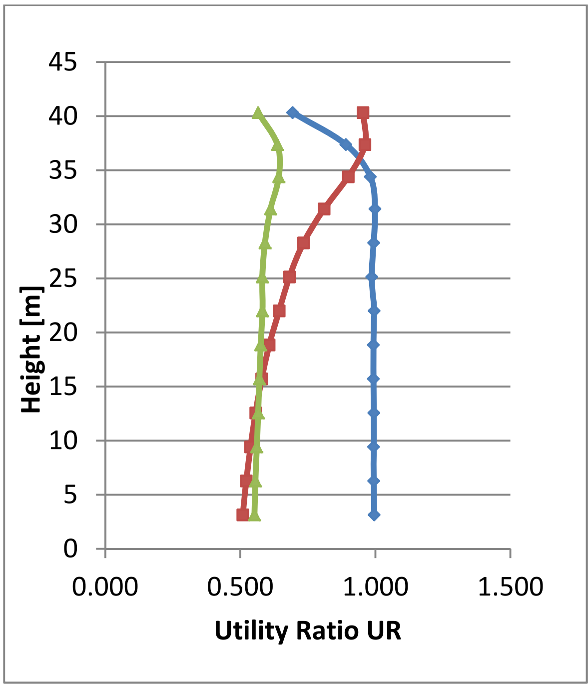
It can be concluded that no benefit is gained by changing the shaft diameter, therefore the foundation is seen to be optimized when D = 5 m

Table 2.9 ULS maximum design loads in production at mudline

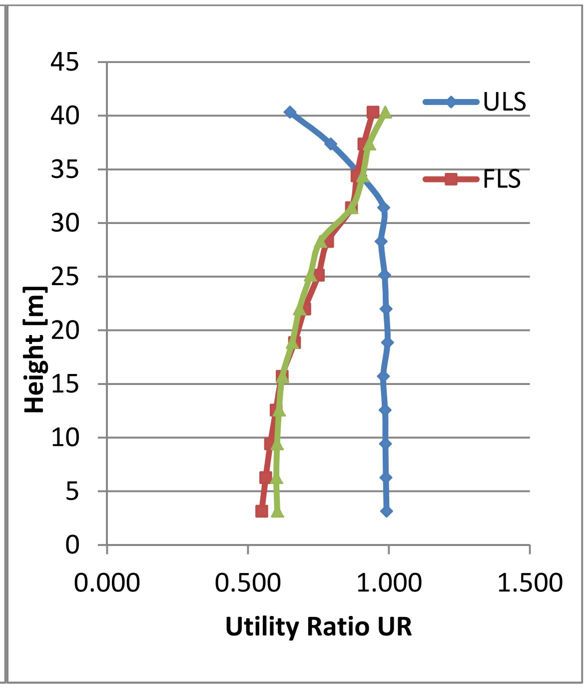
Pile diameter [m]	$F_{y,wind+wave}$ [MN]	$F_{z,self-weight}$ [MN]	$M_{x,wind+wave}$ [MNm]
3	5.36	7.51	224.81
4	5.55	7.07	228.31
5	5.79	6.90	232.81
6	6.09	6.91	238.32

Table 2.10 Foundation mass for different shaft diameters

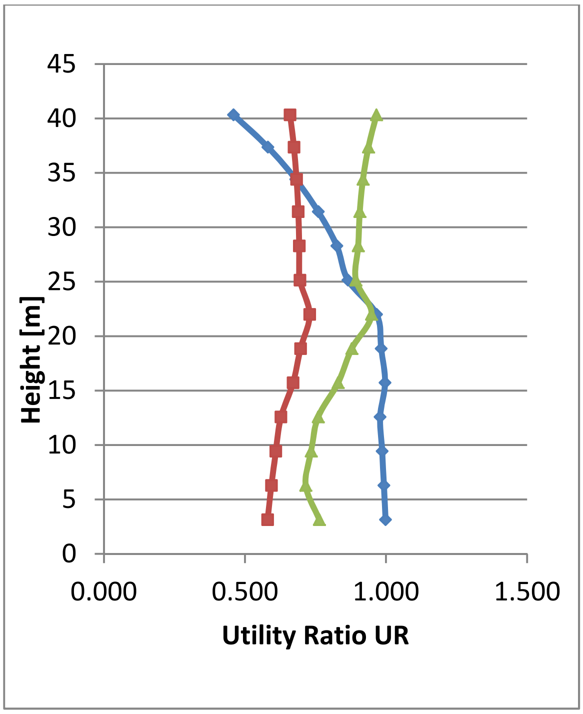
Pile diameter [m]	Mass [T]
3	250
4	196
5	177
6	182



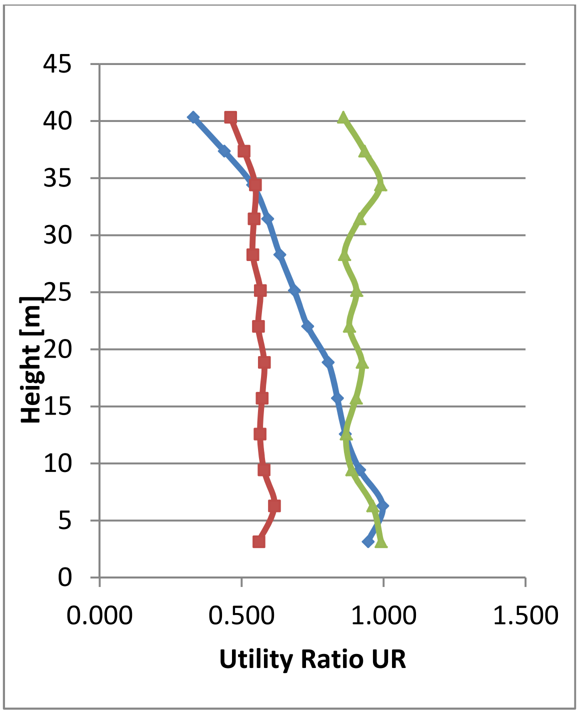
(a) D3



(b) D4



(c) D5



(d) D6

2.2.2.1 Shaft dimensions

The different shaft diameters and plate thicknesses after the sensitivity analysis are presented in **Table 2.11** and **Table 2.12**.

Table 2.11. Optimum shaft geometry. Diameter 5 m

Level [m]	Element length [m]	Diameter [m]	Thickness [mm]
40.3	3.4	5	18
36.9	3.1	5	20
33.8	3.1	5	22
30.7	3.1	5	24
27.6	3.1	5	26
24.5	3.1	5	28
21.4	3.1	5	29
18.3	3.1	5	32
15.2	3.1	5	35
12.1	3.1	5	39
9	3	5	42
6	3	5	45
3	3	5	48
Mudline	-	-	-

Table 2.12. Shaft geometry comparison. Diameters 3, 4, 5 and 6 m

Level [m]	Element length [m]	Thickness [mm] D = 3 m	Thickness [mm] D = 4 m	Thickness [mm] D = 5 m	Thickness [mm] D = 6 m
40.3	3.4	28	19	18	18
36.9	3.1	32	22	20	19
33.8	3.1	38	25	22	20
30.7	3.1	46	28	24	22
27.6	3.1	55	33	26	24
24.5	3.1	64	37	28	25
21.4	3.1	73	42	29	27
18.3	3.1	83	47	32	28
15.2	3.1	93	53	35	30
12.1	3.1	103	58	39	32
9	3	113	63	42	33
6	3	123	68	45	33
3	3	133	73	48	37
Mudline	-	-	-	-	-

2.2.3 Bucket skirt design

The second structural section to investigate is the bucket caisson as shown in **Figure 2.7. Bucket skirt.** To develop this task it is essential to have the loads affecting the entire structure and the design soil profile from the position where the structure is planned to be projected.

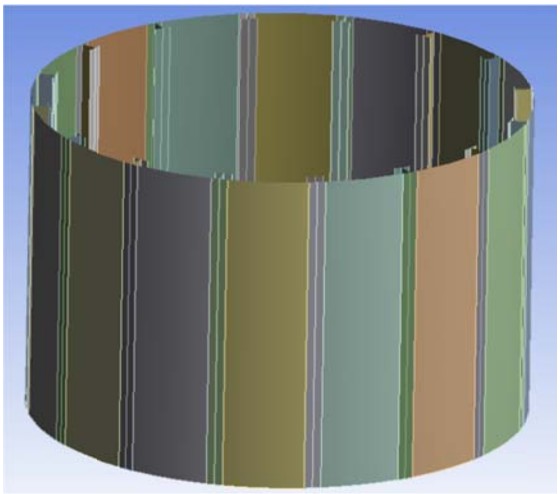


Figure 2.7. Bucket skirt.

The shaft analysis presented on section 2.2.1 provided the resultant loads at mudline. At the time of the analysis, a prototype for Wavestar C6 was planned to be installed in THV Mermaid. This Offshore wind park is located approximately 50Km from the Belgium cost, contains more 28Km^2 and is planned to be fully operational by the end of 2017. The soil conditions at the area are predominated by dense to very dense sand layers with typical sandy deposits with thickness around 15m from seafloor. Since the exact soil profile was not provided, UFOAS utilized a representative soil profile from a Wind farm nearby THV Mermaid. The design soil profile is presented in **Table 2.13**.

Table 2.13. Design soil conditions.

Depth Range of Soil [m]		Soil Description	Submerged unit weight, γ' [kN/m^3]	Undrained shear strength, c_u [kPa]	Effective Friction Angle, φ' [°]
Top	Base				
0.0	1.6	Medium to dense SAND	10	-	36
1.6	4.2	Dense to very dense SAND	10	-	40
4.2	11.1	Very dense SAND	11	-	42
11.1	12.2	Dense to very dense SAND	10	-	40
12.2	13.2	Loose to medium SAND	10	-	34
13.2	17.2	Very dense SAND	11	-	42
17.2	38.2	Stiff CLAY	9	110	-

2.2.3.1 Bucket skirt design

The conceptual design for the bucket caisson consists on:

1. Bearing capacity analysis
2. Penetration analysis

The output from such analysis provided a rather accurate bucket dimensioning in a concept level. Figure 2.8 is a graph presenting the output from both analysis. The intersection from both curves corresponds to the optimal design in terms of bucket diameter and bucket skirt.

