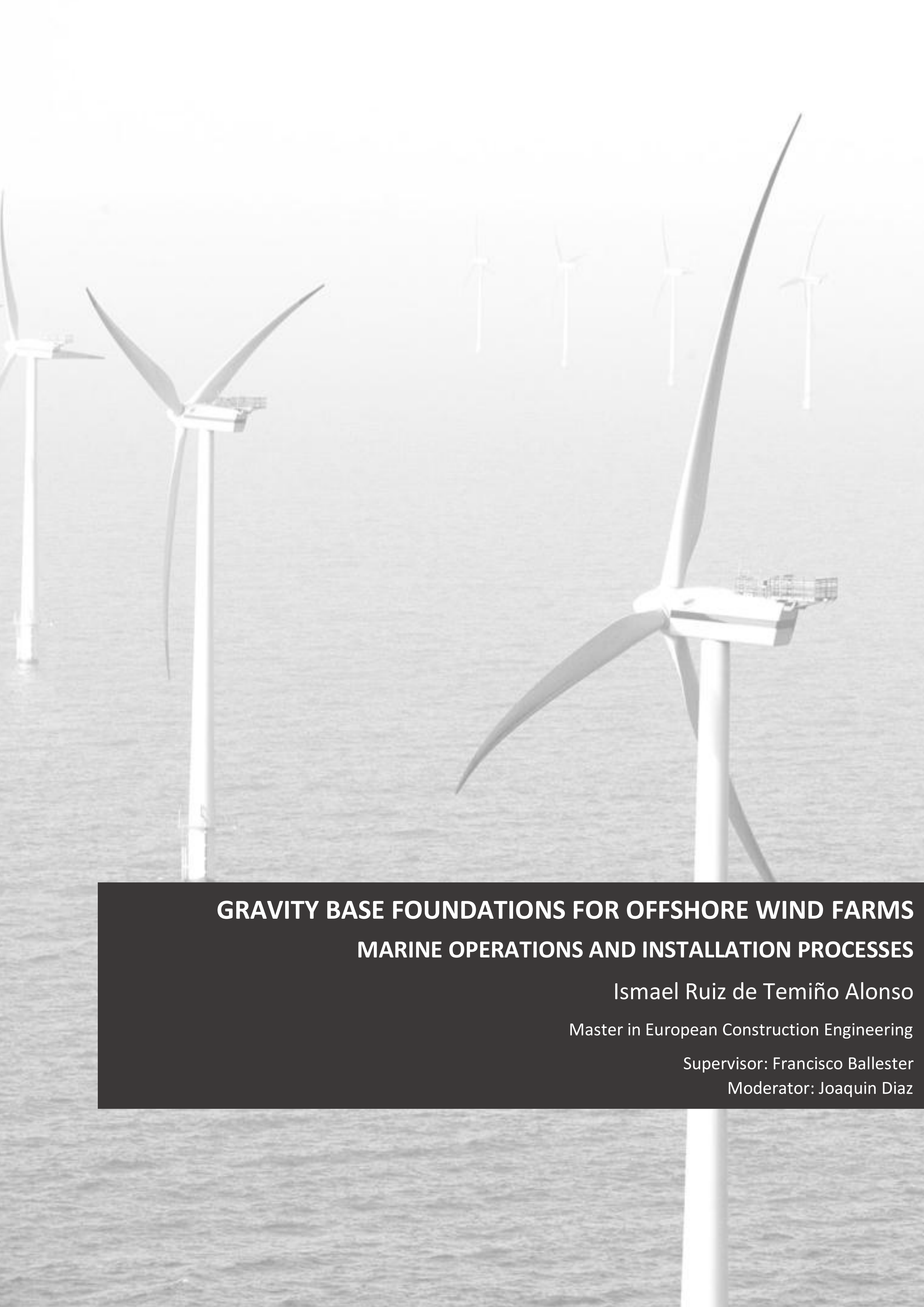

GRAVITY BASE FOUNDATIONS FOR OFFSHORE WIND FARMS

MARINE OPERATIONS AND INSTALLATION PROCESSES

Ismael Ruiz de Temiño Alonso

Master in European Construction Engineering

Supervisor: Francisco Ballester
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2012- 2013

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ABSTRACT

Marine operations required in the installation of gravity base foundations for offshore wind farms were studied. This dissertation analyses the operations of transport, seabed preparation, installation and scour protection. This analysis was carried out through the study of the eight most relevant offshore wind farms with gravity base foundations, four significant foundation designs, and the application of techniques from other offshore construction sectors. Within each operation, the main procedures both used so far and expected for the future were investigated. It was also identified the main factors to consider in each operation and the means required. Further analysis studied different transport and installation configurations.

KEYWORDS

Offshore wind energy; Offshore wind farms; Gravity base foundations; Marine operations; Transport; Installation; Seabed preparation; Scour; Procedures; Wind turbines; Pre-assembly; Future trends.

RESEARCH STATEMENT

This dissertation is the result of an individual research of the author and the collaboration with the research group GITECO. The Construction Technology Applied Research group (GITECO) was born in 2002 and since then, it has successfully developed more than 70 projects related with civil construction sector. GITECO is part of the Department of Transports and Technology of Projects and Processes of the University of Cantabria and it operates in the School of Civil Engineering in Santander (Spain).

One of the research areas on which GITECO is currently working is gravity base foundations for offshore wind farms. The author has developed this dissertation as an interesting area for the research group, and both sides have exchanged information to establish a mutually beneficial collaboration.

ACKNOWLEDGEMENTS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

GBF: Gravity Base Foundations

GPS: Global Positioning System

MW: Megawatts

SPMT: Self Propelled Modular Transporter

1. INTRODUCTION

1.1. BACKGROUND

The global warming of our planet along with the limitation of supplies of conventional fuels has led humanity to search for new energy sources. In this context, the EU-27 has committed to reduce its greenhouse gasses emission by at least 20 % in the year 2020 compared to 1990 values. In 2009, the emissions of EU-27 were approximately 17.3% below 1990 level (European Environment Agency, 2010).

Humans have utilized wind as an energy source for hundreds of years, but the optimization of its exploitation has implied recently important developments and innovations and nowadays it has become one of the most important renewable energy sources, producing with 106 GW in 2012 about 11.4 % of EU's installed generation capacity (EWEA, 2013).

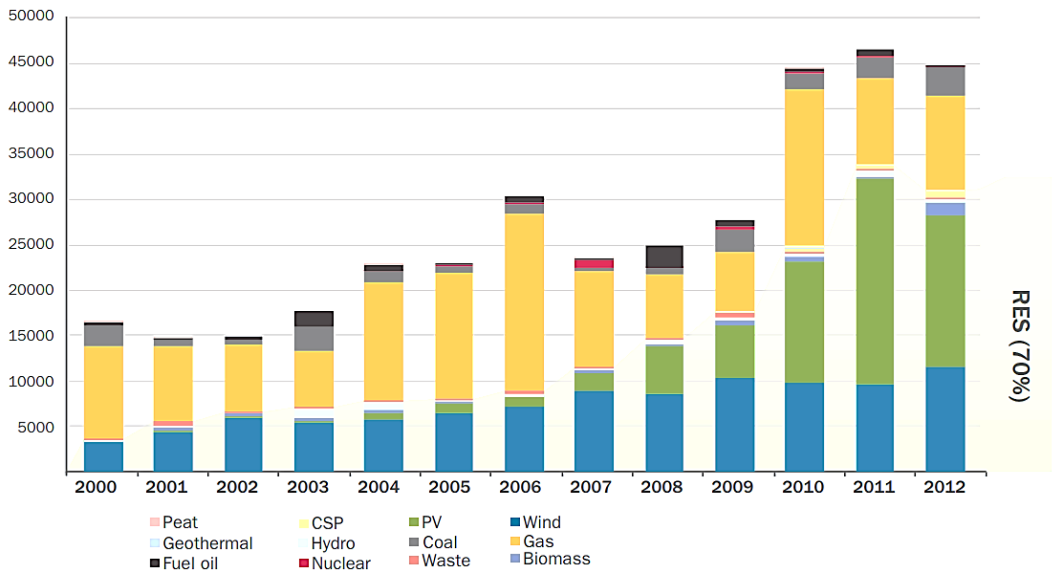

Figure 1: Installed power generating capacity per year in MW and RES share (%) (EWEA, 2013)

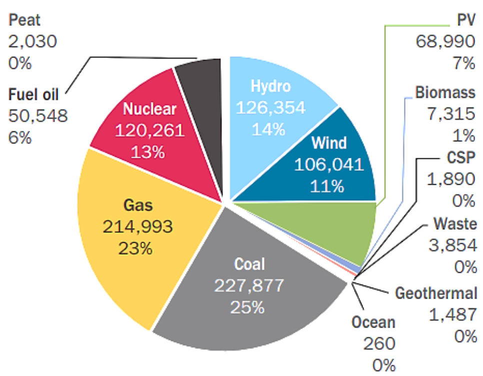

Figure 2: EU Power mix 2012 (EWEA, 2013)

Offshore wind energy is being used since in 1991 Denmark installed the first offshore wind farm. Nowadays, there are more than 50 European offshore wind farms, mainly in waters of Denmark, Belgium, United Kingdom, Germany and Sweden. 2012 represented a record year for offshore installations with 1,166 MW of new capacity grid connected, reaching a total offshore installed capacity of 4,993 MW (EWEA, 2013).

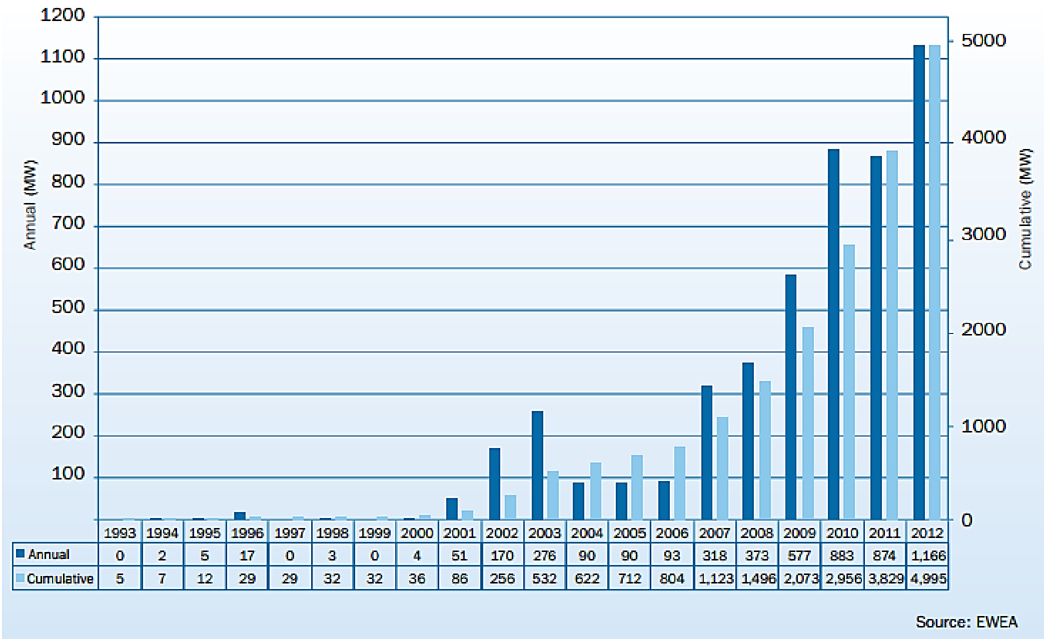

Figure 3: Annual and accumulative installations of offshore wind in Europe (EWEA, 2013)

Offshore wind farms offers several advantages over onshore-based projects: the wind is steadier, higher and more suitable, the visual impact is less important, the new turbine sizes are easier to be transported offshore than over land, and the transmission lines are shorter since offshore wind usually is closer to the highly populated areas. However, the cost of offshore wind power is still not competitive, due mainly to the important costs of the foundations and the expensive maritime operations.

Gravity base foundations (GBF) are the second most frequently used type of foundations (monopile is the most common) and currently represents about 16 % of the total amount of foundations for operational offshore wind farms (LORC, 2013). However, this type of foundations is expected to became more and more important in the coming years, as they are more suitable for higher depths and higher turbine power capacity (Arup & Hochief, 2011) (Vølund, 2005).

Marine operations for the installation of gravity base foundations are an important area to develop, as they represent a significant part of the total cost of the installation. The technologies and methods are still in its early days, and there is plenty room of improvement. Furthermore, other offshore construction sectors as oil and gas platforms, immersed tunnels or harbour constructions may have experiences, applicable procedures and techniques to share with the offshore wind field.

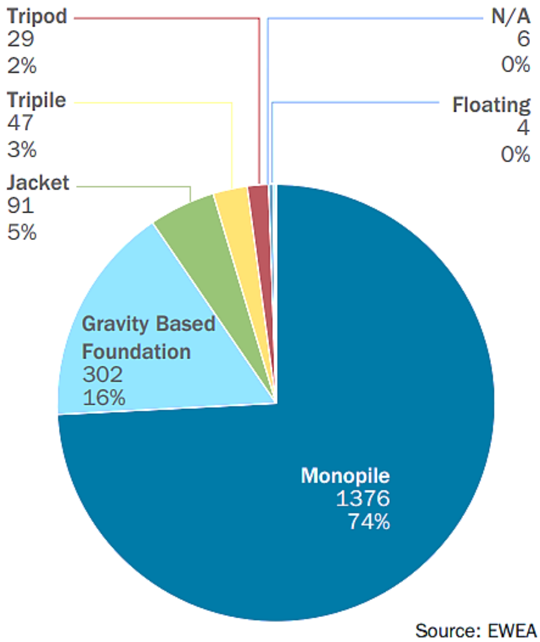

Figure 4: Share of substructure types, end 2012 (EWEA, 2013)

1.2. AIMS AND OBJECTIVES

The main objective of this report is to provide a study on the marine operations required for the transport and installation of gravity base foundations.

Hence, this dissertation aims to:

- Collect data of the most significant wind farms with GBF and investigate the main procedures and techniques used in the transport and installation of the foundations.
- Create a general approach of the future trends of GBF and investigate some significant innovative designs and their associated transport and installation procedures and techniques.
- Study other offshore constructions as oil platforms, immersed tunnels and harbours and try to apply their experience and techniques to the offshore wind sector.
- Summarize and analyse the main procedures in the marine operations of transport, seabed preparation, installation and scour protection, both used so far and expected for the near future.
- Identify the main factors that affects each marine operation and the means required to carry them out.

- Discuss the different wind turbine configurations in the transport and installation of a GBF, from complete pre-assembled turbines to assembly on site.

1.3. RESEARCH METHODOLOGY

Technical data, procedures and techniques from previous offshore projects with GBF have been collected and analysed through reports, documents, papers, brochures, newsletters, websites of the stakeholders and contacts with the companies involved in the projects. Besides, information provided by research group GITECO was used occasionally.

The cases studied were all the currently operational wind farms with gravity base foundations and installed capacity higher than 10 MW, excepting *Kemi Ajos I & II* and *Avedore Holme* for being considered not interesting for the study. These are:

- *Nysted I (Rødsand I)*
- *Nysted II (Rødsand II)*
- *Lillgrund*
- *Middelgrunden*
- *Thornton Bank I*
- *Vindpark Vänern*
- *Sprogø*

The currently under construction wind farm of *Kårehamn* was also included in the study as some of the operations have already been finished.

For the forecasted procedures and techniques, some wind projects in their concept phase and innovative designs were analysed, and a patent study provided by GITECO studied. Being considered more interesting for the study, four of them have been analysed more deeply:

- *Strabag system*
- *Cranefree foundations*
- Gravitas solution
- *Vinci – GBF solution*

Offshore projects related with different areas as oil and gas platforms, immersed tunnels or harbour construction have been considered through the analysis of projects and bibliography (especially related with oil and gas prospections) and the application of their techniques to wind projects commented.

1.4. LIMITATIONS AND SCOPE

The scope of this study is limited to the marine operations of foundation transport, seabed preparation, installation of the foundation and scour protection. The document does not cover, therefore, any process of transport and installation of wind turbine components.

The study is focused on gravity base foundations for offshore wind farms, so it does not cover any other type of foundations or GBF for other purposes.

Wind farms with less installed capacity than 10 MW and experimental wind farms were not considered. Wind turbines installed in distances below 1 km from the shore or water depths lower than 3 meters were not considered either.