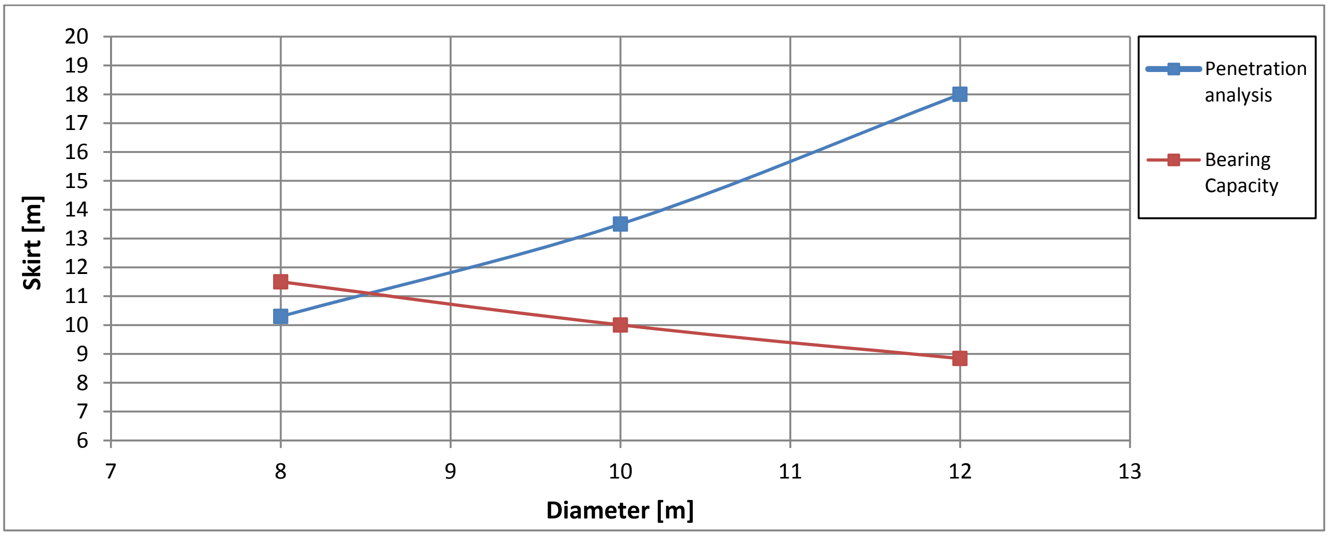


Figure 2.8. Skirt versus diameter output from geotechnical design.

The results present that the optimal geotechnical design came up with a bucket dimensions equal to:

- Diameter equal to 8.7 meters.
- Skirt length equal to 11.2 meters.

However, an optimal bucket skirt design must also consider other issues such us manufacturing and installation phases. UFOAS has considered a number of points to evaluate before concluding on the final skirt dimensions. The points considered are presented here:

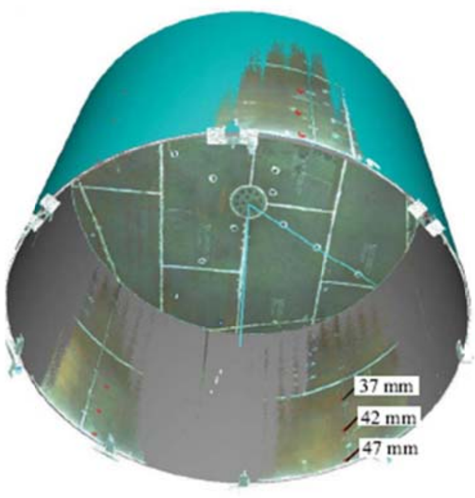
- Optimal bearing capacity design.
- Optimal manufacturing approach.
- Optimal installation scenario.

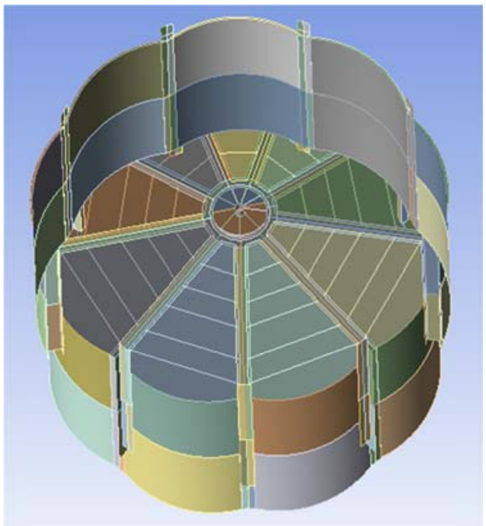
For the bearing capacity study, the skirt length plays an important role. It is approximately to the power of 4 the increase on bearing capacity if the skirt is also increased. Therefore the preferable option was to increase the skirt in contrast to increase the diameter if the dimensions were not enough. All comments on manufacturing approach are presented in section 4.4.2. Although the tendency is that the structure becomes more costly manufacturing wise if the diameter is increased. Finally the installation scenario presents the opposite trend. In order to facilitate the Universal Foundation installation an increased diameter leads to a higher driving force to penetrate the bucket into the soil. The current Universal Foundation designs are targeting for skirt length to bucket diameter ratio equal 0.5 to 1. Three Universal Foundations are currently installed in the North Sea following the presented skirt to diameter ratio approach. So UFOAS has relevant experience on installations on such conditions. The fact that installation phase is one of the main challenges on this project lead to the conclusion that the final dimensions must fulfil the closest skirt to diameter ratio from 0.5 to 1. Therefore the preferable bucket dimensions are:

- Diameter equal to 10 meters.
- Skirt length equal to 10 meters.

2.2.3.2 Investigation on bucket skirt concepts

An investigation was performed into the bucket skirt to evaluate the most cost effective design in a concept level. Two different bucket shapes were investigated in terms of manufacturing costs. The two shapes are a circular bucket, see Figure 2.9. a. and the Universal Foundation multishell concept, see Figure 2.9. b.





(a) (b)

Figure 2.9. (a) Circular bucket concept. (b) Multishell bucket concept.

UFOAS has designed foundations utilizing both concepts. For instance the Universal Foundation installed in Horns Rev II Offshore Wind Park utilizes the circular concept. Conversely, the Universal Foundation installed in Dogger Bank Offshore Wind Park utilizes the multishell concept. Both concepts have proved to be working successfully. A major advantage is seen on the multishell concept, the skirt configuration with inner beams and pre-buckled shells possess a higher buckling capacity compare to an equivalent circular bucket with the same plate thickness. The study presented in [13] demonstrated that a 25mm multishell bucket has approximately the same buckling capacity compared to 33mm circular bucket, see **Figure 2.10**. Nonetheless no buckling assessment was performed on this project since is a task developed on a detail design. Instead, the circular bucket with plate thickness equal to 33mm is compared with an equivalent multishell bucket with plate thickness equal to 25mm in terms of manufacturing. It is assumed that both concepts would have the same response in terms of installation and bearing capacity. By comparing both concepts in terms of tonnage, the optimal concept will be picked in a conceptual level. However that election might be revoked in a detail design phase. **Table 2.14** presents the weights for the different structural sections for the multishell concept. **Table 2.15** presents the weights for the different structural sections for the circular concept.

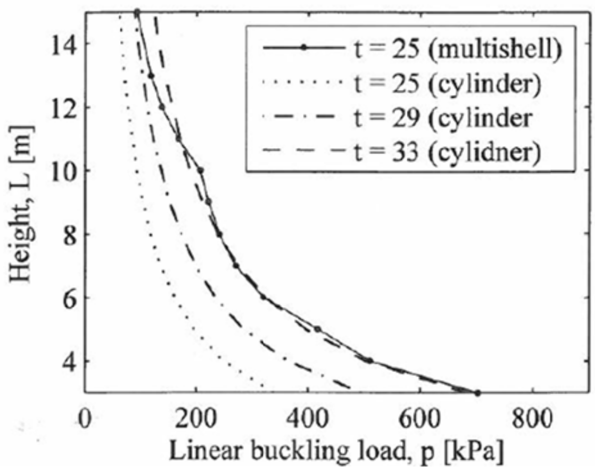


Figure 2.10. Buckling study results presented in [13].

Table 2.14. Estimated tonnage for Multishell concept.

Section	Weight [t]
Shaft	177
Bucket	166
Total Primary structure	343

Table 2.15. Estimated tonnage for circular concept.

Section	Weight [t]
Shaft	177
Bucket	151
Total Primary structure	328

The results after Table 2.14 and Table 2.15 reflect that the circular bucket presents a smaller weight compared to the multishell concept. So the circular bucket is presumably the most economical option in terms of manufacturing cost. Pros and cons for the two concepts are presented in section 4.4. Therefore in a concept level, the circular bucket is the most cost effective concept. Appendix B is presenting both Universal Foundation concepts after the conceptual design.

2.2.4 Lid configuration design

The last structural element to design is the lid configuration. This task is performed after the bucket is dimensioned. This structural element is composed by a number of webs that secure the connection between shaft and bucket caisson, see an example in **Figure 2.11** a. The web configuration is the mechanism that procures the load transfer from the shaft to the foundation. The web frames are extended inside the bucket caisson by the so called inner beams, see **Figure 2.11** b. The web frame configuration is in fact a number of stiffeners that procure the structural integrity against loads from superstructure and the environment.