This dissertation has been carried out between mid-April 2013 and mid- August 2013.

1.5. DISSERTATION REPORT OUTLINE

The report was divided in six chapters. After the first introductory section, it was devoted one chapter for each marine operation considered: transport, seabed preparation, foundation installation and scour protection. The sixth and final chapter studies the different possibilities of configuration of turbine and foundation during the operations of transport and installation.

The sections devoted to the marine operations are, at the same time, subdivided in four main sections: introduction, procedures, factors and means.

2. TRANSPORT

2.1. INTRODUCTION

The operation of transport is one of the most important aspects in the implementation of offshore wind farms with gravity base foundations. This is due to the huge weights and dimensions of these structures. It has already been transported foundations of up to 3,000 tonnes and 40 m height, and it is expected that the coming foundations, designed for deeper waters, will reach up to 7,000 tonnes. These huge dimensions require special vessels and means, whose availability is limited, and with very important costs. Even it may be necessary specifically built vessels for one project.

Transport operation affects the whole project. From the concept phase, transportation is taken into account and even some designs are specially aimed at facilitating the transport of the foundations. The transport planning is very important as well, since the means of transport are so expensive that a mistake in the planning would trigger important costs for the project.

Market is moving currently to decrease the high risks and costs of depending so much in specific vessels. The trend of installing wind farms in deeper waters triggers bigger and heavier solutions that makes unsuitable the methods used so far, and lead to buoyant or semi-buoyant solutions.

In this chapter it will be analysed the main transport procedures both used so far and proposed for the near future, the most important aspects to consider, and the means required.

2.2. TRANSPORT PROCEDURES

The transport of gravity base foundations may be carried out in three main procedures:

- Group transport with large barges or pontoons
- Individual transport by heavy lift vessels
- Transport of buoyant foundations

2.2.1. GROUP TRANSPORT IN LARGE BARGES OR PONTOONS

This procedure is the most commonly used in the transport of gravity base foundations, and it has been chosen for the operational wind farms of Nysted I (Rødsand I), Nysted II (Rødsand II), Lillgrund, Sprogø and Kårehamn (under construction).

In this way of transportation, the construction of the foundation is carried out directly on flattop barges or pontoons, and when all the foundations of the barge are finished, they are carried to the wind farm. Tugs are required in order to tow not self-propelled barges. Some vessels used, as the pontoon "Giant 4", are self-propelled, so tugs are necessary only for auxiliary operations. Up to 12 foundations have been transported in one barge (Kårehamn wind farm), but it depends on the dimensions and weight of the foundations.

Figure 5: Foundations construction and transport in Kårehamn (Jan de Nul S/A, 2012)

When the foundations arrive to the wind farm, a special vessel, as a heavy lift vessel, is necessary to pick up each foundation and start the installation process. Semi-submersible vessels (as the pontoon "Giant 4" or other semi-submersible barges) may be used, both to facilitate the assembling of the foundation with the heavy lift vessel and to reduce the weight that this vessel have to hoist. In some cases this operation of sinking some centimetres the barge is compulsory, as the heavy lift vessel may not have enough lifting capacity.

The main advantage of this procedure is that it allows the transport of several foundations at a time, making it more effective for large distances, as it optimize the transport. Thus, in the offshore wind farms where this procedure was used, the transport distance ranged from 200 km to 2,000 km (Kårehamn wind farm). Besides, the construction of the foundation is carried out directly on barges, so the launching operation is avoided. On the other hand, a heavy lift vessel is required to pick up the foundation from the barge or pontoon. The availability of these vessels is low and the cost very important.

Regarding the future of this type of transport, it seems to be less suitable for heavier and bigger foundations, not for the transport itself (there are pontoons capable of carrying more than 24,000 tonnes), but because the existing heavy lift vessels required for hoisting and installing the foundations are not capable of lifting so heavy weights. The adaptation of other heavy crane vessels, semi-submersible pontoons and some degree of buoyancy of the foundation may allow the use of this transport procedure for bigger foundations.

2.2.2. INDIVIDUAL TRANSPORT BY HEAVY LIFT VESSELS

This procedure is quite common, and it has been chosen in operational wind farms as important as Middelgrunden or Throntonbank I.

The main characteristic of this type of transport is that a heavy lift vessel, picks up the foundation from the harbour, carries it directly to the wind farm and installs it on the seabed. In the previous procedure, the heavy lift vessel only picked up the foundation when it was already in the wind farm, and it installed the foundation. In this one, the heavy lift vessel carries out the transport as well, one by one.

Figure 6: Foundation transport in Thorntonbank (Luc van Braekel, 2008)

In the previous procedure, the foundations were built directly on the barges or pontoons that would transport it. In this one, the heavy lift vessel will pick up the foundations from the quay, so the construction site and launching operation must be planned. The main construction and launching procedures for this type of transport are:

- **Construction onshore** and, when the foundation is finished, it is carried from the construction site to the quay or launching area by means of SPMTs (self-propelled modular transporter). Once there, it is lifted by the heavy lift vessel and transported to the wind farm.
- **Construction in dry docks** and, when it is finished, the dry dock is flooded and the heavy lift vessel picks up the foundation. This latter procedure has the advantage that the foundations are partially submerged when the vessel lift them up, so the weight to be hoisted is lower.
- **Construction on floating docks**. This procedure has not been used yet in wind projects but it have some advantages that makes it interesting for the future.

Figure 7: Foundation launching in Thorntonbank (Scaldis, 2008)

Figure 8: Foundation construction in dry docks (Aarsleff, 2001)

The advantage of this process is that it does not need a large barge or pontoon to carry the foundation from the construction site to the wind farm, it is carried by the same vessel that will install the foundation. On the other hand the heavy lift vessel only is capable of transporting one foundation at a time. The conclusion is that this procedure is more suitable than the former for short distances. Thus, in Middelgrunden the wind farm was only a few kilometres away from the harbour (in Copenhagen).

For the future, this type of transport has been chosen (with some variations) in some design proposals, as *Strabag* solution, where the transport is carried out by means of a specifically built vessel. The foundations of this system are suitable for depths up to 60 m and they weigh up to 6,000 tonnes, so the transportation is carried out with the foundation semi submerged. This example points out the future trends of this procedure, with a partially submerged foundation to reduce the enormous weights.

2.2.3. BUOYAN SOLUTIONS TRANSPORT

The tendency to install offshore wind farms in deeper waters and consequently the increase in the size and weight of the foundations makes quite difficult the two previous ways of transport, as currently it does not exist heavy lift vessels capable of lifting more weight. It could be constructed a specifically built vessel for the task, but it would increase not only the costs of transport, but also the risks of so restricted availability. Thus, the trends point to self-buoyant solutions that are towed to the wind farm by means of standard tugs. The availability of these tugs is much higher than heavy lift vessels used in the previous types of transport, and the cost is lower.

As in the previous procedure, the construction site and launching operation must be planned. Thus, there are three main types of construction and launching operations for buoyant solutions:

a) **Construction onshore**. One simple method may be the construction of the foundation onshore and, when finished, it is transported to a launching area where a submersible pontoon lower the foundation until it is buoyant, and then, it is assembled to the tugs or transport vessels used.

b) **Construction in dry docks**. Other important method that has been used in the construction of immersed tunnels is the construction of the foundation in dry docks that are flooded when the foundation is ready to be transported.

c) **Construction in floating docks**. Floating docks has some advantages as the high efficiencies of construction and the not dependency of expensive shipyards or other facilities. On the other hand, the curing of the concrete occurs in the sea water, what has to be considered carefully, and the availability of suitable floating docks may be limited.

This procedure of self-buoyant solution is quite innovative and no operational wind farms have used it so far. However, the concept is similar than the successfully used in the construction of immersed tunnels or oil platform foundations, so the method and techniques have already been tested. Foundation design companies as Seatower or Gravitas have based their solutions in this concept for foundations that may be installed up to 60 m depth.

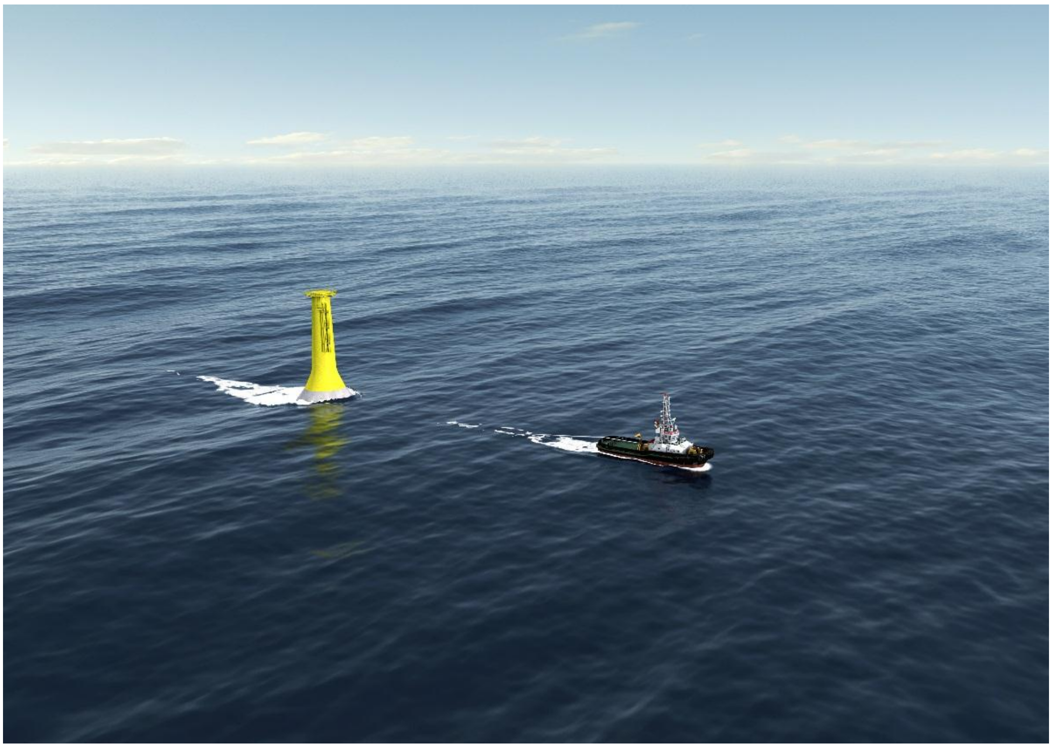

Figure 9: Self-buoyant foundation transport (Seatower, 2012)

The concept is not only for self-buoyant foundations. Some designs may not be completely self-buoyant, or may be self-buoyant in water depths higher than available. In this cases, the procedure is similar, with the difference that auxiliary means have to be used to provide enough buoyancy and ensure stability. This means could be pontoons, floating structures attached to the foundation, specifically designed vessels, or other means. Besides, some completely self-buoyant solutions do not have enough stability, and auxiliary means have to be used to ensure enough stability during the transport by increasing the moment of inertia and the metacentric height of the floating structure.

2.3. FACTORS

In this chapter it will be analysed some important aspects that affects the transportation phase. Thus, the factors analysed have been:

- Transport distance
- Sea and weather conditions
- Time window
- Weight and geometry
- Buoyancy
- Storage

2.3.1. TRANSPORT DISTANCE

The distance from the construction site to the wind farm affects the whole offshore project. Not only the transport procedure chosen depends on the distance of transport, but also the construction procedure and launching operation. Thus, large distances of transport may recommend a group transport in large barges or pontoons if possible, and shorter distances would allow individual transport.

However, the closeness between the wind farm and the construction site is only one factor to consider in the choice of the most suitable harbour, and they are other relevant aspects as harbour logistics, port infrastructure, the location of the suppliers, etc. (Uraz, 2011). This is the reason why in most of the important offshore wind farms with gravity base foundations, the emplacement of the construction site was far from the wind farm location. Thus, in the wind farms of Nysted I (Rødsand I), Nysted II (Rødsand II) and Lillgrund, located in Denmark and Sweden respectively, the construction site was established in the harbour of Swinoujscie, Poland. The foundations were towed about 200 km in a 24 hours trip. It is more impressive that in the under-construction wind farm of Kårehamn (Sweden), the foundations have been carried from the port of Zeebrugge (Belgium), in a trip of about 1,800 km.

2.3.2. SEA AND WEATHER CONDITIONS

Weather and sea conditions pose big challenges for the proper conduct of the operations of transport and installation in offshore wind projects.

The main parameters taken into account to characterise weather conditions are:

- Wind speed
- Visibility
- Wave height
- Wave period
- Tidal currents
- Snow and ice (if necessary)

The suitable conditions must be set in each case, and it will depend on the type of transport, the design of the foundation, and other parameters. Thus, a group transport in barges will admit less demanding requirements than an individual transport, as the stability of the former is higher.

Although it varies in each project, some publications establish as a guideline a maximum sea state of 1.5 meters of wave height (significant Hs) for the transport operation (Herman, 2002). *COWI A/S*, company involved in most of the offshore wind projects that have used gravity base foundations, have provided the information of a limiting wave of Hs < 2 m from previous experiences. Therefore, and always considering that the typology of transport and design of the foundation will determine more accurate numbers, it can be assumed as a guideline limiting wave heights of 1,5 – 2 meters (Hs). These values are the same than the one used for maintenance operations (Carbon Trust, 2012). Some innovative designs enable higher wave heights, as *Gifford – BTM* design (up to 3 meters) (Gifford & BTM, 2009).

2.3.3. TIME WINDOW

Also called “weather window”, it means the amount of time required with suitable conditions to complete the operation safely. Time window in this case is the amount of time required with adequate sea and weather conditions to carry out the transportation and installation of the foundation. Regarding transport, the time window depends mainly on the two previous commented aspects: transport distance, and sea and weather conditions. The weather window must be calculated accurately to avoid possible problems both during the transport and on site.

The next table shows an example of a persistence table in a location in front of the Dutch coast. This table shows the likelihood of occurrence of a significant wave height during a minimum length of window. Thus, the percentage of occurrence of a significant wave of 1.5 for at least 36 hours is 29 %.

AMETS Persistence Table

Significant Wave Height (m)	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
3	64	63	62	61	60	58	57	56	55	54	53	52	51	50	49	47
2.9	62	61	60	59	57	55	55	53	51	50	49	49	49	48	47	46
2.8	60	59	58	57	56	54	52	49	48	48	47	45	44	44	42	41
2.7	58	57	56	55	53	52	49	48	47	47	46	44	43	42	40	40
2.6	56	55	54	53	51	48	47	46	45	45	43	42	41	41	39	38
2.5	54	53	53	51	48	47	45	45	44	42	42	40	40	38	38	37
2.4	52	51	51	49	46	44	44	43	43	40	39	38	37	36	36	35
2.3	50	49	48	46	44	43	42	42	41	39	38	37	36	35	35	34
2.2	48	48	45	44	43	42	41	40	40	37	37	36	35	34	34	33
2.1	46	46	44	42	42	41	41	39	38	36	36	35	33	33	33	33
2	44	43	42	41	40	39	38	37	36	35	34	31	31	30	30	30
1.9	42	40	39	39	38	38	36	34	33	32	30	30	27	27	27	27
1.8	39	38	37	36	36	35	34	33	31	31	30	27	26	26	26	26
1.7	37	36	35	34	34	33	32	31	30	29	27	24	24	24	24	23
1.6	35	34	32	32	32	31	30	29	28	27	25	23	22	22	22	22
1.5	32	31	31	31	29	29	28	26	26	24	21	21	20	19	19	19
1.4	30	29	29	28	28	27	26	25	23	21	20	19	19	19	19	16
1.3	28	27	26	26	26	25	22	22	20	19	18	17	17	17	16	13
1.2	25	24	23	23	23	20	18	17	15	14	14	14	14	13	12	11
1.1	22	21	21	20	18	16	15	13	13	13	13	12	11	10	9	8
1	18	18	17	15	14	12	10	9	9	9	9	8	8	8	6	6

Minimum Length of Window

% Occurence

Figure 10 Example of persistence table. (O’Connor, et al., 2012)

The seasonality of these values is significant, and the next graph shows an example of how the mean wave height in the coast of Netherlands varies in a year.

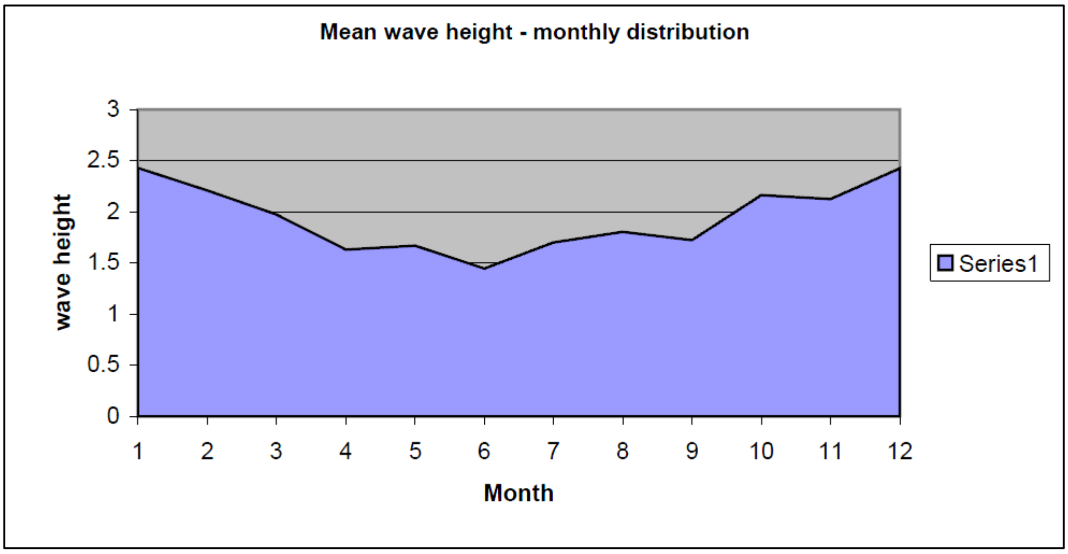

Figure 11 Mean wave height monthly distribution. (Herman, 2002)

2.3.4. WEIGHT AND GEOMETRY

Gravity base foundation are enormous structures whose weight and geometry are a challenge for engineers. Currently operational wind farms have used foundations that weight up to 3,000 tonnes empty, and whose height reaches more than 40 meters. The coming foundations, designed for deeper waters are expected to weight up to 7,000 tonnes empty with a height of more than 60 meters.

The transport of so heavy loads are not a problem, as it has been used pontoons capable of bearing 24,000 tonnes. The problem is that if it is used a pontoon or barge to carry several foundations, a heavy crane vessel must lift the foundations and install it, and there is no suitable means to do so. The heaviest foundation installed so far weighted about 3,000 tonnes, and it was installed by RAMBIZ, whose lifting capacity is 3,300 tonnes. There are only 6 heavy crane vessels in the world capable of lifting more than 7,000 tonnes, and not all of them are adequate to transport or install gravity foundations. This gives an idea of the low availability of this kind of specific vessels, the high costs of using them, and the risks of being so dependent on them.

There are not many solutions to this problem. One of them may be submersible barges or pontoons, so that once on the wind farm, the pontoon is submerged, and with the foundations partially submerged, the lifting capacity required to position the foundation is lower. But the trendy solution to this problem is to build self-buoyant or semi buoyant foundations. Thus, for self-buoyant solutions the transport could made by standard tugs, helped by other auxiliary means, and for partially buoyant solutions the foundation auxiliary means give enough buoyancy to the solution, that can be carried by tugs, or special vessels designed to transport them.

2.3.5. BUOYANCY

It has already been mentioned the reasons why foundation design companies are basing their coming foundations on buoyancy concepts. These concepts are based on the Arquimedes principle and its calculation is quite simple. The main parameters to understand the buoyancy and stability of a foundation are:

- **Centre of gravity**: It is the point where all gravity forces can be simplified in one downward force acting through it. The centre of gravity will influence the stability of the foundation, and in general, the lower the centre of gravity, the more stable the foundation is.
- **Centre of buoyancy**: The upward buoyancy force on an object acts through the centre of buoyancy, and it is also the centre of mass of the displaced volume of fluid.
- **Draft**: It is the distance from the waterline to the deepest point of the foundation. The accurate calculation of the draft is very important since so big buoyant structures will have significant draft values and therefore they will require significant water depths both in the construction site and during the transport. Some future buoyant foundations are expected to reach drafts of more than 15 meters. So import values will affect both the election of the construction site and the transport process.

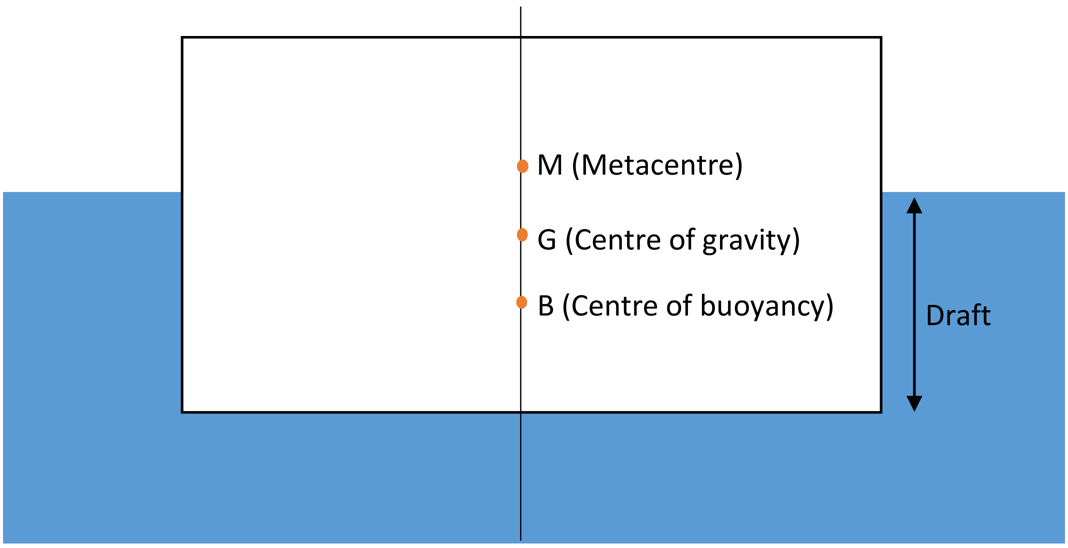

Figure 12: Buoyant body centers diagram

- **Metacentric height**: This parameter is used to assess the stability of a buoyant structure. If a buoyant body is slightly rotated, the centre of buoyancy generally will shift (depending on the shape of the body and the position in which it is floating). The intersection of the lines of action of the buoyant force before and after the rotation is called metacentre "M" and the distance G-M is called the metacentric height. If the metacentric height is positive (M above G), the body is stable, because a rotation will trigger a restoring moment. If the metacentric height is negative (M below G), the body is unstable, since a slight rotation will produce an overturning moment. Spanish guidelines for the design and execution of reinforced concrete floating caissons for sea works recommends a minimum value of 0.5 meters, but the different characteristics of these structures would recommend the use of higher values. Buoyant gas platforms foundations uses metacentric heights of at least 1 meter. (O´Riordan, et al., 1990)

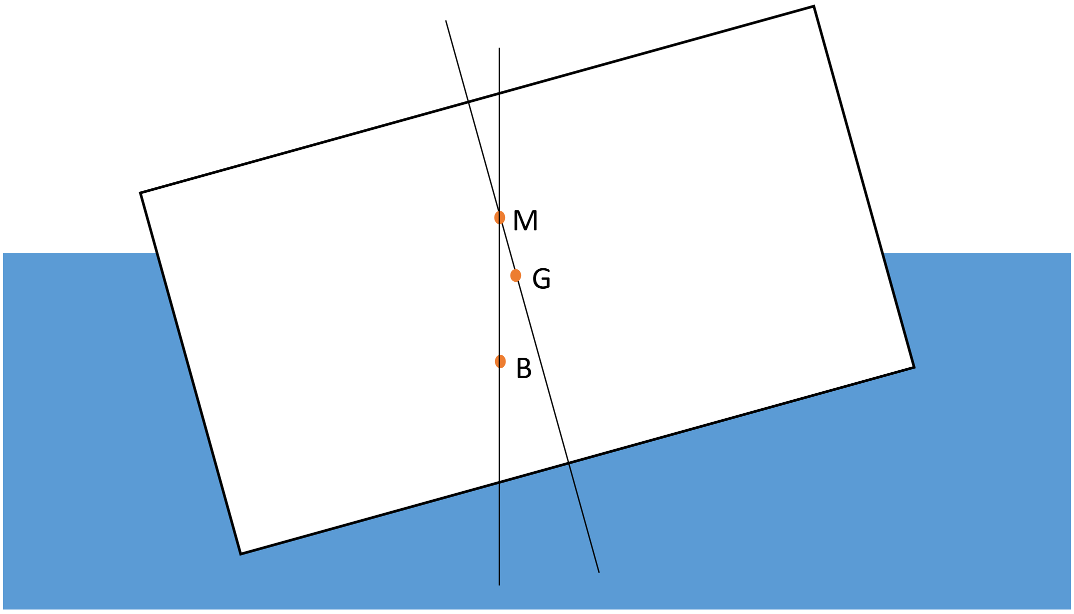

Figure 13: Stable buoyant body

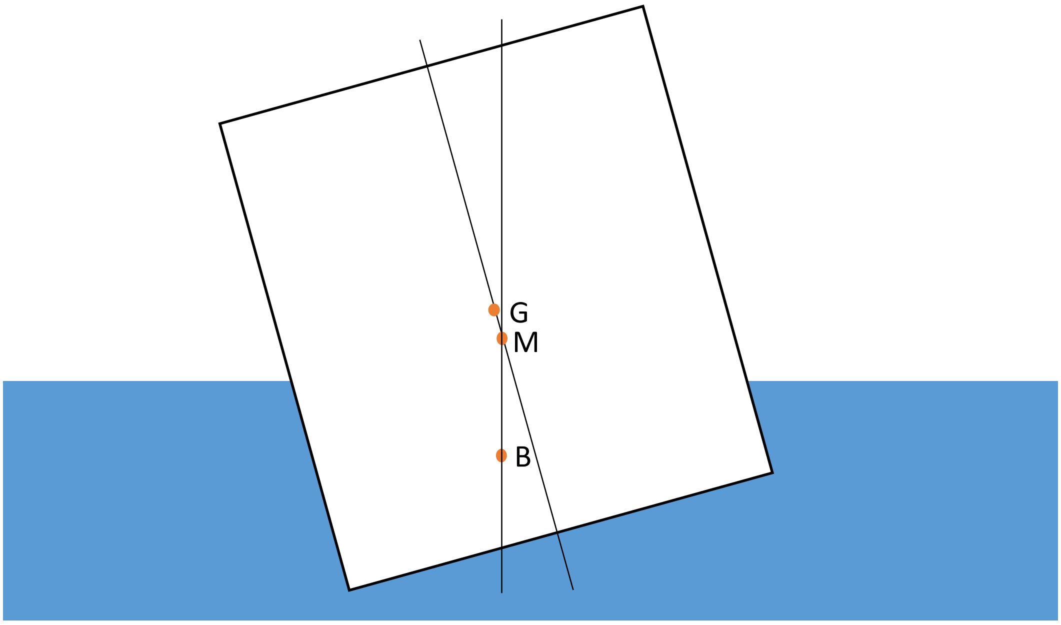

Figure 14: Unstable buoyant body

- **Moment of inertia on the water plane**: The moment of inertia of the waterplane about the centreline (I_{WPAXX}), is a measure of roll resistance, and it is also an important consideration for small-angle stability.

Some self-buoyant foundations are able to be towed only by standards tugs, but sometimes they need auxiliary means for three main reasons:

- The foundations are buoyant but the draft is too high for the available depth
- The foundations are not completely buoyant for a safe transport
- The foundations are buoyant but with not sufficient stability.

In all these cases auxiliary means are required. Some foundation design companies as VINCI have proposed the construction of a specifically built barge to give enough stability and buoyancy to their solutions. A specifically designed floating device does not have to be costly, as its only purpose would be provide enough buoyancy and improve the stability of the system, being the technical requirements low.

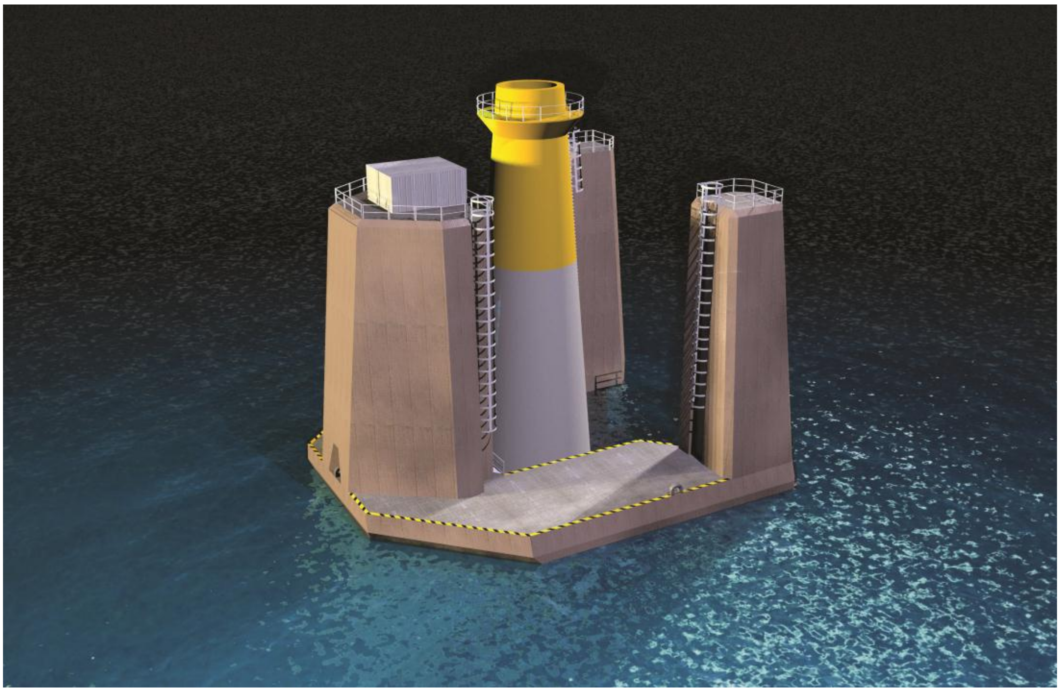

Figure 15: VINCI solution transportation (GBF, 2013)

An alternative solution is the use of pontoons, which attached to the foundation would improve the buoyancy and stability of the system during the transport. The use of pontoons for transporting buoyant structures is not new, as in the construction of immersed tunnels this method is used for the transport and installation of the sections.

Both with a specifically designed device and with the addition of pontoons, these auxiliary means would be an important part in the installation of the foundation.

2.3.6. STORAGE

In case of bad weather, some foundations have the possibility of being safely stored in the sea and refloated later. The technique has already been used in the construction of ports with floating caissons. This feature has some advantages:

- The foundation could be stored in the sea close to the construction yard for several reasons: the transportation is not possible for bad conditions, transport vessels are not available, facilities problems, etc. As the foundation is stored in the sea, the construction yard is not occupied so the construction is not interrupted.
- The foundation could be stored in the sea during the transport phase for bad weather / sea conditions or technical problems during the trip.
- The foundation could be stored in the wind farm before installing for bad weather / sea conditions or technical problems.

Having the possibility of leave the foundation on the seabed temporarily could reduce the time window required, the risks, the waiting times, etc. However, this is not an easy operation so it has to be considered carefully.

2.4. TRANSPORT MEANS

The size and weight of the foundations to be transported makes the transport means a limiting factor for the whole project and an important aspect to consider and plan. The most important transport means are:

- **SPMTs**: Self-propelled modular transporter. They are used to transport the foundation on shore from the construction yard to the quay or the launching area. They consist of a platform vehicle with a large array of wheels commonly used for transporting massive objects in construction.
- **Barges and pontoons**: They have been frequently used for transporting several foundation simultaneously and basically they are floating devices that are able to carry heavy loads. They may be self-propelled or not. In this latter case they are towed by tugs to the wind farm. The capacity of these means is not a constraint as they have already been used pontoons capable of carrying 24,000 tonnes (*"Giant 4").* Some pontoons are semi-submersible to facilitate the unloading of the foundations.
- **Heavy lift vessels**: They have been used both for transporting and installing foundations. Only two vessels have carried out the tasks in all the relevant projects so far: *EIDE Barge 5* (1,450 tonnes of lifting capacity) and *RAMBIZ* (3,300 tonnes of lifting capacity), what gives an idea of the so low availability of these vessels. This low availability makes them means of transport costly and risky.
- **Auxiliary means for buoyant solutions**: They consist of simple floating devices whose purpose is only to increase the buoyancy of a foundation or

improve the stability of a buoyant foundations. They may be pontoons attached to the foundation or specifically built devices.