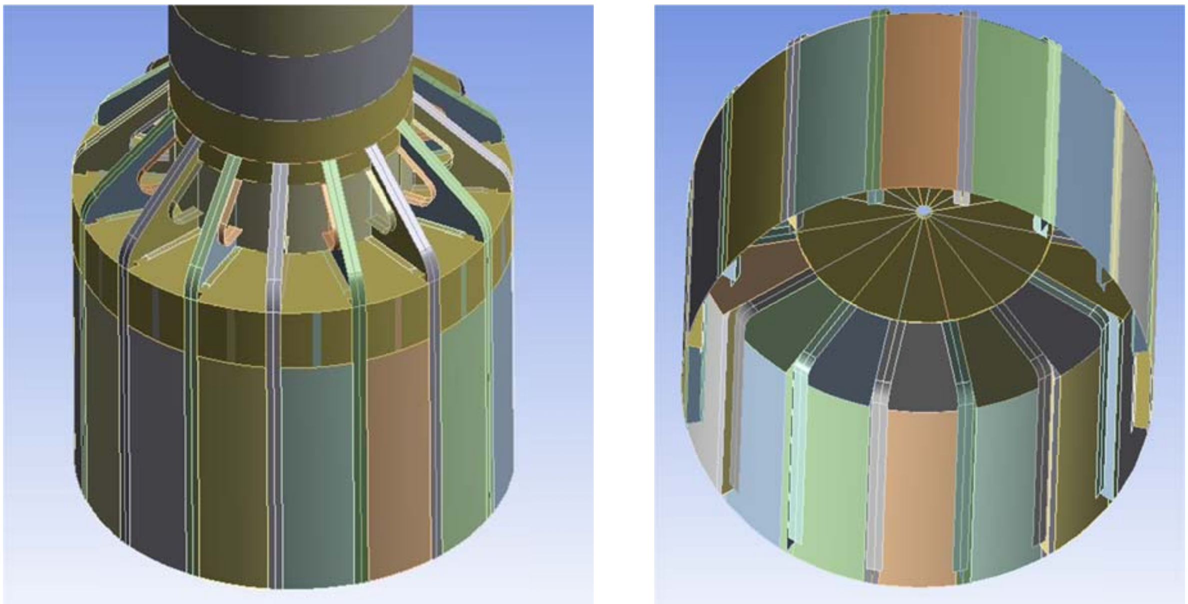
The lid configuration is depending on the following factors on a concept level:

- Bucket diameter.
- Steel plate dimensions.
- Differential pressure.

The bucket diameter indicates an optimal number of webs in terms of manufacturing, if certain plate dimensions are previously defined. Manufacturing costs for example in terms of steel prices and rolling plates determine the most cost effective plate dimensions that configure the bucket skirt. Thereafter a first number of webs are defined. Secondly the maximum differential pressure between inside and outside of the lid may adjust the optimal plate size that configure the lid arrangement, thus changes the number of webs slightly. This differential pressure has two inputs:

- It is limited by the total water column (max water depth).
- Required suction pressure to install the foundation.

In fact, the design pressure on the lid is the required suction needed for installation. The mechanism to design a safe bucket lid takes in consideration the number of webs as well as the transversal stiffeners on a lid section presented in **Figure 2.12**. Both set of stiffeners i.e. number of webs and transversal stiffeners make a more robust design for the lid configuration.



(a) (b)

Figure 2.11. (a) Web frame configuration connecting shaft and bucket. (b) bucket Inner beam.

The predefined site conditions determined a reference water depth equal to 30 meters. Then it is from UFOAS experience in previous Universal Foundation designs that the preferable plate dimensions for such conditions and bucket diameter equal to 10 meters is in the range of 3 to 4 meters plate dimensions. If such plate dimensions are employed considering a bucket dimensions equal to 10m, the resultant number of webs is equal to 9.

Conversely the installation design is analysing the suction values required during installation. In this study the stresses affecting the structure due to installation phase. However such analysis is performed in a detail design phase therefore is not assessed in the conceptual design phase. The output from such analysis might modify slightly the final lid configuration.

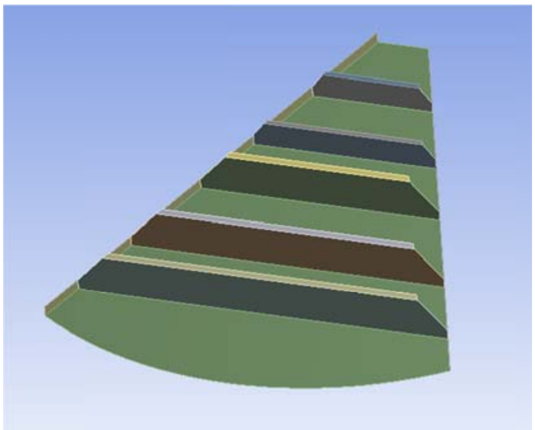


Figure 2.12. Section of lid composed by a number of transversal stiffeners.

3. Investigation on installation approach

The selected installation approach is presented in this chapter. Different strategies were evaluated at the first phase for this Task 1.2. The nature of this project being the first full scale Wavestar C6 projected in real offshore conditions made this task challenging. Furthermore one of the premises at the beginning of the project was to provide solutions in order that WEC can be self-installing without subcontractors. The idea behind such approach was to provide cost competitive solutions that reduce installation times. Therefore the first requirement that the project impose was to assemble the foundation and superstructure onshore.

In the second phase UFOAS performed a brainstorming fulfilling project requirements on possible installation methodologies looking at the most feasible and cost effective solutions. In all the cases the foundation and superstructure assembly was carried out onshore. The solutions evaluated were:

- Transport with a Jack up vessel capable to lift approximately 2300t.
- Transport with semi submerged barge or a vessel and use more than one crane to lift the entire foundation and superstructure system.
- Transport with semi submerged barge and install the foundations individually one by one.
- Transport with submerged barge and install the foundations simultaneously.

All four options presented a new challenge that was the necessary logistics to transport the structure into the installation site. The scenario presented in Table 3.1 was used to find the adequate transport system to ship the structure. Dimensions in terms of length & width for Wavestar C6 and bucket diameter are presented.

Table 3.1. Foundation and superstructure weight and dimensions.

	Weight [t]	Dimensions [m]
Wavestar C6	≈1600	L=80, W=17
Foundation leg 1	≈330	D=10
Foundation leg 2	≈330	D=10

By assembling the foundation and superstructure on key side, the total weight for the system reaches around 2260t. A reduced number of vessels are able to lift with their cranes such load and the idea of using more than one crane also creates a difficult and rather expensive scenario. A cost study on different vessels was performed to prove this statement. Thereafter the semi submerged barge was the preferable option. A large number of barges with sufficient capacity are available on the market and the most attractive option was to use a non-propelled barge with the support of tug boats. Another cost study was performed to find out which semi submerged barges were suitable for the project. This last option resulted to be more economically feasible and 2260t were not a barrier. Additionally the wavestar prototype installed in Hanstholm used a similar approach to install the machine, see Figure 3.1.

The installation scenario was proved by the prototype installed. Although the dimensions of this structure were of lower magnitude since it was a scaled 1:2 WEC. Next step then was detail the installation approach and to carry out a risk assessment to see the limitations and possible installation failures.

Figure 3.1. Wavestar prototype during installation phase in Hanstholm.

3.1 Installation strategy

After the brainstorming and the cost studies, UFOAS developed an installation strategy on a concept level. The first interesting point was that the submerged barge has potential solutions that might benefit the foundation installation in a high degree. For instance the fact that a barge can submerge entirely can guarantee the right positioning of the buckets as well as contribute on the self-penetration by the barge submerged weight. Secondly if the submerge barge self-weight is to be used, the buckets caissons have to be attached to the barge while they are installed simultaneously, see **Figure 3.2**. If the two foundations are installed at the same time, two pump units will be necessary during installation. Thereby the installation approach is described in a number of steps:

1. When the complete assembly i.e. foundations and Wavestar C6, are positioned on the installation site, the barge is started to be submerged synchronizing this procedure with the foundation lowering process until touch down on the seabed. By using such approach the bucket installations will be performed on the exact location.
2. While the barge is submerging and the buckets lowering down, Wavestar C6 is floating on the surface by the floaters and contribution of the tub boats if required.
3. Before the bucket self-penetration process is begun, the barge submerging process is concluded. Thereafter the self-penetration process is carried out with the contribution from barge submerged weight. Any additional vertical load benefits the bucket self-penetration and guarantees the necessary seal to start applying the suction process.
4. The foundation is achieving self-penetration until finding the bearing capacity that does not allow further self-penetration. Then suction process is applied simultaneously on the two buckets. Note that barge is still attached to the caisson and contributes on the buckets penetration.
5. Final penetration is achieved.
6. The barge is release from the two buckets and starts to be lifted to the surface.
7. The Wavestar C6 is fully connected to the foundation shafts and jacket up to operational conditions.

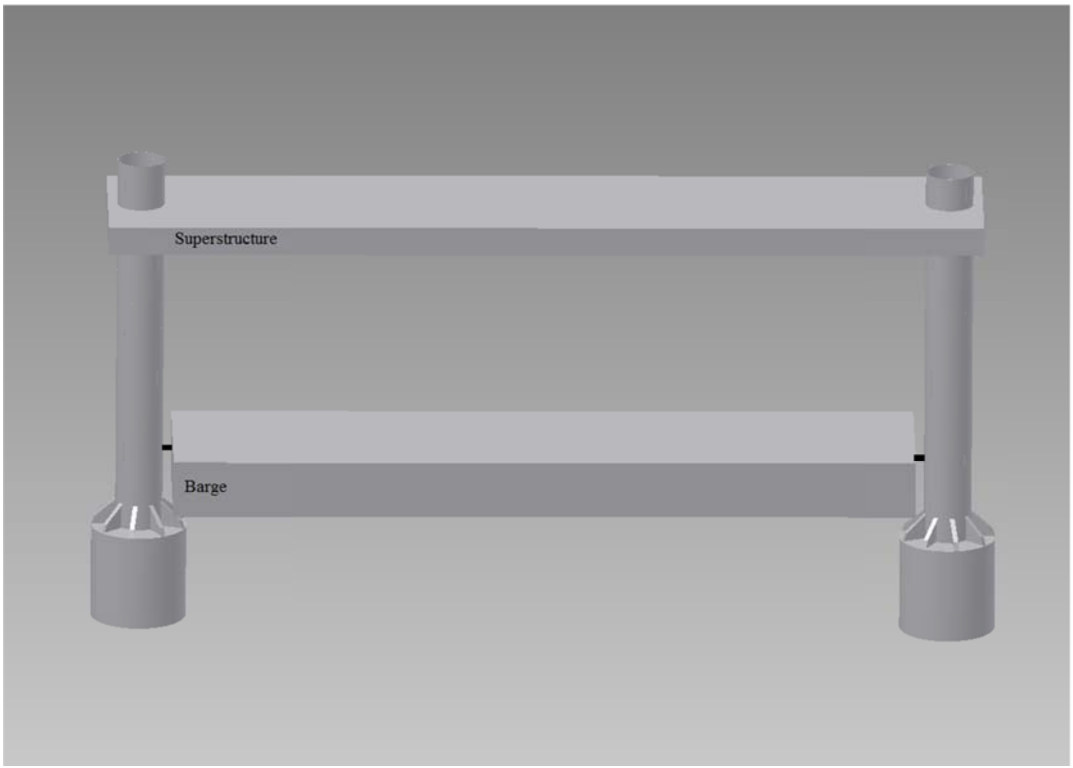


Figure 3.2. Sketch for installation phase with the two foundations, barge and superstructure.

4. Cost modelling of foundation and installation method.

This chapter is presenting the work package activities enclosed in Task 1.1. So the cost modelling of foundation and installation is presented in this chapter. A number of total project costs are investigated here to determine first indicative prices for different project phases. Especial attention is given to three of the project costs, those are:

- Engineering costs.
- Manufacturing cost.
- Installation cost.

By analysing these three items individually and provide indicative prices, the aim of the Task 1.1 will be investigated. The objective of developing cost effective foundations and installation systems will be determined if the provided solutions are economically feasible. Furthermore the challenges encountered in the manufacturing phase between the two bucket caisson concepts evaluated in section 2.2.3.1.1 will be discussed to avoid unexpected problems that slow down the project progression.

4.1 Engineering cost

UFOAS is responsible for the overall design of the Universal Foundation concept. As stated on the introduction, the concept has proved to be a potential solution to sustain OWTs and WECs. This concept can significantly reduce the project costs due to significantly less amount of steel is required compare with other foundation solutions., see the study presented in [2]. Although one of the major challenges are to have competitive engineering cost compare to other concepts that have been broadly used. In this section, the engineering cost for a Universal Foundation will be compared with the engineering cost for a monopile. Nowadays a monopile concept has been used in several offshore wind projects and this issue leaded that several foundation designers have fully developed a design configurator. Therefore the monopile concept is the most economic option to sustain an OWT. **Table 4.1** is presenting the indicative engineering cost for the Universal Foundation concept. **Table 4.2** is presenting the indicative engineering cost for the monopile concept.

Table 4.1. Indicative Engineering cost for Universal Foundation concept

Universal Foundation concept	Cost [€/unit]
Universal Foundation design	200000
Total indicative Engineering cost = 200.000€/unit	

Table 4.2. Indicative Engineering cost for monopile concept

Monopile concept	Cost [€/unit]
Monopile design	75000
Total indicative Engineering cost = 75.000€/unit	

Even though the price level is significantly different, those figures are applicable for OWT projects. Since a Wavestar C6 is adding a different loading scenario, the engineering cost for a pile would increase significantly due the design configurator could not be applied. Therefore the costs presented on **Table 4.1** and **Table 4.2** is just some indicative values that cannot be directly applied on a WEC project.

4.2 Manufacturing cost

The manufacturing costs are assessed considering a direct input provided from a manufacturing company headquartered in the north of Europe. Since the Wavestar C6 prototype is to be installed in THV Mermaid, a manufacturing company located in central Europe is also included in this cost study. No direct price input was supplied from the Belgium manufacturer but their price level is known. Instead the challenges that might vary the final cost are discussed here. Since the optimal Universal Foundation concept at this stage of the project is the circular bucket caisson, **Table 4.3** is presenting the total indicative manufacturing costs for the Universal Foundation concept. The input presented in **Table 4.3** is referenced to the north Europe manufacturer.

Table 4.3. Manufacturing cost for Universal Foundation concept

Universal Foundation	Weight [t]	Cost [€]
Shaft	177	283200
Lid	23.1	77385
Skirt	128	428800
Total indicative unitary cost = 789,385€		

A cost level study was made to compare the input provided in Table 4.3 with what would be the cost to produce the foundations if a central Europe manufacturer is chosen. UFOAS has contacted with three companies in the area capable to manufacturer the foundations. The result shown that the manufacturing costs are in the same range and in particular cases with a maximum cost difference of ± 10%. The difference comes from fabrication limitations including initial investment on machinery, crane capacity, storage space, sufficient space to fabricate and other capacity constraints. Another factor is that those companies are serial manufacturers and are not focus on one off prototype. Therefore the total cost can also be increased.

Since a conceptual design for a pile has not been performed, it is hard to compare the effectuated Universal Foundation design with other foundation concepts in terms of manufacturing cost. However some tendency is observed from the study presented in section 1.2.1. The analysis revealed that the monopile design weighted 20% more than the Universal Foundation design. In terms of price, the monopile concept was around 9% more expensive than the Universal Foundation concept. So some indication might be taken from the presented analysis for manufacturing costs.

4.3 Installation cost

After the installation approach is described in chapter 3, an assessment for the total installation costs is developed here. One of the project goals is to provide solutions in order that Wavestar C6 and the two Universal Foundations can be assembled onshore. Then the requirement of using different subcontractors to install the foundations and the superstructure can be avoided. Therefore UFOAS investigated different installation approaches considering the total installation cost as the driving parameter. The major advantages of using the Universal Foundation concept reminds on the required installation times to install the foundation. Compare to the installation time rates from other concepts that requires around 24h for a complete installation, the Universal Foundation is able to perform a full installation in approximately 12-15h. The time savings during installation phase is an essential measure to have cost competitive installation solutions. As presented in section 1.4.4 around 50% of the CAPEX is invested on the foundation and installation so a significant cost is utilized in the installation phase. Other advantages are the no need for heavy equipment such as driving hammers. Instead, pump units are utilized to create the necessary net driving force to penetrate the soil. The installation costs are presented in **Table 4.4**. All installation costs are slip depending on

Table 4.4. Indicative installation cost.

Indicative Installation costs	Indicative cost [€/day]
Submerged barge	21790
Tug boat	10900
Personal expenses	2000
Foundation Installation team	4800
Foundation Installation equip-ment	6000
Wavestar Installation team	-
Wavestar equipment	-
Total indicative installation cost = 45490€/day	

logistics and foundation installation personal and equipment. Wavestar installation team and equipment is not assessed in **Table 4.4**.

4.4 Pros and cons on cost modelling

In this section all pros and cons faced on the different cost modelling phases presented in sections 4.1, 4.2 and 4.3 are described. The goal of this section is to state all benefits and challenges experienced in the cost modelling in order to have valuable input for a tender design phase.

4.4.1 Pros and cons on engineering cost

From an engineering cost point of view the Universal foundation is compared with a monopile concept. The fact that approximately 79% of the OWT are sustained by monopiles plus the simple geometry for the concept lead to the conclusion that this solution has been further developed compared to the Universal Foundation. The companies in charge with monopile designs have fully developed their design configurator. Not surprisingly the engineering cost for a monopile is of lower level compared to the engineering cost for the Universal Foundation. However the difference on loading conditions between an OWT and a WEC structure demands that the foundation structure is investigated carefully from scratch. Therefore a site specific design has to be developed for any foundation concept consider suitable. This fact makes that to compare the engineering cost of a monopile and a bucket becomes a serious challenge. In such situation no benefits or drawbacks can be presented for any of the foundation concepts in terms of engineering costs.

4.4.2 Pros and cons on manufacturing cost

From a manufacturing point of view the main points that have an impact on the two analyzed structures i.e. circular and multishell concept, are the complexity and the vulnerability towards damages during manufacture due to large diameter of the bucket skirt. Conversely the difference in total weight from both structures does not have an impact on the manufacturing. Nonetheless the total foundation weight is affected by the steel price. An individual analysis is developed to point out pros and cons for the circular and multishell concept.

Universal Foundation circular bucket concept:

Pros:

- Skirt structure is easier to manufacture.
- Skirt structure faster to manufacture.
- Reduced risk for defects during manufacturing due to less complex structure.
- Less complex structure gives higher number of possible suppliers.

Cons:

- The weight of the pates composing the skirt structure is higher.
- The structure is more vulnerable for deformation of skirt during manufacturing, shipping and installation due to combination of large diameter and relative small plate thickness.

Universal Foundation multishell bucket concept:

Pros:

- Reduced material weight.
- More rigid concept is less vulnerable for deformation during manufacturing and shipping.

Cons:

- Skirt structure more complex to manufacture.
- More complex structure reduces number of possible suppliers.
- Longer manufacturing leads to longer time therefore higher costs.

4.4.3 Pros and cons on installation cost

From an installation point of view several uncertainties were aroused due to the nature and the maturity of the project. Since almost no experience is available installing a WEC in offshore conditions it is challenging to program a full installation campaign. However the installation approach presented in chapter 3 is a concept investigation that might be used as start point on a more detailed installation study. UFOAS is presenting here the pros and cons that were faced during the installation study developed for CEFIWE project.

Pros:

- Total installation costs since the installation expenses were the driving parameter.
- No subcontractors needed to perform the installation.
- No jack up vessel with massive crane required.

Cons:

- Complete new installation concept.
- Transportation for the total assembly i.e. Wavestar C6 and foundations due to final dimensions
- Synchronization for suction installation, Wavestar C6 floating state and barge positioning.

5. References

[1] **Cost Effective Foundation and Installation of Wave Energy Converters CEFIWE**. Application for FoskEL. Name of the applicant: Lars Bo Ibsen.

[2] **Concept Study of Foundation Systems for Wave Energy Converters.** Master thesis. Vaikunaite. E Devant Molina. S. Aalborg University Department of Civil Engineering – Spring 2012.

[3] **Comparison of Foundation systems for Wave Energy Converters Wavestar**. Vaitkunaite.E, Ibsen L.B, Nielsen. B, Devant Molina. S. 10TH European wave and tidal Energy Conference EWTEC 2013.

[4] **ULS_Production_Max_loads.** 2014. File provided by Wavestar and Aalborg University.

[5] **FLS_JP_loads_fixed_support_bin_size_fixed.** 2014. File provided by Wavestar and Aalborg University.

[6] **2014-02-25 CEFIWE_DNV_Storm_ver1.** 2013. File provided by Wavestar and Aalborg University.

[7] **Comparison_ULS-storm_VS_ULS-production.** 2014. File provided by Wavestar and Aalborg University.

[8] **Some first conclusions on the FLS Jacking and Pile loads.** 2014. File provided by Wavestar and Aalborg University.

[9] **DNV-OS-J101 - Design of Offshore Wind Turbine Structures,** Det Norske Veritas. February 2013.

[10] **Loads on jacking system from floats in operation.** Ver. 1 - 2014-01-27. File provided by Wavestar and Aalborg University.

[11] **DNV-RP-C203. Fatigue Design of Offshore Steel Structures.** Det Noske Veritas. October 2012.