3. SEABED PREPARATION

3.1. INTRODUCTION

Gravity base foundations are the type of foundations that require the most important seabed preparation as they are heavier and they transfer the loads directly to the seabed surface. The main objectives of this process are:

- Obtain sufficient bearing capacity in the seabed**.**
- Level the seabed in order to ensure that the turbine will stand perfectly vertical.

Seabed preparation is one of the main marine operations to install a gravity base foundation. The site investigation necessary and the enormous dimensions of the foundations (some gravity bases require gravel beds up to the size of a soccer pitch) trigger significant costs. This is the reason why some innovative designs enable less seabed preparation, even avoid it.

In this chapter it will be explained the most commonly used procedures to prepare the seabed, the main aspects of seabed preparation, and the means required.

3.2. SEABED PREPARATION PROCEDURES

3.2.1. STANDARD PROCEDURE

In all the operational wind farms the procedure used to prepare the seabed has been practically the same, and it is based in two phases:

<u>Dredging</u>

The first step is dredging the first layer of material, usually clay or loose sand. Thus, the surface of the seabed is removed until a level where undisturbed soil is found. In some projects, the excavation was performed in two steps, bulk dredging and a final accurate dredging.

The equipment used so far has been predominantly large back-hoe excavators aboard barges and split hopper barges for loading the material excavated. It also has been used hopper dredgers in some projects, which are more suitable for deeper waters.

If the material excavated is adequate for fill in the foundations in the installation phase, it may be disposed nearby in order to use it later, if not, it must be disposed at sea in registered sites.

The thickness of the layer to be removed varies in each project (it depends on the bathymetry, lithology, morphology, geotechnical properties, etc.) and it would ranges from 0.5 to more than 10 meters.

The approximate duration of the dredging of each foundation for a typical installation with 3 meters of average excavation is expected to be 3 – 4 days (Danish Energy Agency, 2013).

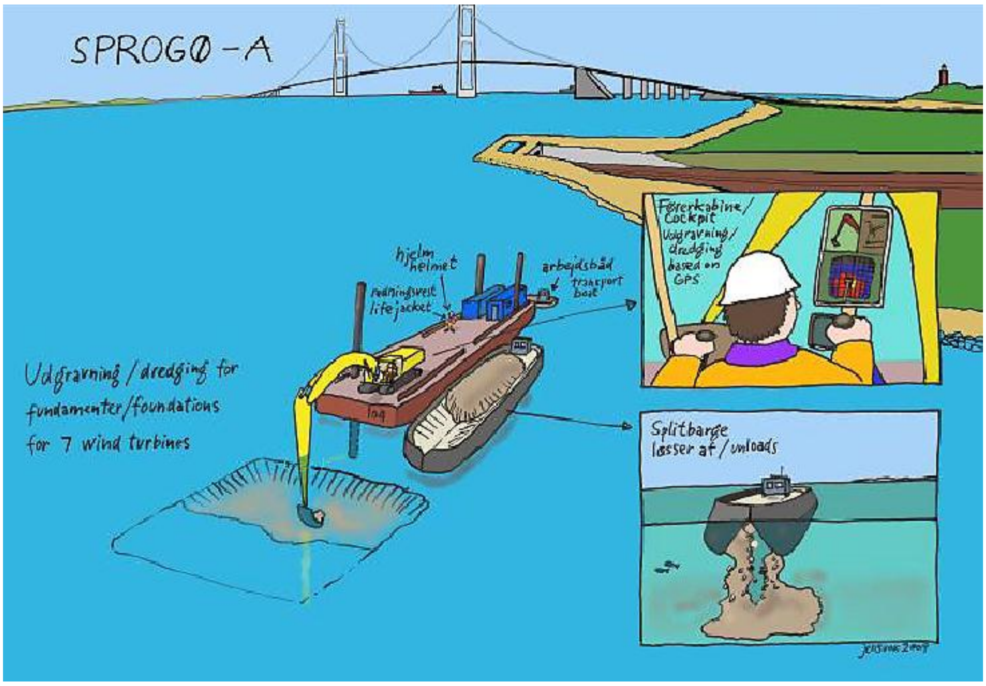

Figure 16: Sketch of a backhoe on a pontoon in Sprogø (ABJV, 2012)

<u>Gravel bed installation</u>

When the suitable level is reached, it is installed a bed of gravel, crashed rock or similar. The most frequently used method is:

1) Lowering a steel frame and a centrepiece to facilitate the process. The exact position is achieved by means of divers and GPS systems.
2) Washing the seabed surface.
3) Filling the frame with gravel, crashed rock, stones, or similar.
4) Divers level the layers by means of a movable boom that rests on the steel frame.
5) Frame removal.

Final compaction may be carried out if necessary, and grout injections are a possibility for specific purposes or problems. In some projects (Middelgrunden) grout injections were required as a consequence of compaction problems.

It has been widely used a configuration in two layers:

- Filter layer (0-63mm)
- Gravel layer (10-80mm)

As indicative numbers, in Thorntonbank, one of the most demanding projects so far, it was installed a filter layer (0-63mm) of about 1,5 meters thickness and a gravel layer (10-80mm) of about 0,7 meters thickness (2,2 meters in total).

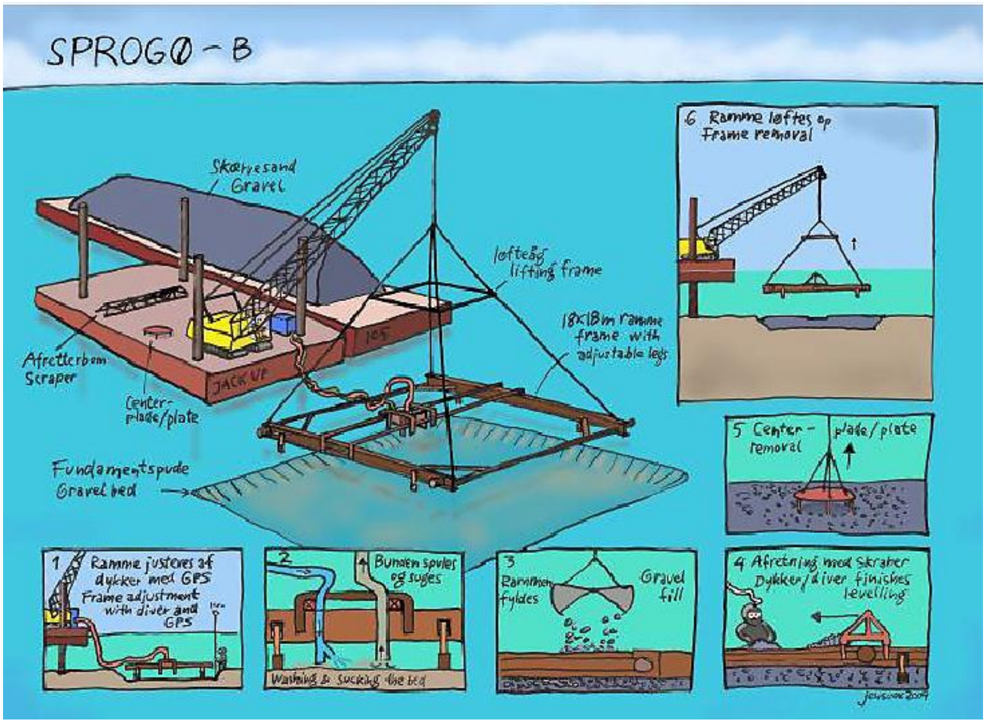

Figure 17: Gravel bed installation scheme (ABJV, 2012)

The surface must be perfectly horizontal with important accuracy (3-5 centimetres average). However, due to the difficulties of achieving so high accuracy it exists several methods to correct slight deviations.

The next table shows as an example indicative values of area prepared, material excavated and gravel bed material for different turbine sizes, assuming an average thickness of excavation of 3 meters.

Turbine size	3.6 MW	5 MW	8 MW
Indicative prepared ground diameter (m)	50	55	60
Prepared seabed area per foundation (m2)	1,963	2,375	2,827
Average soil thickness removed (m)	3	3	3
Material excavation per foundation (m3)	5,889	7,125	8,481
Indicative gravel bed diameter (m)	30	35	40
Indicative gravel bed thickness (m)	2	2.25	2.5
Material for gravel bed (m3)	1,414	2165	3,140

Table 1: Indicative values of prepared seabed area, excavation material and material for gravel bed

The approximate duration of gravel bed installation for a typical wind farm is expected to be 3 days per foundation (Danish Energy Agency, 2013).

3.2.2. SKIRTED FOUNDATIONS

Gravity base foundations require an important seabed preparation that rises the costs of the project. Trying to minimize this operation and optimize the foundation performance, the concept of skirted foundations is starting to be considered for the coming projects.

Skirted foundations are usually circular shaped and includes a “skirt” at the bottom, usually made of steel, that makes the base open. The foundations penetrate partially into the seabed, increasing the bearing area. In these structures, the load is transferred down to lower underlying layers, lateral load capacity is improved by the skirt lateral resistance and the moment load capacity rises. Besides the foundations resists uplift. (Ahmadi & Ghazavi, 2012).

No significant wind farms with gravity base foundations have used this concept so far. However, it has been widely utilized in other offshore projects, as oil platforms. Since 1970, about 30 skirted gravity structures have been installed successfully in waters from 40 to 300 m deep.

Skirted foundations not only improve the structural performance of the foundation, but they also minimize seabed preparation, as they accommodate existing seabed slopes and surface sediments, and allows less demanding properties of the first layers. Other important advantage of this concept, is that it minimizes scour phenomenon, so scour protection is reduced as well.

It is possible to achieve further penetration in the installation phase by pumping water out of the hollow between the seabed and the foundation, creating an underpressure inside. The difference between the hydrostatic water pressure outside the cylinder and the reduced inside water pressure gives a differential pressure that acts as a penetration force in addition to the weight. Besides, this suction effect can be used to control the levelling of the structure, by pumping water from different compartments of the foundation.

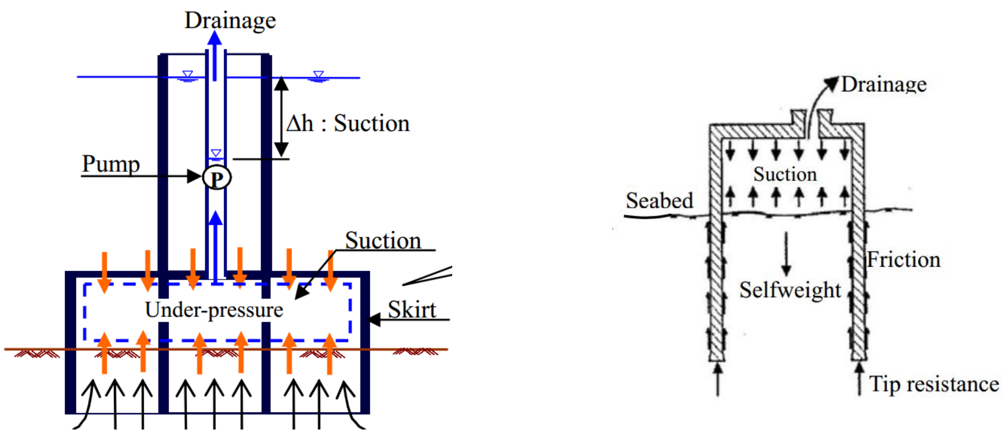

Figure 18: Suction during installation (Saito, et al., 2008)

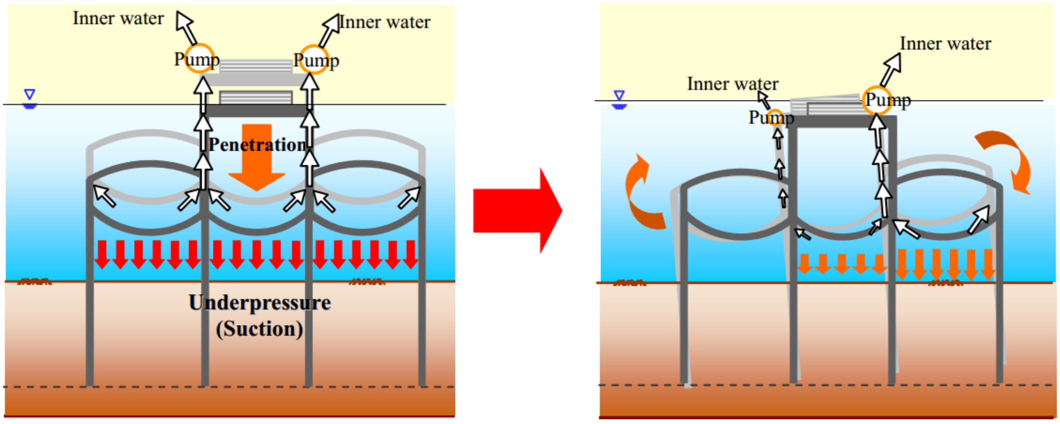

Figure 19: Penetrating (left) and levelling (right) scheme (Saito, et al., 2008)

Furthermore, concrete grout may be pumped to fill the void under the foundation to provide a full contact between the seabed and the foundation. This method has been chosen by *Seatower* for its innovative foundation design *Cranefree*. *ARUP* and *Hochtief* have developed a foundation with the skirt concept as well.

Figure 20: Seatower Cranefree System (Seatower, 2013)

3.3. FACTORS

The main factors regarding the seabed preparation are:

- Site investigation
- Environmental aspects
- Sea and weather conditions
- Material disposal

3.3.1. SITE INVESTIGATION

Site conditions need to be perfectly defined for the design and planning of the seabed preparation, as for other phases of the project. The perfect knowledge of all the characteristics of the seabed, the definition of the various soil and rock information, their physical and mechanical properties and their forecasted behaviour during both the installation and the operation of the turbine will determine the success of the project.

The area of interest regarding offshore wind farms lies in the continental shelf region, with depths that range from 10 to 500 m with an average slope of 1 degree (Puolos, 1988). The soil types along the area of interest are fluvial marine deposits of sand and silt, silt – clay mixtures and clay, as figure 17 shows.

Seabed soils usually are consolidated and exhibit significant compressive characteristics, but they can vary considerably in some areas, as in the UK, where loose sand banks and soft clay are often found at shallow depths (Westgate & DeJong, 2005).

The costs of performing a good site investigation may be significant, typically averaging 1M euro per week, mainly due to the mobilization of the vessels required (Randolph & Kenkhuis, 2001).

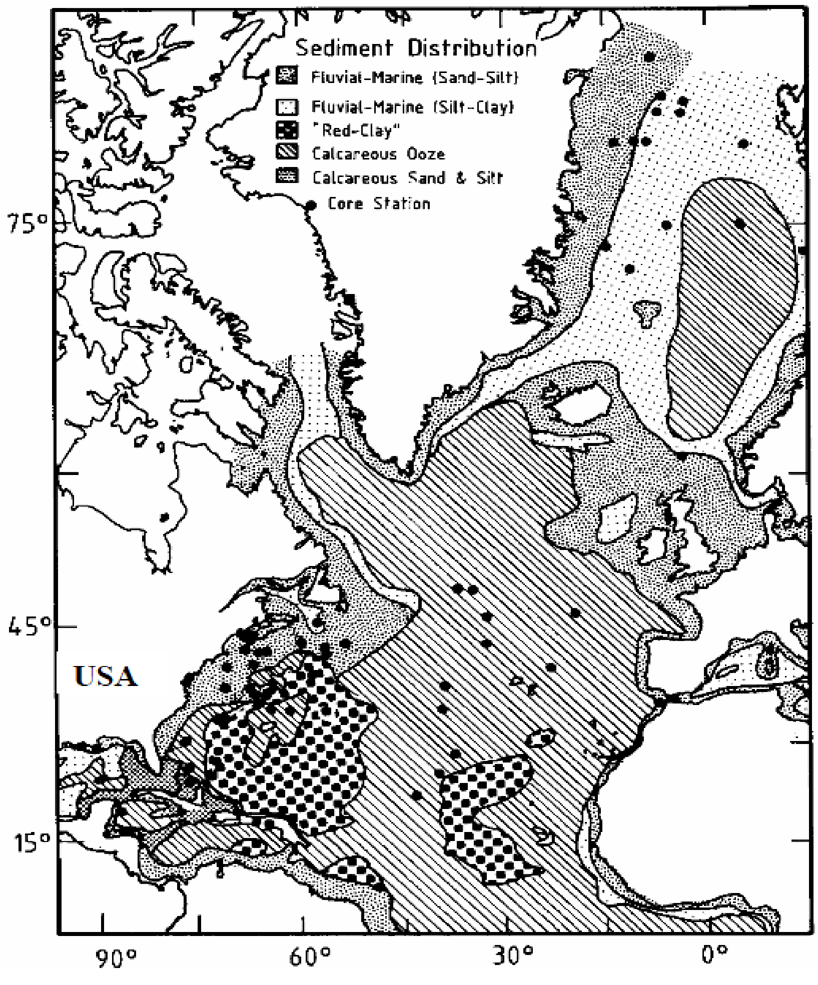

Figure 21: Ocean sediment distribution throughout the Northern Hemisphere (Puolos, 1988)

The characterization of the site properties may be performed through several studies classified in geological studies, geophysical survey and geotechnical site investigation.

- **Geological studies.** They are based on the geological history of the area, and aims at performing a study of the lithology and tectonic structures in the project area as well as the bedding conditions of the soil.
- **Geophysical survey.** It determines seabed topography, morphology and bathymetry, and identifies possible hazards. The seabed bathymetry and topography is determined using echosounding techniques, while seabed morphology is obtained by means of traditional sonars and magnetometers. Sub – bottom information is determined by reflexion seismic systems, refraction high resolution seismic systems and electrical resistivity surveys.
- **Geotechnical survey.** It characterizes the properties of the soil in terms of five main components: macroscopic, microscopic, mechanical, chemical and water content properties.

The most important geotechnical issues of study related with a gravity base foundation installation are: bearing capacity, permanent and cyclic displacements, soil reaction stresses, penetration of skirts, liquefaction potential, scour and erosion. The next table shows a typical geophysical and geotechnical survey. Project specific factors require the addition of further studies.

Survey purpose	Minimum survey area	Means of survey
Bathymetry	Usually 1 km x 1 km in shallow water, 2 km x 2 km in deep water. Possible extension to 5 km x 5 km in areas with geo hazards to incorporate possible platform location shifts etc.	Swath bathymetry, preferably multi beam
Seabed features		Sidescan sonar, line spacing 100-200 m depending on water depth, sonar range set to provide 200 % coverage from line overlap.
Subsurface information		Ultra-high resolution / High-resolution seismic survey for shallow geology and fault offset analysis. Line spacing: 100 m to 200 m depending on water depth. It may be performed simultaneously with sidescan sonar. Besides, 3D exploration seismic data for regional geo hazard analysis and drilling hazard analysis to approximately 1000 m depth

Table 2: Typical scope of geophysical survey for platforms (International Society for Soil Mechanics and Geotechnical Engineering, 2005)

Scope of work	Penetration (m)	Sample testing
1 borehole with continuous sampling down to 15 m, thereafter sampling with less than 0.5 m gaps to 0.5 x to 0.7 x platform diameter, followed by alternate sampling and CPT (preferably (P)CPT) with less than 0.5 m gaps.	1.5 x platform diameter	· Index testing · Triaxial tests · Odometer tests. · Permeability tests. · Simple shear tests and anisotropically consolidated compression and extension triaxial tests, monotonic and cyclic. · Shear wave velocity measurements by bender elements to determine initial shear modulus. · Resonant column tests. · X-ray photographs to determine soil layering within the tube, inclusions, and sample quality. · Radioactive core logging (optional).
3 boreholes with continuous sampling to 15 m, thereafter sampling with less than 0.5 m gaps.	50 m	
10 continuous (P)CPTs	50 m or 1.5 x platform diameter	

Table 3: Typical scope of geotechnical survey for platforms (International Society for Soil Mechanics and Geotechnical Engineering, 2005)

These in situ investigations are about 80% of the costs of site investigation. Laboratory tests, engineering analysis, planning and other studies entails the remaining 20%.

3.3.2. ENVIRONMENTAL ASPECTS

Monopile foundations have been criticized for the environmental damage during piles driving, as the subsea noise from the hammers disturbs marine mammals and other ocean life. But gravity base foundations are not free of environmental concerns, as they normally require an enormous seabed preparation, and the dredging of the seabed disturb the benthos, which may affects the whole habitat. The dredged material disposal is other important issue due the enormous amount of material disposed. On the other hand, the gravel bed could allocate artificial reefs and allow new life. Despite several studies have been carried out about environmental problems of monopile driving, further research is necessary regarding gravity base foundations.

3.3.3. SEA AND WEATHER CONDITIONS

Sea and weather conditions during seabed preparation are a constraint as in all marine operations. Thus, wave heights of 1.5 – 2 m maximum are expected to be required, depending on the specific features of the project and the exact phase. The use of divers for some tasks triggers the necessity of good visibility as well.

3.3.4. MATERIAL DISPOSAL

Loose sand, clay and other unsuitable material dredged range from 6,000 to 10,000 cubic meters per turbine for typical installations (in Thornton bank it was dredge up to 90,000 m3 per foundation), so the disposal of this excavated material is an important economic, environmental and technical issue to handle. The dredged material in the seabed preparation normally is loaded onto split hopper barges. The excavation required for each foundation is expected to produce between 5 and 10 barge loads. Commonly, this material is used later as ballast of the foundation within the structure or as scour protection, so it is disposed nearby. If the material is not necessary for later operation, or is not suitable, it is disposed at sea at registered disposal location.

3.4. MEANS

The enormous dimensions of the seabed preparation for the installation of gravity base foundations makes necessary an intensive use of heavy vessels, barges and other means. The most frequently used for this phase are:

- **Large back hoe on a pontoon:** The installation of a land-type back hoe excavator on a standard pontoon provides a cost efficient and simple mean to perform the required dredging and excavation of the first layers of the seabed. Fix back hoes on pontoons may be used as well. The main drawback is its limitations, as for important water depths it is not feasible. They not only are used for dredging but also for dumping the material back to the sea.

Figure 22: Back hoe on a pontoon (FKAB, 2013)

- **Dredgers:** They are vessels used to excavate and remove material from the seabed. There are many types of dredgers depending on their excavation method. Suction dredgers are the most commonly used for this task due to the characteristics of the first layers to remove. Regarding the disposal of materials, in a hopper dredger the materials goes to an on-board hold called "hopper". If the dredger does not have this storage area, they dispose it in other barges.
- **Hopper barges:** They are used to carry and dispose material. In this case, they are used to store temporarily the excavated material, and dump it in to the ocean where planned, or into the foundation as ballast. Standard hopper barges have on the bottom of the hull a door opening downwards that opens when the barge arrives to the location where the materials must be dumped. Split hopper barges have the same purpose, but instead of the door on the hull, the hull of the whole barge splits longitudinally, so it opens when the material have to be disposed.

Figure 23: Hopper barge (FPS, 2012)

- **Fall pipe vessels:** They are vessels used to dump rocks or gravel on the seabed with high accuracy. They have a flexible fall pipe that allows the installation of gravel / rocks beds for the foundations. "*Seahorse*" is the largest rock-dumping vessel in the world (19.000 tonnes of loading capacity), and it has worked in some of the most important offshore wind projects.

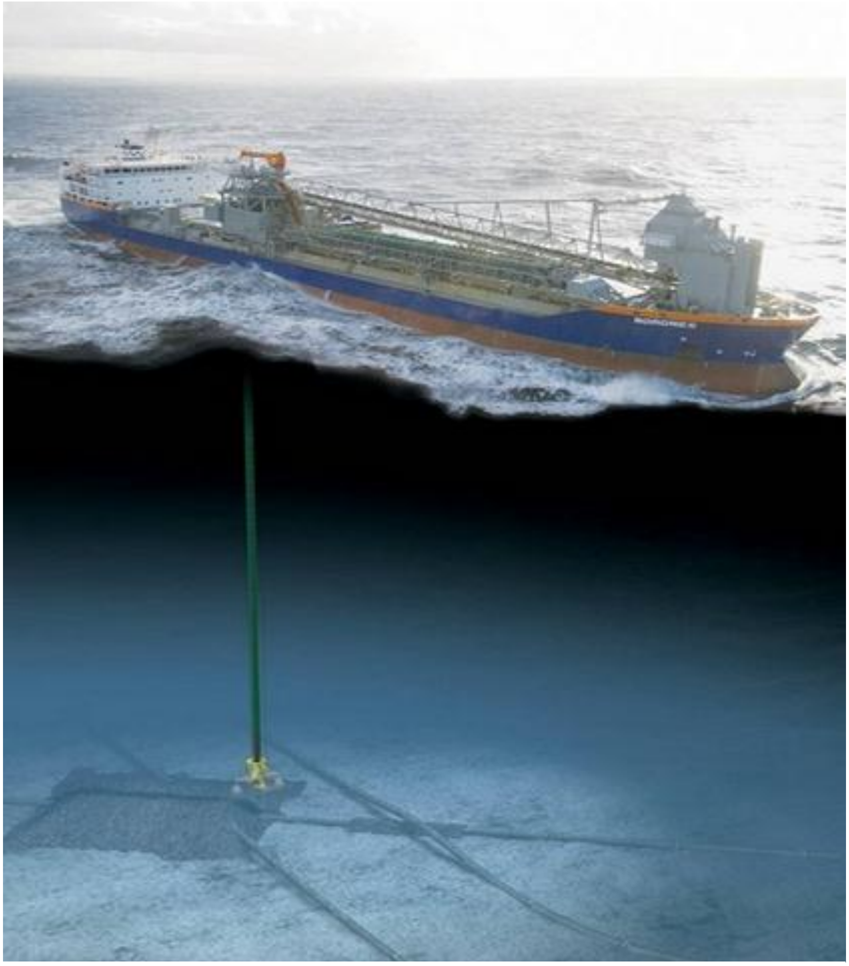

Figure 24: Fall pipe vessel (www.theartofdredging.com, 2013)

- **Divers:** Some operation within the seabed preparation, especially the installation and levelling of the gravel bed, require the skills of professional divers.
- **Positioning and tracking systems:** Most of the vessels mentioned (Dredgers, fall pipe vessels, hopper barges, etc.) require the use of GPS systems, or other positioning and tracking systems in order to achieve the high accuracy necessary.
- **Site investigation vessels and equipment:** To study all the features required for the project not only before the seabed preparation, but also during it.

4. FOUNDATION INSTALLATION

4.1. INTRODUCTION

When the foundation arrives to the wind farm, and after having prepared the seabed, it is time to install the foundation. In this operation, the foundation will be accurately placed on the seabed and ballasted to provide weight enough to withstand the loads. Installation is one of the most delicate phases of the project and requires accurate techniques and procedures. The trend towards the installation in deeper waters triggers bigger and heavier foundations that led to the application of techniques not used so far in offshore wind farms, and the adaptation of procedures used in gas platforms and immersed tunnels.

In this chapter it will be studied both the main procedures of installation used so far and the applicable concepts for the near future, the main factors that affect the installation, and the means required.

4.2. FOUNDATION INSTALLATION PROCEDURES

The installation processes will be studied subdivided in three main operations:

- Positioning
- Hoisting and lowering
- Fillings

4.2.1. POSITIONING

The first step is to place the foundation above its final location. To do so, all the means required are equipped with accurate GPS systems and other positioning and tracking devices. Divers and cameras may be used to monitor the operation.

4.2.2. HOISTING AND LOWERING

This is the main and most demanding operation. Hoisting (if required) and lowering the foundation depends directly on the typology of transportation used, and on the foundation features. Thus, this operation will be different with each transport method:

a) Foundations transported by barges or pontoons

As it has been analysed in the transport chapter, one important type of foundation transport is in groups, on flat-top barges or pontoons. With this method, the foundation have to be picked up by a heavy crane vessel, and then this vessel will lower the foundation to the seabed.

The hoisting operation is the bottleneck of the whole process, as a heavy lift vessel must hoist a foundation that may weigh up to 7,000 tonnes empty, and only half a dozen heavy crane vessels around the world have so huge lifting capacity. To continue allowing the use of this interesting way of transport with the oncoming bigger foundations it must be considered the use of semisubmersible pontoons. This concept is simple and it is based on transporting the foundations in a submersible pontoon that will be submerged with all the foundations so that the weight to be hoisted is lower. The wind farm of Rødsand II used this technique.

Figure 25: Pontoon partially submerged in Rødsand (ABJV, 2012)

The lowering phase is usually carried out in two steps. Firstly the foundation is lowered above its final location, and after checking the position, it is lowered slowly the last centimetres. In the wind farm of Sprogø, the processes of hosting and lowering the foundation lasted from 12 to 18 hours.

b) <u>Foundations transported by heavy lift vessels</u>

In this case the heavy lift vessel performs the whole process. It hoists the foundation directly on the quay and transports it to the wind farm, where the foundation is lowered in the same way as the previous procedure.

Figure 26: Foundation transport and installation by RAMBIZ (Scaldis, 2012)

c) Buoyant foundations

The installation of buoyant foundation is a challenge for engineers. The process is less dependent on unavailable huge means but, on the other hand, it is a technically more difficult procedure. No operational wind farms have used this procedure yet, but the trend is towards buoyant solutions and the technique has already been used in the construction of immersed tunnels or gravity foundations for oil and gas platforms.

There are two basic operations in the lowering of a buoyant solution: flooding or ballasting (usually with water), and the position control. Regarding the former, buoyant foundations have compartments uniformly distributed that would be flooded symmetrically. As the foundation weight rises, it descends onto the sea bed. The position is controlled by means of towing vessels with the help of anchors, or by means of pontoons.

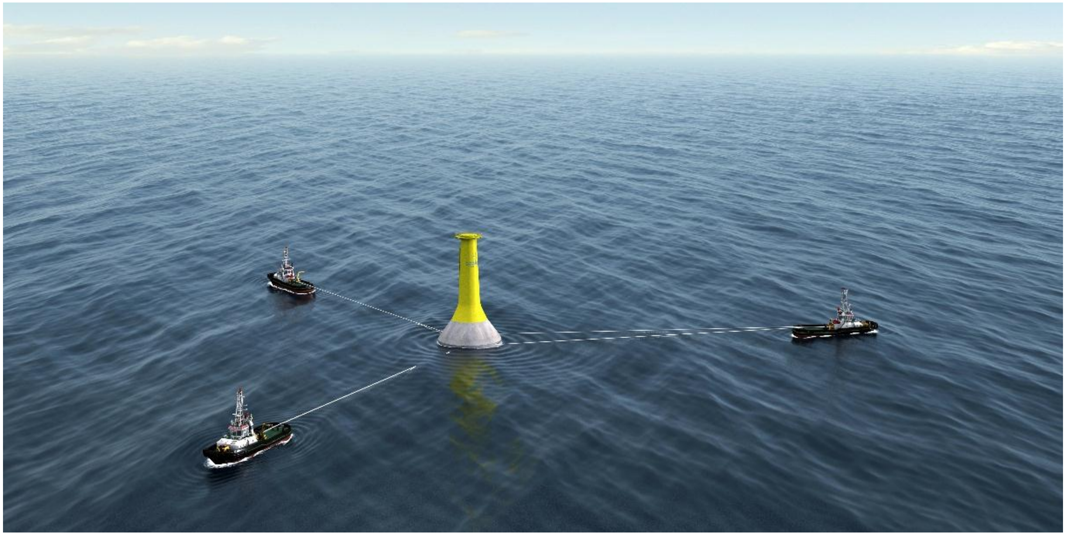

Figure 27: Simulation of foundation lowering controlled by three vessels (Seatower, 2012)

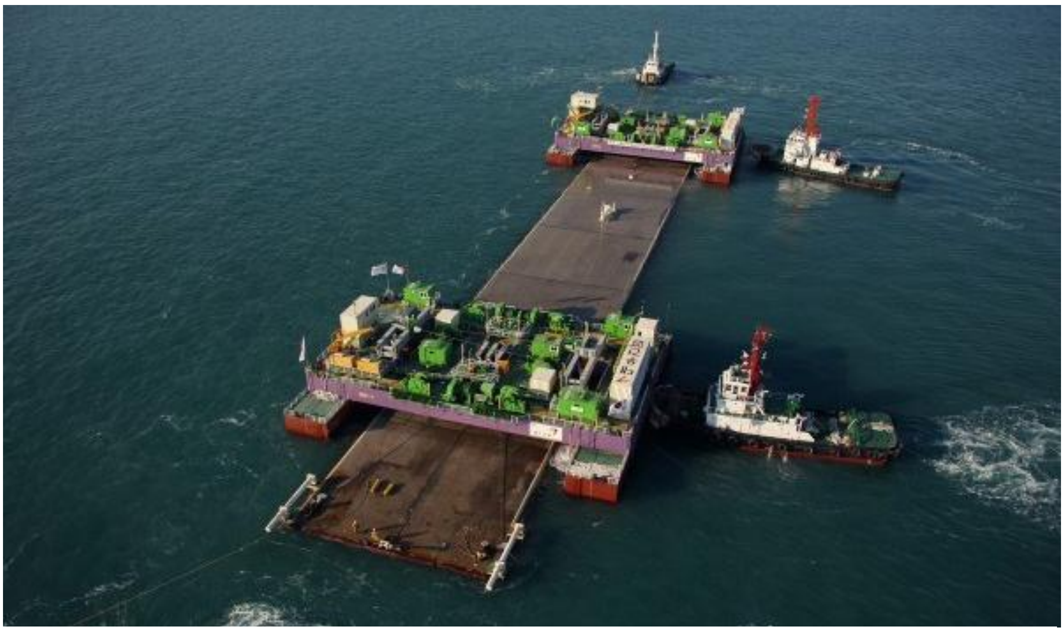

Figure 28: Immersed tunnel installed by pontoons (www.struktonciviel.com)

For oil prospections, the majority of GBF have been installed using parallel installation methods, but it is also possible an inclined installation, that offers some advantages. As it has been commented before, floating stability is ensured when the metacentric height is positive (0.5 – 1 meter minimum is recommended). The parallel lowering produces a significant drop in the metacentric height when the top of the caisson passes below the water line, and the platform becomes unstable. Inclined descent produces a stable descent, as it get benefit from the moment of inertia of the area of the inclined shaft as it passes the water surface. Besides, inclined installation avoids the need of expensive dense ballast to lower the centre of gravity (O´Riordan, et al., 1990). On the other hand, the procedure is technically more complicated and risky, the structure suffers more during the installation and the seabed may be damaged both as a consequence of the important forces at touchdown and due to scour erosion during the installation. The inclined installation is achieved by flooding the compartments in a predefined sequence.