[12] **DNV-RP-C202. Buckling Strength of Shells.** Det Noske Veritas. January 2013.

[13] **Alternative Shape of Suction Caisson to Reduce Risk of Buckling Under High Pressure.** S. Madsen, L.V Andersen L.B Ibsen. Department of Civil Engineering at Aalborg University.

Universal Foundation

Appendix A

Conceptual drawings after Feasibility analysis

Project:	Cost Effective Foundation and Installation of Wave Energy Converters CEFIWE
Document no.:	804-20-5201
Revision:	A
Date:	05.12.2013
Client doc. no.:	-

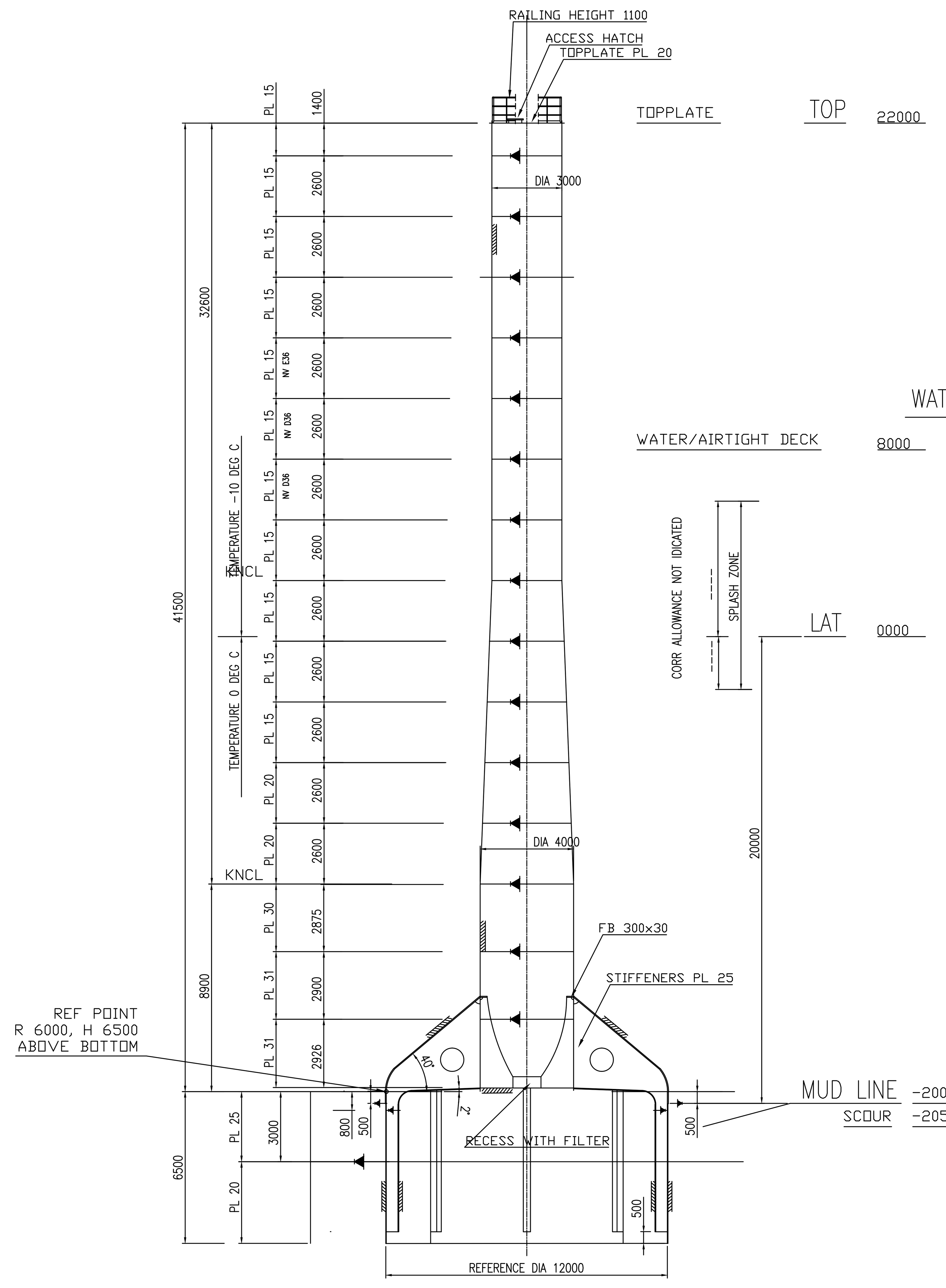
CHANGE LOG:

Rev.	Issue date:	Description:	Prep. by:	Check. by:	Appro. by:
A	05.12.2013	First release	SDM/LGC	MF/MJV	SAN

Universal Foundation A/S
Langerak 17, 1. sal
9220 Aalborg Øst
Denmark

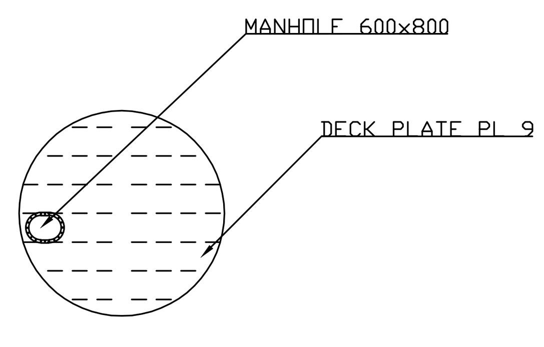
Phone: +45 70 23 02 44
E-mail: contact@ufoas.dk
www.universalfoundation.dk

Enterprise no.: 26046246

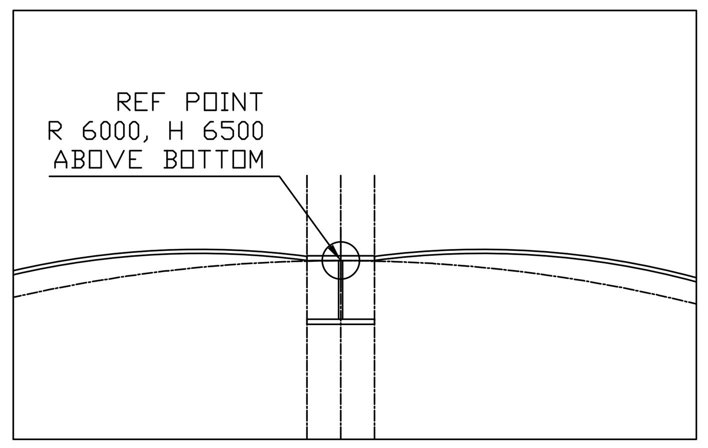


LATERAL SECTION IN CENTER

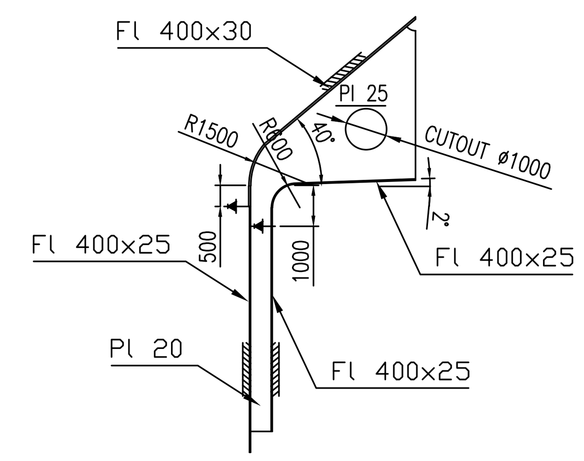
→ INDICATE PLATE SEAM.
FOR WELDING DETAILS SEE DRAWING 230-30-3xxx-xx
PLATE THICKNESS ARE GROSS VALUES I.E. BUILDING VALUES
NO CORROSION ADDS INCLUDED
(FIGURES IN ( ) ARE NET VALUES, WITHOUT CORROSION ADDS)