Figure 29: Inclined installation method in Sakhlin 2 (Vinci Ventus, 2010)

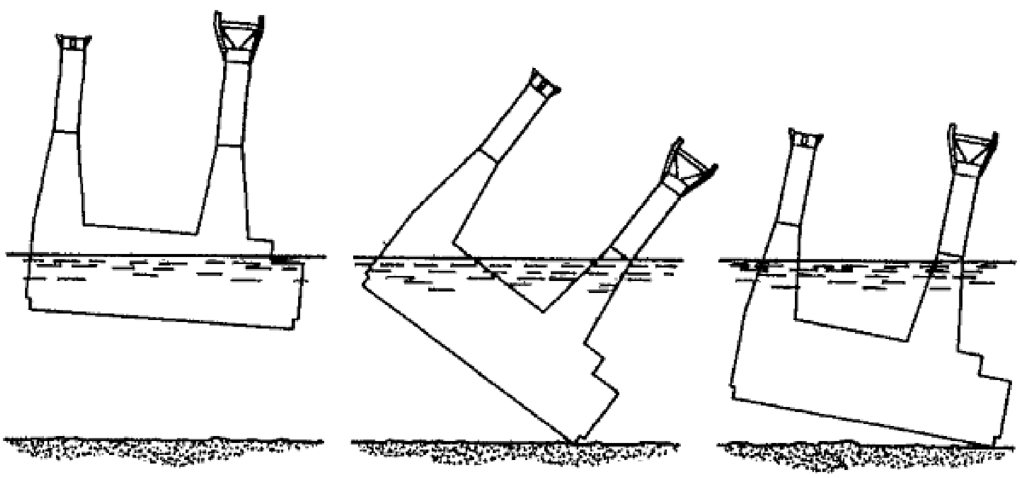

Figure 30: Inclined installation steps scheme (O´Riordan, et al., 1990)

The following graph, drown originally by O´Riordan, et al. (1990) shows how the metacentric height varies during the descent of the foundation. As a model for the calculations it was chosen a basic foundation composed of a cylindrical caisson and a cylindrical shaft. The caisson measures 35 m diameter and 10 m high, and the water depth is 25 meters. It can be seen how with a parallel installation the metacentric height drops drastically as soon as the caisson passes the water line, reaching negative values, which means the instability of the foundation. In contrast, with an inclined installation the structure remains stable the whole decent.

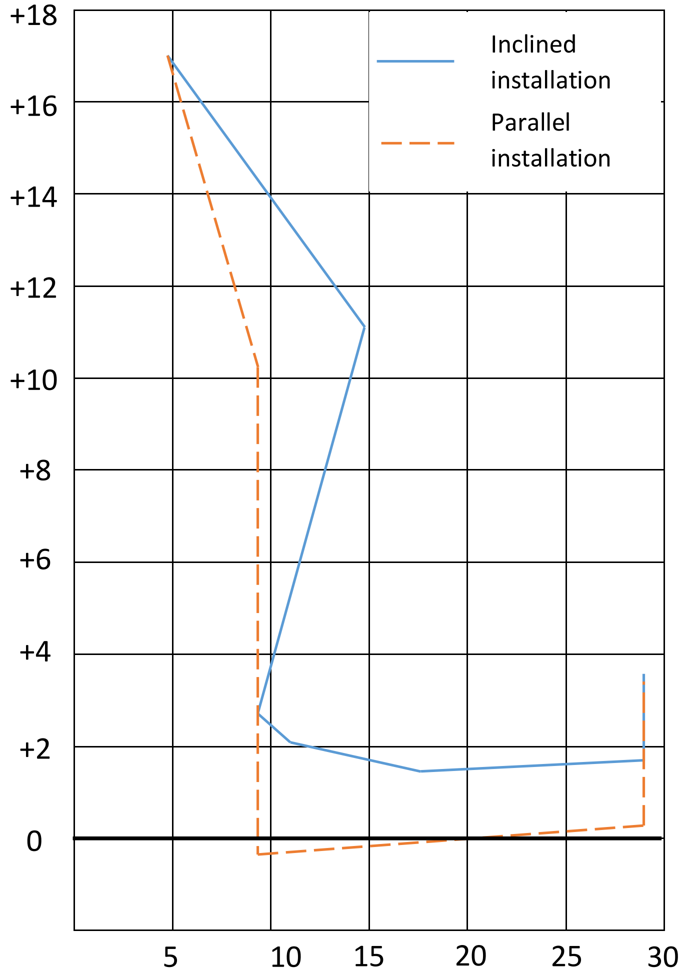

Figure 31: Metacentric height during installation

c) Skirted foundations

Skirted foundations concept has been introduced in previous chapters. This technique have not been used yet in the installation of offshore wind farms. However, the concept is basic in foundations for offshore oil platforms, and some designs for future wind farms include this technique. The installation procedure of skirted foundations depends, as in the not-skirted foundations, on the method of transportation, but what makes different the foundation installation is the last centimetres of lowering, where the skirt penetrates the seabed. This part of the installation is the most delicate, as several factors must be monitored and controlled: penetration rate, inclination, liquefaction phenomena, etc.

One of the main parameters to consider in the installation of a skirted foundation is the penetration resistance. Lunne and St John (1979) gave a relationship for skirt penetration resistance per run of skirt, which formed the basis of DnV and API rules:

$$Q = k_t \cdot q_c(d) \cdot A_t + \int k_f \cdot q_c(z)$$

- k_t and k_f are empirical coefficients.
- $q_c(d,z)$ are the net cone resistance at a total depth d and intermediate depth z.
- A_t is the area of the skirt per m run.

With skirts of 15 and 30 mm thickness, Lunne and St John reported the following values of k_t and k_f:

	k_t	k_f
Clays	0.4	0.03
Sands	0.6	0.003
Mixed layers	0.5	0.014

Table 4: Reported values of k_t and k_f (O´Riordan, et al., 1990)

These values were obtained with skirt penetration rates from 0.004 to 0.019 cm/s. Gravels and clean sands are not very sensitive to penetration, but with clays, the values can vary significantly.

The penetration rate is controlled primarily by controlling the rate of ballasting. When the foundation is penetrating vertically, the void under the foundation has trapped water. This water must be pumped out to avoid liquefaction in the surface sands and bearing capacity failure of soft clay. The water volume and pressures inside the skirted compartments must be controlled, intending to cause a local bearing capacity failure around the skirt to facilitate its penetration (O´Riordan, et al., 1990). The different pressures create a suction effect that allows the penetration to stronger strata and a better control in the levelling, as it was explained in previous pages.

Furthermore, grout injections may be carried out in the interface between foundation and seabed to improve the contact surface.

4.2.3. FILLINGS

Gravity base foundations normally are enormous hollow structures where the structural weight is intended to be as small as possible due to the difficulties to transport and install them, and the massive means required to do so. The required final weight to withstand the loads is achieved by ballasting the foundation. There are two main types of fillings:

- **Backfilling:** After the foundation is placed, the foundation pit dredged in the seabed preparation phase is filled. The material used is usually sand or gravel, sometimes from the previous excavation, but it also has been used rocky material. Some designs have a base plate so that the backfill material covers this plate and gives the foundation uplift resistance.
- **Infilling:** The hollow shaft (and compartments in some designs) are filled as well. Normally the material used is sand, gravel or rocky material. In the case of using sand, it has to be re-mixed in the vessel with water so that it can be pumped into the foundation. However, in Kårehamn, an under construction offshore wind farm, it is being used crude iron ore, with higher density than gravel or rock. In oil platforms foundations it is not rare the use of dense ballast in order to lower the centre of gravity for stability reasons during the installation

4.3. FACTORS

4.3.1. SEA AND WEATHER CONDITIONS

As in the transport phase, sea and weather conditions are of vital importance in the installation of the foundations, especially in the lowering phase. The main parameters to characterise sea and weather conditions are the same than in transportation: wind speed, visibility, wave height, wave period, tidal currents, snow and ice. Underwater visibility may be necessary as well in some phases of the installation.

As some examples, in the Nysted I wind farm, the heavy lift vessel “EIDE barge 5” worked with 0.8 meters of wave height (Vølund, 2005). However, better anchors and winches, and other installation vessels could allow severer conditions. Furthermore, the important company *COWI A/S* have reported that the limiting wave from previous experiences in the installation of foundations have been Hs < 1 – 1.5 meters. *Strabag*, a company that has designed an interesting solution that weights up to 7,500 tonnes completely assembled and can be placed in water depths of about 40 meters, says that using a DP2 positioning system and a heave compensation in the winch system they are able to install the foundation with a sea state of 2.5 meters of wave height (significant), what seems to be quite optimistic. Gifford design allows significant wave heights up to 1.25 meters (Gifford, 2009). As for the tidal currents, the values allowed for the lowering have to be considered carefully, as the positioning of the foundation on the seabed is a critical operation and high accuracy is required. The next figure shows the distribution of tidal currents in the North Sea, one of the most interesting areas in Europe for the implementation of offshore wind farms.

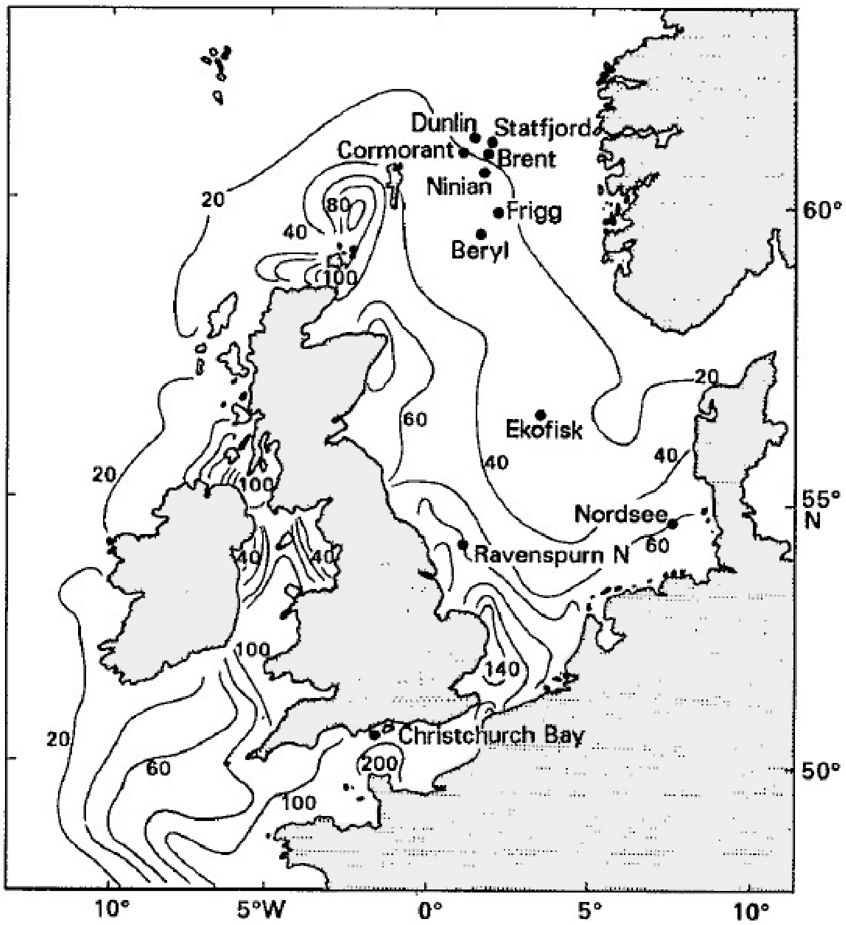

Figure 32: Distribution of tidal currents in the North Sea in cm/s (Partly after Dyer, 1980)

4.3.2. TIME WINDOW

Time window refers to the amount of time required with adequate sea and weather conditions to carry out the transportation and installation of the foundation. The time required to install the foundation depends on several factors: sea and weather conditions, water depth, technical difficulties, type and design of the foundations, etc.

The time to install a foundation must be determined in each case, but as a guideline, the time required to install completely Nysted I foundations ranged from 6 to 24 hours, so the time window necessary with suitable conditions including transport and installation was from 30 to 48 hours for each foundation.

4.3.3. WEIGHT AND GEOMETRY

It has already been commented that weight and geometry of the foundations are an important constraint and they will determine not only the transport method but also the installation techniques. Thus, the weight of the coming foundations makes impossible the application of some installation procedures used so far, and most of the new designs are based on buoyancy concepts, and sometimes on purpose-designed floating devices both to provide enough stability and buoyancy to the foundation and facilitate the installation process.

The geometry of the foundation is an important factor as well, as it will determine the stability of the foundation, especially during the descent. It has already been explained how in foundations based on a caisson and a shaft, the metacentric height drops drastically when the caisson passes the water line. This effect is more important in deeper waters, as the shaft is higher, what rises the centre of gravity and lowers the metacentric height. Inclined installation and conical shaped foundations avoids this problem.

4.3.4. ENVIRONMENTAL ASPECTS

It has been mentioned in previous chapters the environmental advantages of gravity foundations in the installation phase, as in monopile foundations, pile driving may disturb ocean life. This advantage is partially compensated by the environmental damage in the seabed preparation.

4.4. MEANS

The most important means used for the installation phase have already been mentioned in previous phases, so it only will be commented briefly. These means are:

- **Heavy lift vessels:** Used to install not buoyant solutions. “Rambiz” and “Eide Barge 5” have carried out the installation of all the gravity foundations for offshore wind farms so far.
- **Tugs:** Used to control the position of some buoyant solutions while lowering.
- **Pontoons:** Used to control the position and stability of some buoyant solution while lowering. They also are used in the filling phase.
- **Dredgers:** To dredge the sand required for the fillings.
- **Spreader pipe / fall pipe systems:** To spread the backfilling.
- **Divers:** To monitor and control the whole phase, and install the J-tubes.

5. SCOUR PROTECTION

5.1. INTRODUCTION

The placement of a gravity base foundation in the seabed modifies the flow of the water, triggering sediments movements around the structure that was firstly reported by Dahlberg (1983). The study of this phenomenon and a correct design of the protection against its development is required for the success of the project. Although there are some methods to predict the scour and the protection behaviour they are still in its early stages and specific hydraulic model tests are necessary in each project.

5.2. SCOUR BASIS

Scour is an erosion of sediments in the seabed that occurs around a fixed structure, in this case the foundation, which can cause a bad support of the foundation on the seabed. The increase in the sediment transport capacity around the foundation is due to three main events:

- Increase in the flow velocity due to the flow contraction
- Development of horseshoe vortex
- Increase of turbulences

This phenomenon is possible both during the installation of the foundation and after the installation.

During the installation phase, the main effects of scour are scour during the initial touchdown and scour on completion of installation. It has been experienced scour erosions up to 2 meters depth only 16 hours after touchdown, so scour protection must be installed immediately after installation at the most vulnerable locations: corners and skirt (in skirted foundations). The scour erosion during the installation can be severer in inclined installation under the leading skirt (O´Riordan, et al., 1990).

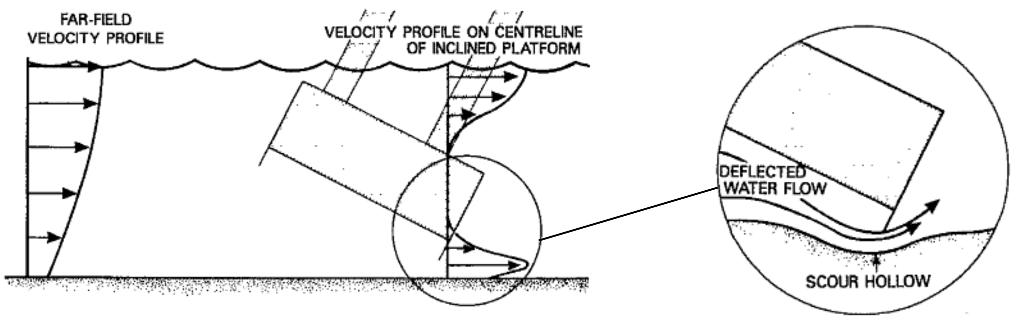

Figure 33: Scour during inclined installation (O´Riordan, et al., 1990)

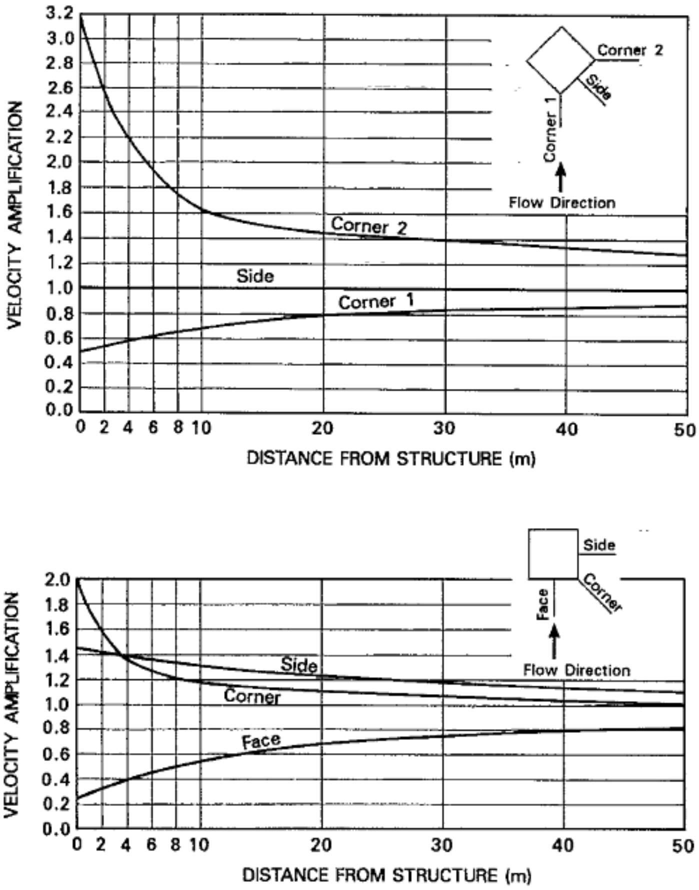

Figure 34: Velocity amplification around a square foundation (O´Riordan, et al., 1990)

When scour is considered as a possible issue, the next step to assess the scour hazard is the prediction of the scour depth. In gravity base foundations, the scour event is related with the diameter (or length of side) of the foundation (Dc) and the height above the sea level (hc). The geometry of the foundation is also very important (Whitehouse, 2011).

There are many predictions of scour depth. Rudolph et al. (2005) proposed a basic formula for a first estimation of the maximum scour depth:

$$Smax = K \cdot hc$$

Where K is a dimensionless coefficient ranging from 0.2 to 2.

However, the process is so complex that predictions are not feasible enough, and normally specific hydraulic model tests are required to assess the scour in the project conditions for the designed foundation, and test the scour protection.

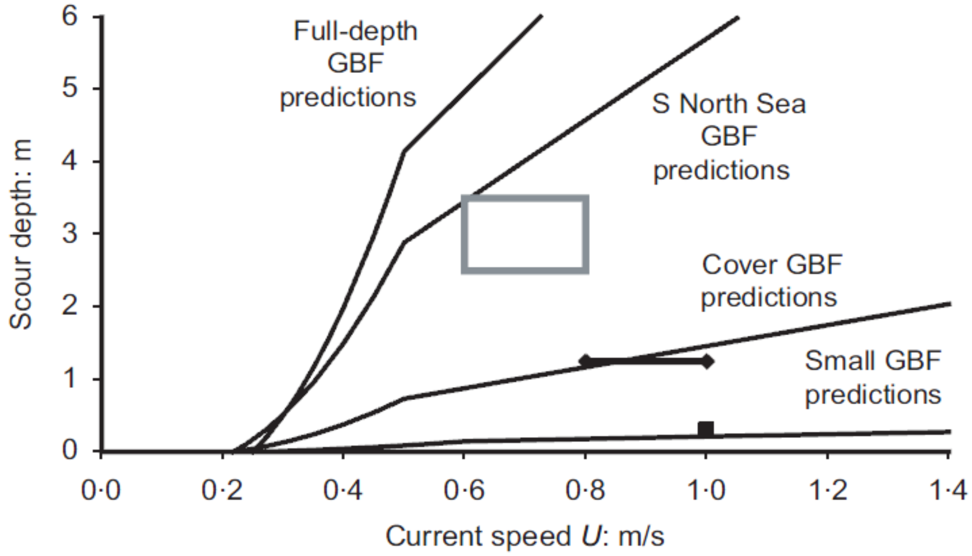

Figure 35: Observed and predicted scour for the range of typical foundation geometries (Whitehouse, 2011)

5.3. SCOUR PROTECTION

In most cases, scour protection is necessary to avoid erosion around the foundation. The prediction of the scour protection behaviour –as the prediction of scour erosion- is difficult, and generic solutions are not available, so the design of the scour protection needs to be quantified in laboratory hydraulic model tests. The main types of scour protection are:

- **With rocky material**: The most commonly used scour protection is achieved through the placement of rocky material armour with appropriate grading, and filter criteria to resist loss of soil. The previous seabed preparation also helps avoiding scour erosion. One of the most important examples is Thornton Bank, where the scour width expected reached 25m downstream in the wake areas, triggering an overall scour protection diameter of 2.5 Dc (diameter of the foundation base) (Whitehouse, 2011). In Thornton Bank it was installed a scour protection based on two layers of rocky material: one filter layer (0-120 mm), of 0.6 m thickness, and one armour layer (20% of 5-40 kg and 80% of 200 kg) of 0.7 m thickness, reaching 1.3 m thickness it total.

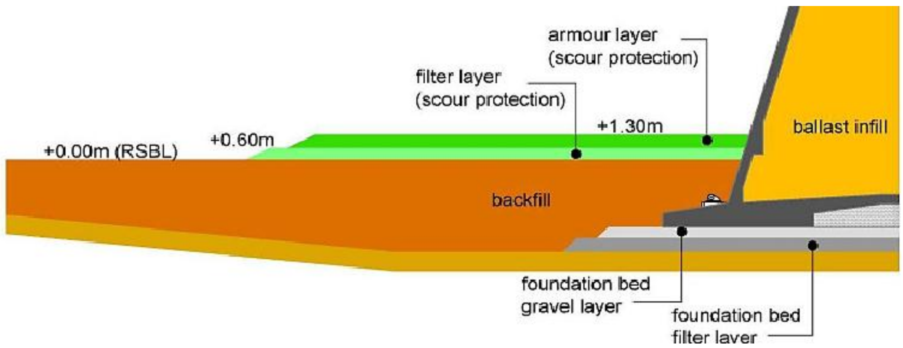

Figure 36: Scour protection in Thornton Bank (DEME 2008)

Figure 37: Scour protection in Thornton Bank (DEME, 2008)

- **With concrete blocks**: Rocky layers of scour protection may be replaced by concrete blocks due to economic and environmental reasons. Besides, concrete blocks can be shaped with almost any geometry.
- **With “Big bags”**: Also called gravel bags. They are sand or gravel-filled geotextile containers that are used as scour protection. Three parameters can be chosen in each project: volume, aspect ratio and type of textile. The material used sometimes comes from the seabed excavation. Their cost is highly competitive.

Figure 38: Scour protection hydraulic test for Strabag foundations (Mayumi Wilms, et al., 2010)

- **Skirts**: Skirted foundations are not a scour protection itself, but studies have demonstrated that although they does not prevent scour from occurring, they help minimizing the effects of scour erosion (Whitehouse, 2011).
- **Other methods**: Although they have not been used yet in gravity foundations, they have been tested successfully in other types of foundations and their principles are interesting for the future. Scour protection with composite and rubber mat and a protection with a collar are some of them.

Figure 39: Scour protection with composite and rubber mat tests (Deltares, 2010)

5.4. FACTORS

Some of the main factors that affects the scour are:

- Geometry of the foundation
- Seabed Material
- Marine dynamics

5.4.1. GEOMETRY OF THE FOUNDATION

The shape of the foundation both in plan and in elevation is one of the most important aspects to consider.

Thus, foundations with rectangular base have severer scour erosion than circular base foundations. This was firstly experienced by Dahlberg (1983). The gravity based foundations of Frigg TP1, installed in fine sand soil in the North Sea (104 meters depth), revealed 2 m depth scour erosion at two corners. The nearby TCP2 structure, installed only 50 m away from TP1, but with a circular base, does not experienced scour problems in the same fine sand. Later, hydraulic model tests confirmed these observations.

Gravity base structures have much bigger diameter at the base of the foundation than in the interface with the turbine. The transition shapes exert influence on the flow and, therefore, on the scour development. The Department of Trade and Industry funded investigation about these transitions and scour with two types of foundations, one with flat-topped transition as well as a conical shape transition (as in Thornton Bank). It was observed that the overall scour for the foundation with the conical shape was deeper than the scour for the flat-topped transition with the same conditions, and the scour rate was 1.8 times faster (Whitehouse, 2004).

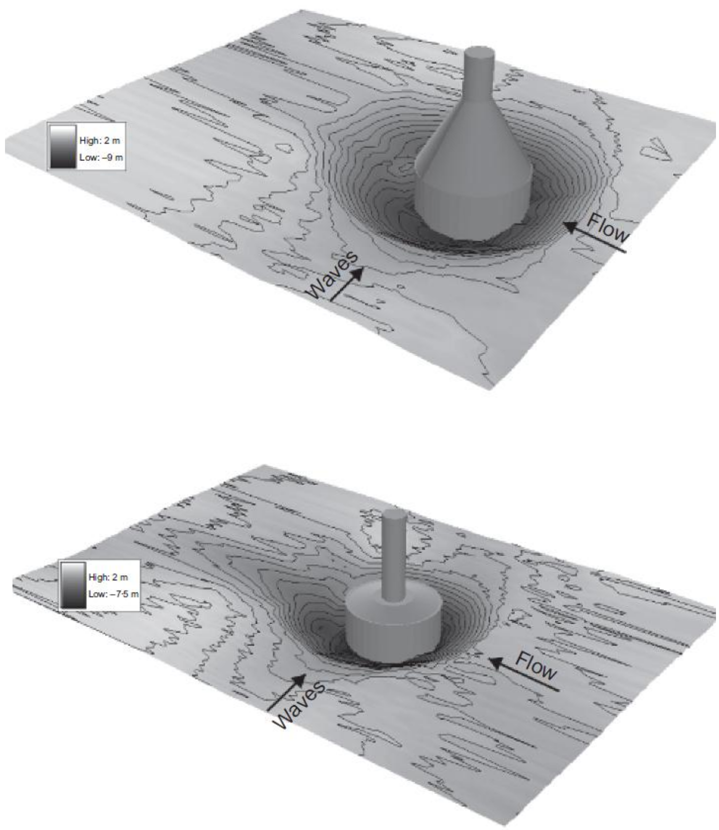

Figure 40: Scour test results for conical transition and smooth top transition (Whitehouse, 2004)

5.4.2. SEABED MATERIAL

If the scour occurs in gravel or sand, the sediments are likely to generate local deposits, while if the scour takes place in silty or clay seabed the material eroded will be carried away in suspension, leaving a depression. A paper published by Hoeg (1991) reported that foundations placed directly on clay in the North Sea without scour protection did not experienced scour erosion. Whitehouse (2011) observed that, despite being necessary more research to confirm this, foundations placed in clay seabed indicated no significant scour problems.

5.4.3. MARINE DYNAMICS

The third main factor that affects the scour is the ocean dynamics. More research is necessary in this area as well, but some investigations have observed that the scour response is progressive with tidal currents and is likely to develop faster under storm conditions. Besides, scour caused by the oscillatory motion of waves is normally less extensive and takes shorter time to develop the equilibrium scour depth (Whitehouse, 2011). Furthermore, May and Escarameia (2002) reported that the scour depth in steady flow was bigger than in tidal flow.

5.5. MEANS

The means required for the scour protection installation are the same as those used in the previous operations, especially in the seabed preparation: dredgers, fall pipe vessels, spreader pipe equipment, hopper barges, divers, and other auxiliary vessels and equipment.

6. FURTHER ANALYSIS: PREASSEMBLY AND ON SITE ASSEMBLY

6.1. INTRODUCTION

Working offshore can be extremely expensive and risky, and offshore wind companies are considering the possibility of pre-assemble tower and turbine to the foundation in the quayside in order to transport and install them at one time. Thus, the works offshore are reduced, so are the heavy installation vessels required and the risks assumed. On the other hand, pre-assembly has its own set of difficulties and challenges.

6.2. CONFIGURATION POSSIBILITIES

6.2.1. CONFIGURATION 1

FOUNDATION SEPARATELY

So far, most offshore wind farms have been installed with this method, where the foundation and turbine components are transported and installed separately. Within this configuration, there are a four variants:

- Installation of the four components separately (foundation, tower, nacelle and rotor)
- Installation of the foundation, then installation of pre-assembled tower and nacelle and finally the rotor
- Installation the foundation first, then installation of tower and finally the pre-assembled nacelle and rotor
- Installation of the foundation first and then installation of pre-assembled tower, nacelle and rotor

Figure 41: Foundation installation in Sprogø (ABJV, 2009)

Figure 42: Pre-assembled turbine being installed in a jacket foundation (turbineel.net, 2013)

6.2.2. CONFIGURATION 2

PRE-ASSEMBLED FOUNDATION AND TOWER

In this configuration, foundation and tower are transported and installed together. The Danish offshore wind farm of Middelgrunden used this method.

Within this configuration there are two main variants

- Installation of pre-assembled foundation and tower, then installation of the nacelle and finally the rotor
- Installation of the pre-assembled foundation and tower, then installation of the pre-assembled nacelle and rotor

Figure 43: Foundation installation in Middelgrunden (Power technology, 2001)

6.2.3. CONFIGURATION 3

PRE-ASSEMBLED FOUNDATION, TOWER AND NACELLE

This intermediate configuration between pre-assembled tower and complete pre-assembled turbine is quite rare as the set is no longer symmetric and offshore rotor installation is still to be carried out.

6.2.4. CONFIGURATION 4

COMPLETE PRE-ASSEMBLED WIND TURBINE

In this configuration, all the components (foundation, tower, nacelle and rotor) are assembled on shore, and the whole set is transported and installed at once. The main aim of this configuration is to avoid the offshore installation of tower, nacelle and rotor, reducing the significant costs of heavy installation vessels and the weather dependency. The method have not been used yet with gravity base foundations, but some innovative designs plan to use this technique.