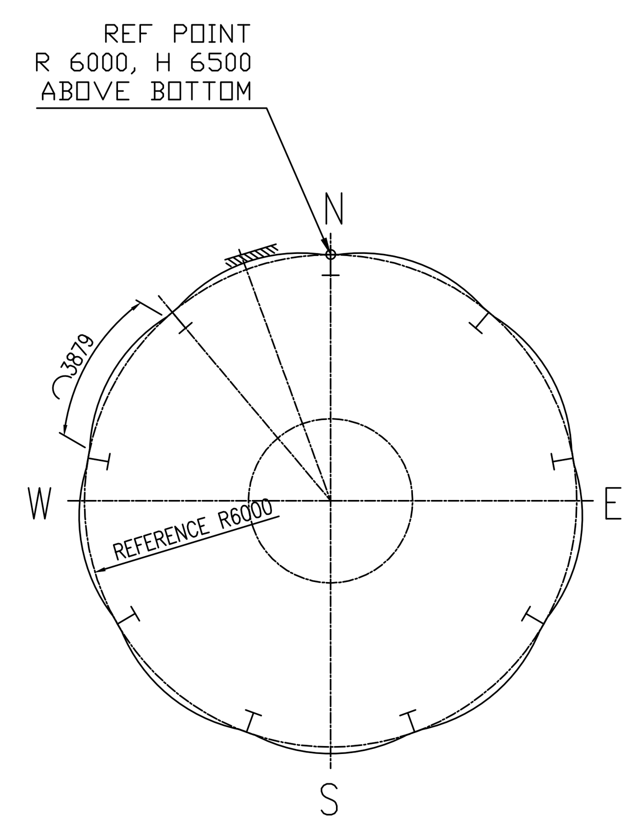
WATER/AIRTIGHT DECK



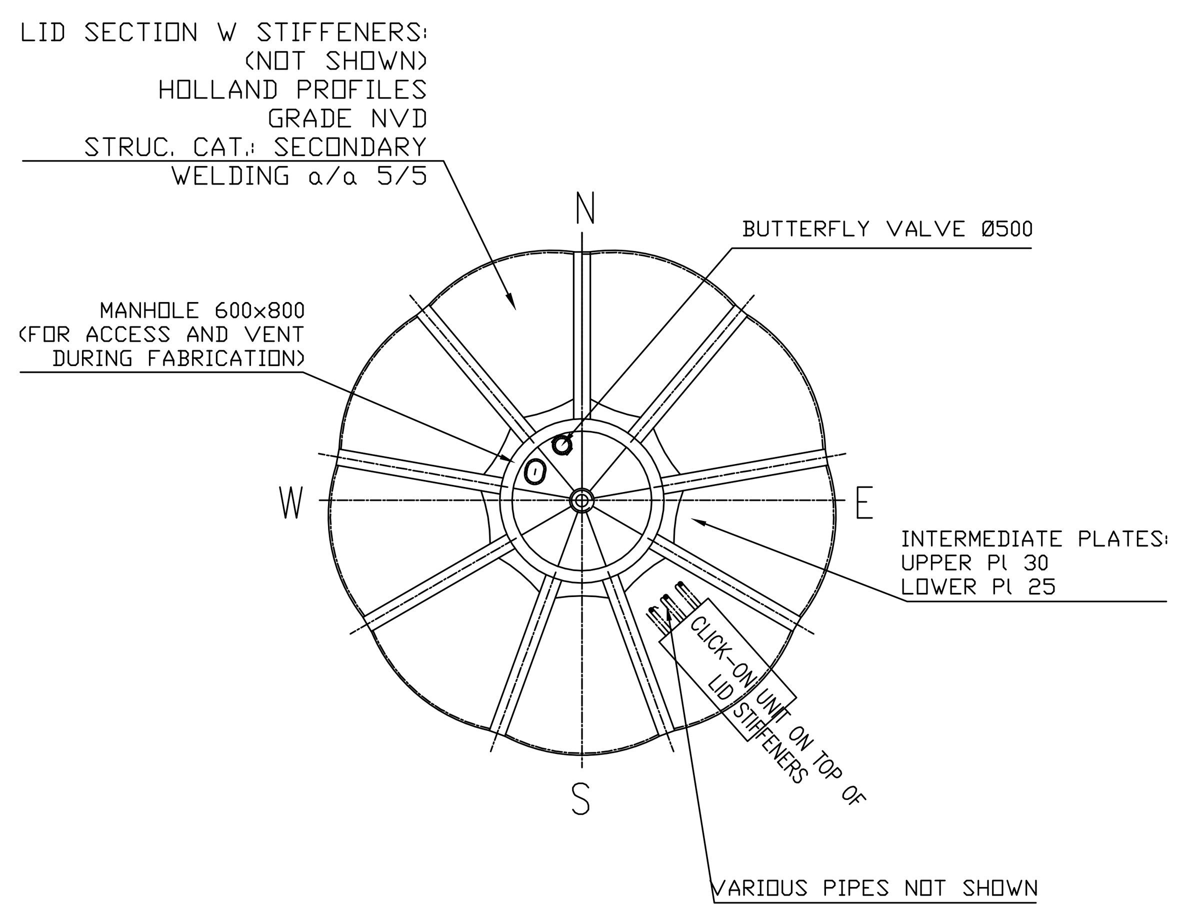
DETAIL IN SKIRT



WEB DETAIL



PLAN SECTION IN SKIRT



PLAN TOP OF LID

POSITIONS OF COMPONENTS ONLY FOR GUIDANCE
LID STIFFENERS NOT SHOWN

NOT FOR PRODUCTION

NOTE:
PLATE DIMENSIONS ARE PRELIMINARY
STRUCTURE HAS NOT BEEN CHECKED FOR BUCKLING
NO LOCAL LOADS HAVE BEEN TAKEN I ACCOUNT
NO SECONDARY STRUCTURE IS TAKEN IN ACCOUNT

ESTIMATED STEEL WEIGHTS (1' ITERATION):
PRIMARY STRUCTURE approx 215 T
Incl.: corr. allowance(approx 6 T)
COG APPROX. LEVEL (REF. LAT)

ALL MEASURES IN MM

Rev.	Date	Draw	Check	Appr.	Revision text
04					
03					
02					
01					
00	05.12.2013	JPH	LGC		Issued for client

SHOP: BUILDING NO.:

BUCKET FOUNDATION, WAVE STAR
STEEL STRUCTURE

VARIOUS: SCALE: 1:150 CUSTOMER: WAVE STAR ENERGY
FORMAT: A1

Universal Foundation
Danalien 1, DK-9000 Aalborg, Denmark
Tlf. +4570230244, email: contact@ufoas.dk

FILE NAME: 804-20-3002-00 DWG Wave Star Steel Struc
PAGE: of
DRAWING NO.: 804-20-3002-00

Universal Foundation

Appendix B

Conceptual drawings after Conceptual design

Project:	Cost Effective Foundation and Installation of Wave Energy Converters CEFIWE
Document no.:	804-20-5201
Revision:	A
Date:	20.06.2014
Client doc. no.:	-

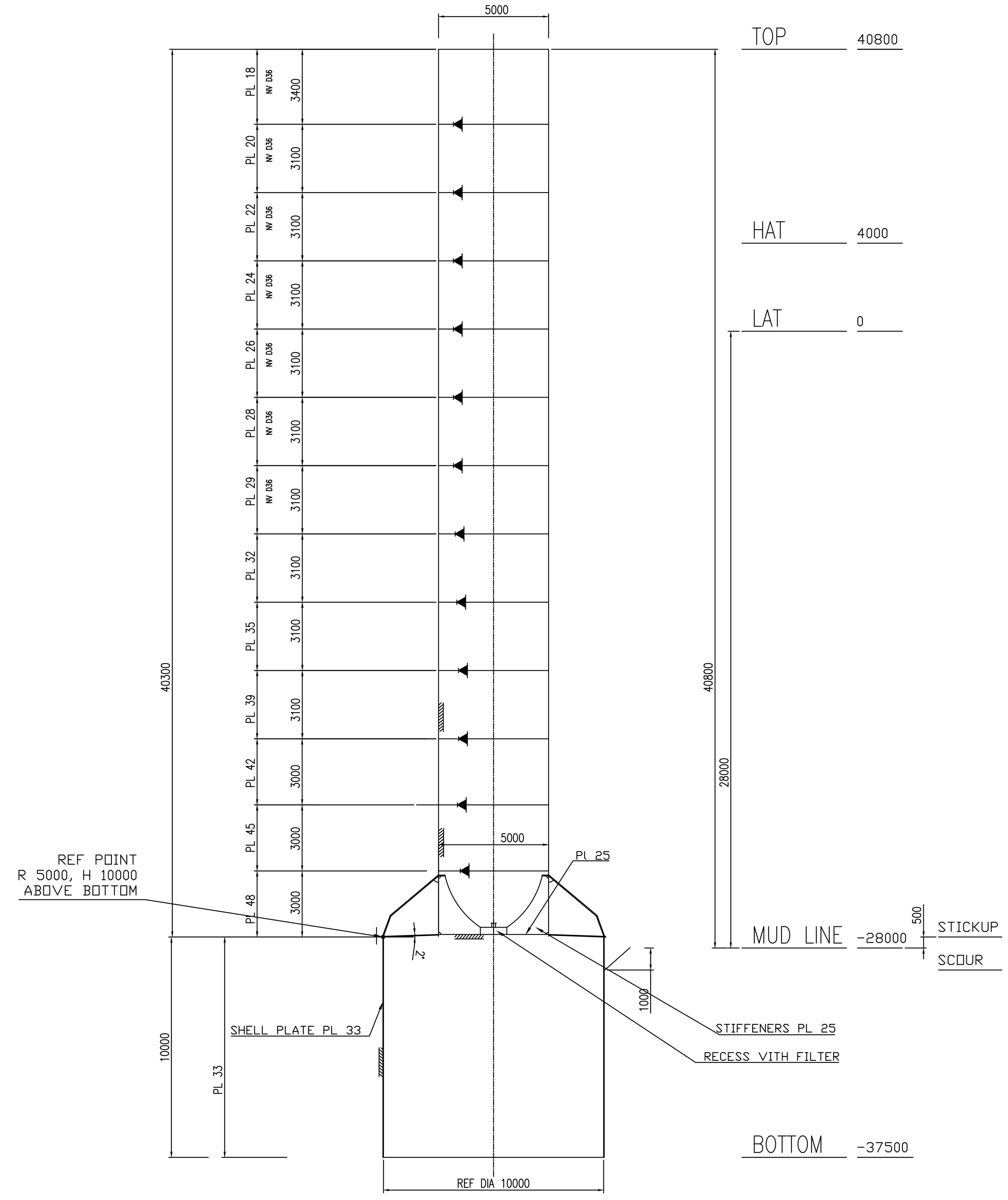
CHANGE LOG:

Rev.	Issue date:	Description:	Prep. by:	Check. by:	Appro. by:
A	20.06.2014	First release	SDM/LGC	MF/MJV	SAN

Universal Foundation A/S
Langerak 17, 1. sal
9220 Aalborg Øst
Denmark

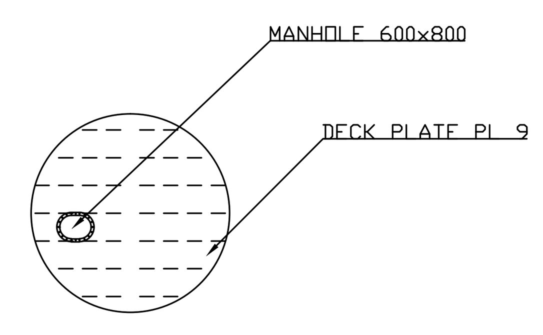
Phone: +45 70 23 02 44
E-mail: contact@ufoas.dk
www.universalfoundation.dk

Enterprise no.: 26046246

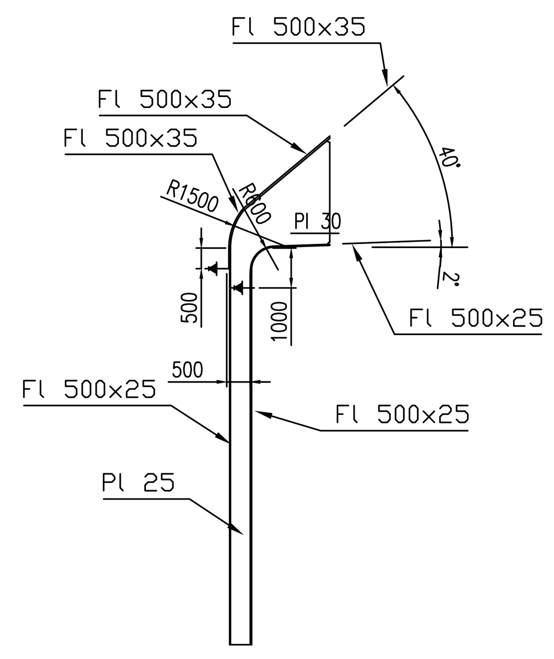


LATERAL SECTION IN CENTER

INDICATE PLATE SEAM.

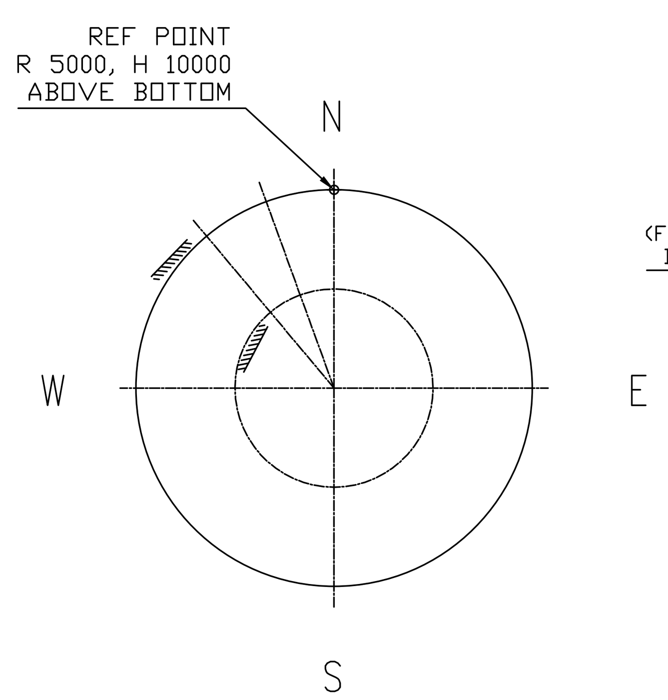


WATER/AIRTIGHT DECK

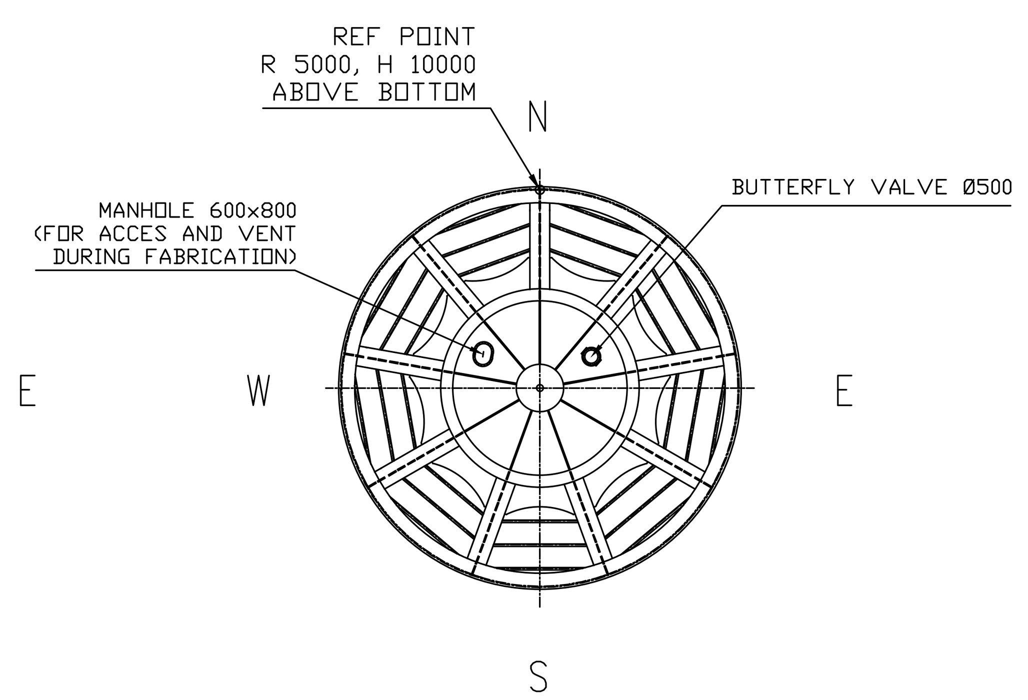


WEB DETAIL

DRAFT



PLAN SECTION IN SKIRT



PLAN SECTION IN SKIRT

ESTIMATED STEEL WEIGHTS (1' ITERATION):
SHAFT STRUCTURE approx 177 T
CAISSON STRUCTURE approx 151 T
PRIMARY STRUCTURE TOTAL approx 328 T
Exclusive corrosion adds

NOTE:
PLATE DIMENSIONS ARE NOT REFLECTING
LOCAL LOADS FROM JACKING-UP SYSTEM

Rev.	Date	Draw	Check	Appr.	Revision text
A	28052014	JPH	LGC	MF	Draft

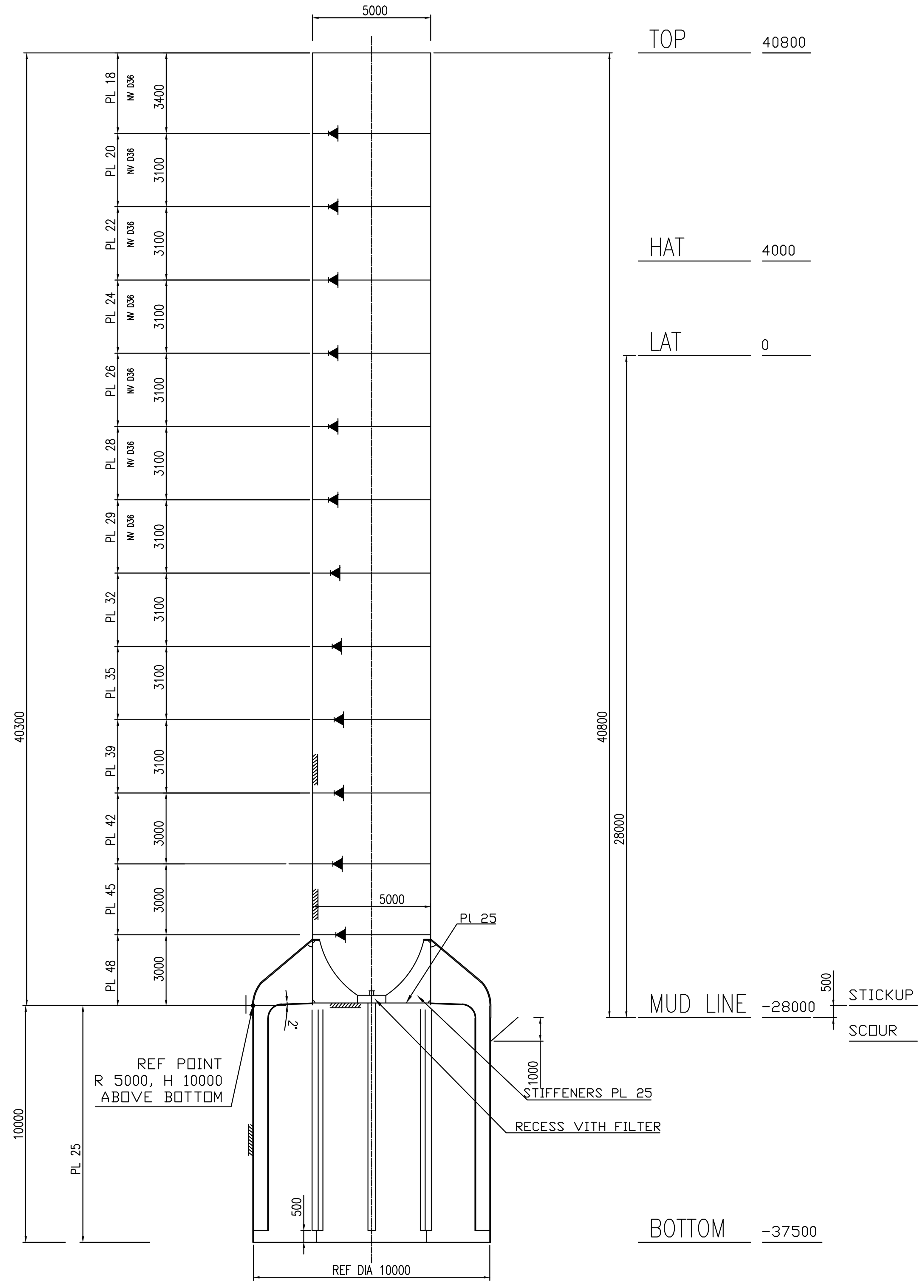
SHOP: | BUILDING NO.:

BUCKET FOUNDATION
STEEL STRUCTURE I, SINGLE SHELL

VARIOUS:	SCALE:	CUSTOMER:
FORMAT: A1	1:150	Wavestar Energy CEFIWE

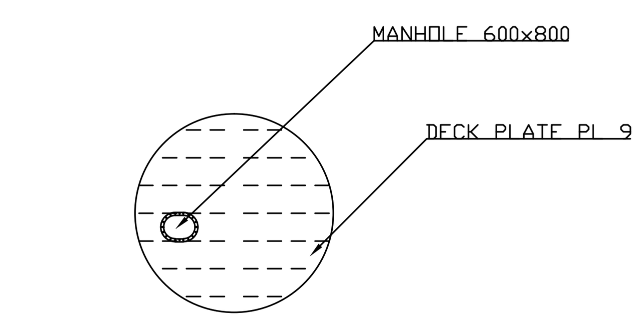
Universal Foundation
Danalien 1, DK-9000 Aalborg, Denmark
Tlf. +4570230244, Mail: contact@ufoas.dk

FILE NAME: 804-20-3303-A Steel Structure I
PAGE: 1 of 1
DRAWING NO.: 804-20-3303-A

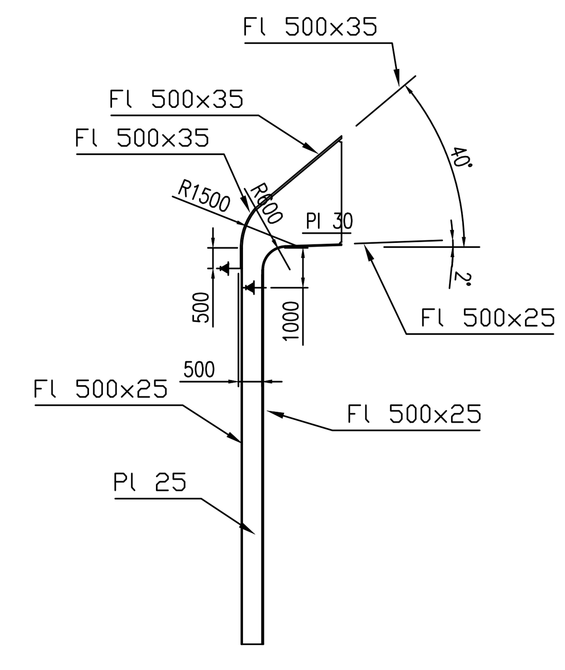


LATERAL SECTION IN CENTER

—▶— INDICATE PLATE SEAM.

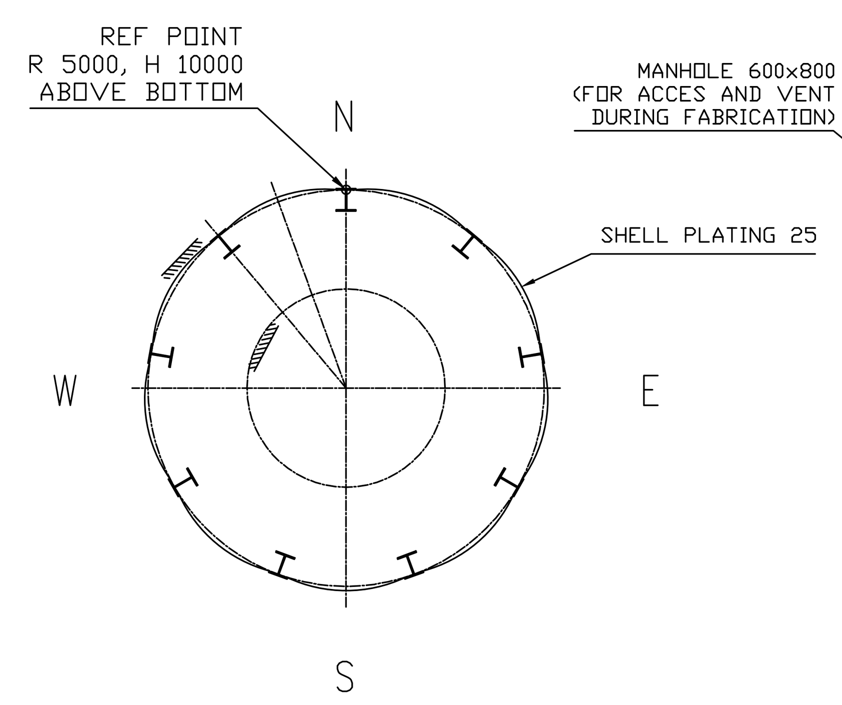


WATER/AIRTIGHT DECK

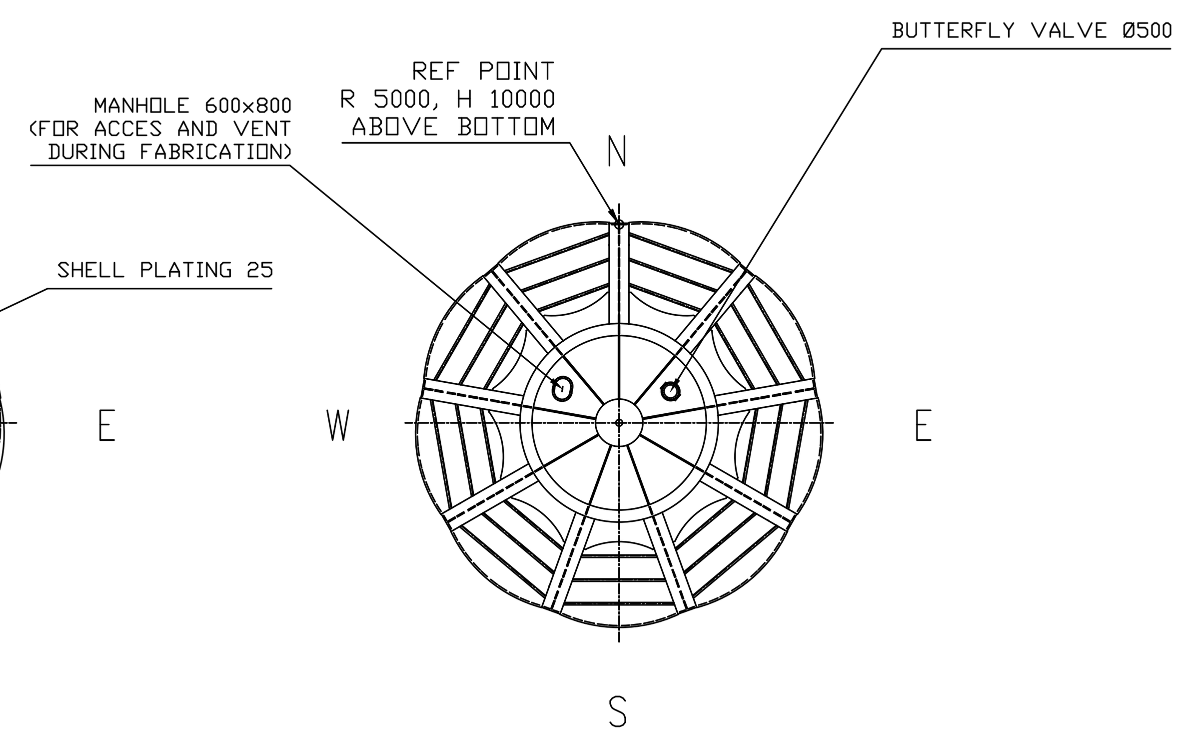


WEB DETAIL

DRAFT



PLAN SECTION IN SKIRT



PLAN SECTION IN SKIRT

ESTIMATED STEEL WEIGHTS (1' ITERATION):
SHAFT STRUCTURE approx 177 T
CAISSON STRUCTURE approx 166 T
PRIMARY STRUCTURE TOTAL approx 343 T
Exclusive corrosion adds

NOTE:
PLATE DIMENSIONS ARE NOT REFLECTING
LOCAL LOADS FROM JACKING-UP SYSTEM

Rev.	Date	Draw	Check	Appr.	Revision text
A	28052014	JPH	LGC	MF	Draft

SHOP: | BUILDING NO.:

BUCKET FOUNDATION
STEEL STRUCTURE I, MULTI SHELL

VARIOUS:	SCALE: 1:150	CUSTOMER: Wavestar Energy CEFIWE
FORMAT: A1		

Universal Foundation
Danalien 1, DK-9000 Aalborg, Denmark
Tlf. +4570230244, Mail: contact@ufoas.dk

FILE NAME: 804-20-3302-A Steel Structure I
PAGE: 1 of 1
DRAWING NO.: 804-20-3302-A

Annex

[1] Molina S.D, Nielsen S.A (2014). Foundation Design, Installation Technique and Cost Study. Universal Foundation. The report is in Appendix A of this report.

[2] Vaitkunaite, E.,(2016). Physical Modelling of Bucket Foundations Subjected to Axial Loading. Aalborg: Aalborg Universitetsforlag. 330 pages.
Can be downloaded from:
http://vbn.aau.dk/en/publications/physical-modelling-of-bucket-foundations-subjected-to-axial-loading%2816c0e315-0125-4c16-8889-f50b6cb8d847%29.html

[3] Vaitkunaite, E., Ibsen, L. B., Nielsen, B. N., and Devant Molina, S. (2013). Comparison of Foundation Systems forWave Energy ConvertersWavestar. *In 10th ewtec 2013 European Wave and Tidal Energy Conference Series: Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark. Technical Committee of the European Wave and Tidal Energy Conference. No. 10.*

Can be downloaded from:

http://vbn.aau.dk/da/publications/comparison-of-foundation-systems-for-wave-energy-converters-wavestar(6da89cab-f483-4ce1-b584-b68756548afe).html

[4] Vaitkunaite, E., Nielsen, B. N., and Ibsen, L. B. (2015). Comparison of design methods for axially loaded buckets in sand. *In Frontiers in Offshore Geotechnics III proceedings of the third international symposium on frontiers in offshore geotechnics (isfog 2015), Oslo, Norway, 10-12 June 2015. (Vol. 1, pp. 331-342). London: C R C Press LLC.*

Can be downloaded from [2] Appendix B

[5] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. (2014). New Medium- Scale Laboratory Testing of Bucket Foundation Capacity in Sand. *In Proceedings of the Twenty-fourth (2014) International Ocean and Polar Engineering Conference, Busan, South Korea. (Vol. 2, pp. 514-520). International Society of Offshore and Polar Engineers.*

Can be downloaded from [2] Appendix C

[6] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. (2016). Testing of Axially Loaded Bucket Foundation with Applied Overburden Pressure. Aalborg: Department of Civil Engineering, Aalborg University. DCE Technical Reports; No. 209.

Can be downloaded from:
http://vbn.aau.dk/da/publications/testing-of-axially-loaded-bucket-foundation-with-applied-overburden-pressure(a3997658-32c8-4903-a206-28d3291ac883).html

[7] Vaitkunaite, E., Ibsen, L. B., and Nielsen, B. N. Bucket Foundation Model Testing under Tensile Axial Loading. *Canadian Geotechnical Journal. Submitted 14-10-2015 [cgj-2015-0497], Re-submitted 06-06-2016 [cgj-2016-0301].*

Can be downloaded from [2] Appendix E

[8] Vaitkunaite, E., Nielsen, B. N., and Ibsen, L. B. (2016) Bucket Foundation Response under Various Displacement Rates. *International Journal of Offshore and Polar Engineering, 26(2), 116-124.*

Can be downloaded from [2] Appendix F

[9] Vaitkunaite, E. (2015). Bucket Foundations under Axial Loading: Test Data Series 13.02.XX, 13.03.XX and 14.02.XX. *Aalborg: Department of Civil Engineering, Aalborg University. DCE Technical Reports; No. 199.*

Can be downloaded from:
http://vbn.aau.dk/da/publications/bucket-foundations-under-axial-loading(5d0d4339-c4c5-464e-813f-fc17938aefe3).html