Figure 44: Complete pre-assembled turbine installation (GBF, 2012)

6.3. COSTS

Most of the advantages and drawbacks of preassembly ultimately can by simplified into a reduction or increase in the operation costs. Thus, in a basic approach it can be assumed that the costs of all the marine operations are:

ASSEMBLY ON SITE

$$C_1 = C_{l1} + C_{ft} + C_{fi} + C_{tt} + C_{ti}$$

Where:

- C_1 : Costs of all the marine operations required to transport and install an offshore wind turbine, including foundation, tower, nacelle and rotor, carrying out the assembly on site.
- C_{l1} : Costs of launching the foundation
- C_{ft}: Costs of foundation transport
- C_{fi} : Costs of foundation installation
- C_{tt} : Costs of turbine transport (include tower, nacelle and rotor)
- C_{ti} : Costs of turbine installation (include tower, nacelle and rotor)

PRE-ASSEMBLY

$$C_2 = C_{pa} + C_{l2} + C_t + C_i$$

Where:

- C_2 : Costs of all the marine operations required to transport and install pre-assembled offshore wind turbine, including foundation, tower, nacelle and rotor.
- C_{pa} : Costs of preassembly. Includes harbour additional costs.
- C_{l2} : Costs of ensemble launching
- C_t : Costs of transport
- C_i : Costs of installation

Costs of transport (C_{ft}, C_{tt}, C_t)

The costs of transport can be simplified as:

$$C_{t*} = C_{mobt} + (t_{workt} + t_{delayt}) \cdot q_{t*}$$

- C_{t*}: Costs of transport
- C_{mobt} : Costs of mobilization of all the transport equipment required
- t_{workt} : Amount of time that the transport equipment is actually working
- t_{delayt} : Delay time, caused normally both by weather conditions and technical problems. It will depend on the probability of time windows and the technical difficulties.
- q_{t*} : cost of transport equipment per day of use

Costs of installation (C_{fi}, C_{ti}, C_i)

The costs of installation can be simplified as:

$$C_{i*} = C_{mobi} + (t_{worki} + t_{delayi}) \cdot q_{i*}$$

- C_{i*} : Costs of installation
- C_{mobi} : Costs of mobilization of all the installation equipment required
- t_{worki} : Amount of time that the installation equipment is actually working
- t_{delayi} : Delay time, caused normally both by weather conditions and technical problems. It will depend on the probability of time windows and the technical difficulties.
- q_{i*} : cost of installation equipment per day of use

Costs comparison

Although the costs estimation must be carried out for each case, it can be assumed that:

- The costs of preassembly are much lower than the costs of on-site assembly. This is the main reason why pre-assembly is interesting. It is not only that the equipment required for pre-assemble is cheaper than the installation vessels for on-site installation, but also due to the costs incurred on offshore delays, risks, etc. On the other hand the pre-assembled transport and installation requires new techniques and equipment that may compensate the savings.
- The foundation transport costs are lower than the preassembled turbine costs. This is because, the pre-assembled turbine is less stable and it probably will require additional stability measures. Besides, the transport of each component separately normally is more efficient as vessels are more easily optimized for components transport in groups, so the costs of transporting the entire turbine finally are not much lower than transporting the components separately.

6.4. STABILITY

One of the most important aspects to consider in pre-assembled turbines, especially in floating structures, is the worsening in the stability and buoyancy of the foundation. As soon as the tower, nacelle and rotor are attached to the foundation, the centre of gravity rises, and the metacentric height lowers.

As an example, it will be considered a buoyant foundation suitable for water depths of about 40 meters composed of a cylindrical caisson and a cylindrical shaft. The diameter of the caisson is 35 meters and it is 17 meters high. The exterior diameter of the shaft is 8 meters and it measures 25 meters high.

It will be shown some stability and buoyancy parameters for different configurations.

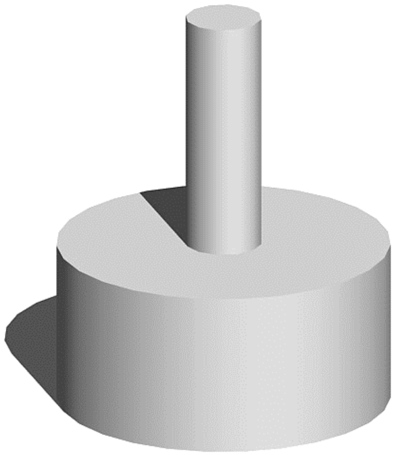

Figure 45: Gravity foundation example

<u>Caisson stability and buoyancy parameters:</u>

Caisson stability and buoyancy parameters	
Inertia on the water plane	70,000 m^4
Draft	7.9 m
Metacentric height (GM)	7.9 m

<u>Complete foundation parameters:</u>

Foundation stability and buoyancy parameters	
Inertia on the water plane	70,000 m^4
Draft	16.5 m
Metacentric height (GM)	4.1 m

<u>Foundation + steel tower parameters:</u>

Foundation + tower stability and buoyancy parameters	
Inertia on the water plane	70,000 m^4
Draft	16.7 m
Metacentric height (GM)	2.9 m

<u>Foundation + tower + wind turbine parameters:</u>

Complete foundation and turbine stability and buoyancy parameters	
Inertia on the water plane	70,000 m^4
Draft	16.9 m
Metacentric height (GM)	0.4 m

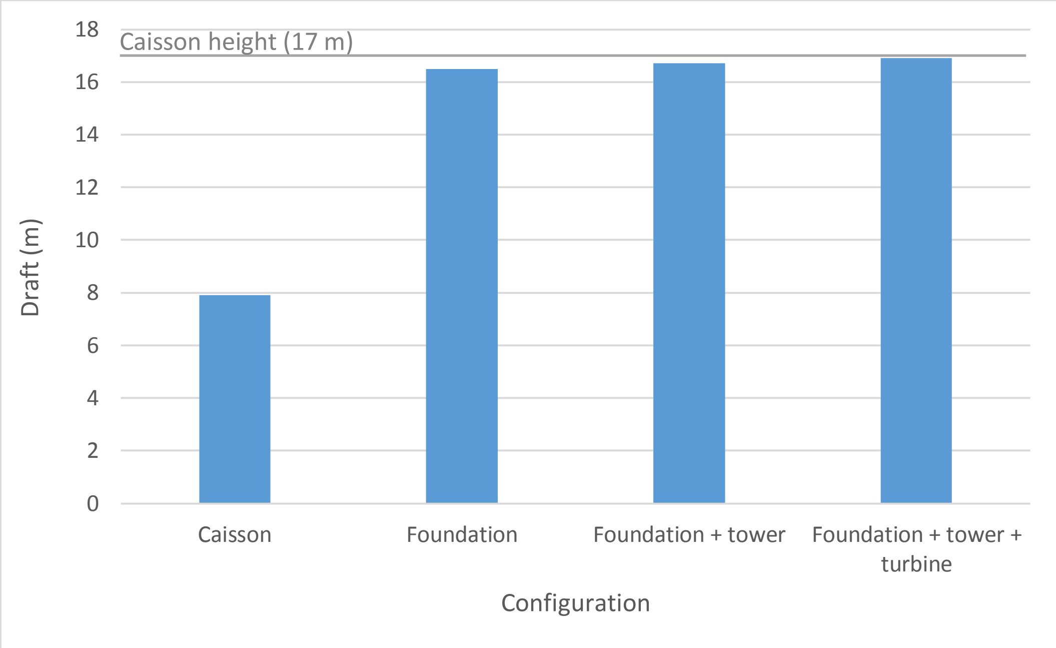

Figure 46: Draft with different configurations

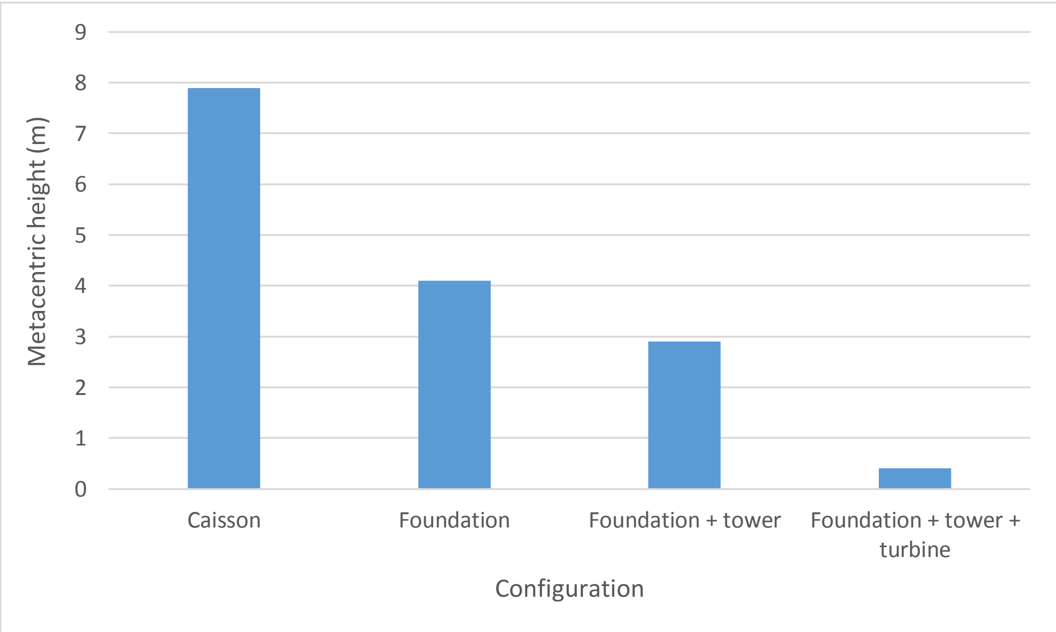

Figure 47: Metacentric height with different configurations

This example shows how a stable foundation becomes completely unstable if it is transported and installed with all the components pre-assembled: a metacentric height of 4 with only the foundation reaches almost 0 if tower and turbine are attached. In these cases, or the foundation characteristics are changed, or a floating device is attached in order to achieve enough stability.

6.5. CONFIGURATION CONCLUSIONS

It is clear that the costs estimation have a lot of components to consider and each foundation have very different features, so there are no generic solution to say if one configuration is more suitable than other. Each solution must be evaluated, and even the same foundation design may require different configurations for different wind farm locations, as the local costs, weather and sea conditions, quay availability, etc. are different. Some advantages and drawbacks of each configuration are:

<u>Pre-assembly advantages</u>

- Reduction in the weather and sea conditions dependency, which involves less delays, and less risks associated.
- Reduction in heavy installation vessels dependency, and the risks associated with their low availability.
- The time required to install a pre-assembled turbine is lower than the installation of the foundation and the assembly of tower and turbine on site.
- If the distance to harbour is far, the crew may stay at sea overnight, which could be expensive and logistically difficult.
- The turbines could be tested before being taken out to sea.

<u>Preassembly disadvantages</u>

- The standardization of turbine installation methods has allowed a lowering in the costs, so pre-assembly does not involve a big benefit in some cases.
- Some turbines are not recommended for the movements of being transported pre-assembled.
- The space requirements and specifications of the port are much more demanding if the components are pre-assembled, so there may not be a port close to the wind farm suitable for this configuration.
- The stability and buoyancy of the foundation decreases with pre-assembly, so additional floating devices could be necessary.
- Wind farm projects are multi-contract projects, so with pre-assembly the complexity of the contracts rises and the coordination becomes more difficult.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

Gravity base foundations are expected to have an important role in offshore wind projects for the near future. The huge weight and dimensions of these structures, along with the special offshore conditions, poses a big challenge for engineers. Marine operations to transport and install the foundations are one of the most demanding and costly phases of the project, and they have to be planned and performed carefully.

The operations of transport, seabed preparation, installation and scour protection were analysed. Within each marine operation, the main procedures and techniques both used so far, and proposed for the near future were studied. It also was analysed the main factors to consider in each operation, and the means required. Besides, a specific chapter (chapter 6) is devoted to different transport and installation configurations (pre-assembly). Seven operational wind farms, one under construction, and four future foundations designs has served as a reference for the study. Procedures and techniques from other offshore construction sectors has been considered and its possible application commented.

Based on this analysis, the following conclusions are drawn:

- So far, transport and installation procedures for GBF have been based on the use of heavy lift vessels along with pontoons, barges and other heavy vessels. The intensive use of these enormous means and their low availability trigger significant costs and risks that companies are trying to avoid by means of new transport and installation methods, based mainly on buoyant designs.
- The development of offshore wind energy is heading towards larger foundations and turbines, further distances and deeper waters, which make not possible the use of current techniques. Thus, future larger foundations are expected to be transported afloat, allowed by its self-buoyancy or helped by attached floating devices. These buoyant solutions would be towed to the wind farms by standard tugs.
- Stability of buoyant solutions is a hard issue to handle, especially in pre-assembled foundations and in caisson base foundations during the installation phase, where it has been shown how the stability decreases drastically. Inclined installation methods have solved this latter problem in foundations for oil platforms.
- Seabed preparation has been carried out virtually in the same manner in all the operational wind farms, based in a dredging and a gravel bed installation. However, this operation is expensive and the costs will rise with deeper waters, so offshore wind sector is intending to reduce these

costs. Skirted foundations minimize the seabed preparation and offer other performance advantages.

- Scour erosion is likely to occur in GBF, both during the installation and in the operational phase. Despite there are some prediction models, the complexity of the phenomenon makes necessary hydraulic model tests. Some scour protection techniques have been commented, being the installation of gravel or rocky layers the most commonly used.
- The possibility of pre-assemble turbine components to the foundations on shore is under discussion in the offshore wind sector. There is no generic solution to this issue, and specific cost and technical analysis must be performed in each project to assess the most suitable configuration.
- Although offshore wind energy is still in its early stages, other sectors have been working offshore with enormous structures for decades: The construction of oil and gas platforms, harbours or immersed tunnels have developed techniques that have been proven many times successfully. Offshore wind sector still has much to learn from these procedures and techniques.

7.2. RECOMMENDATIONS

Due to the limited experience of the sector and the lack of accessible information, it is clear that this work should be updated over time to be adjusted as experience is gained. Besides, this study can be upgraded by the following recommendations:

- Improve the study of the weather and sea conditions required for the transport and installation of a buoyant GBF and the systems and techniques to allow the installation in severer conditions.
- Deeper analysis of transport and installation configurations (pre-assembly). Cost model, application to different foundation designs and wind farm features and comparison of results.
- Further stability study of buoyant GBF during transport and installation phases.
- Study of the structural performance of a GBF during the transport and installation phases.
- Environmental impact assessment of the marine operations required for GBF installation, especially during the seabed preparation.
- Further analysis of techniques and procedures used in other offshore sectors (oil and gas, harbours, immersed tunnels, etc.) and application of these techniques to offshore wind sector.

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APPENDIX A

List of wind farms

A1. LIST OF OPERATIONAL OFFSHORE WIND FARMS

	TOTAL MW	YEAR COMISSION	COUNTRY	TYPE OF FOUNDATION	DEPTH (m)	TURBINE
London Array	630	2013	United Kingdom	Monopile	0 - 25	175 x 3,6
Greater Gabbard	504	2012	United Kingdom	Monopile	4 - 37	140 × Siemens 3.6-107
Walney (phases 1&2)	367.2	2011	United Kingdom	Monopile	-	102 × Siemens SWT-3.6-107
Sheringham Shoal	315	2012	United Kingdom	Monopile	-	88 × Siemens 3.6-107
Thanet	300	2010	United Kingdom	Monopile	-	100 × Vestas V90-3MW
Thorntonbank Phase 2	183	2013	Belgium	Jacket	6 - 20	30 x 6MW
Horns Rev 2	209.3	2009	Denmark	Monopile	-	91 × Siemens 2.3-93
Rødsand II / Nysted II	207	2010	Denmark	Gravity	6 - 12	90 × Siemens 2.3-93
Chenjiagang (Jiangsu) Xiangshui	201	2010	China	Pile	-	134 × 1.5MW
Lynn and Inner Dowsing	194	2008	United Kingdom	Monopile	-	54 × Siemens 3.6-107
Robin Rigg (Solway Firth)	180	2010	United Kingdom	Monopile	-	60 × Vestas V90-3MW
Gunfleet Sands	172	2010	United Kingdom	Monopile	-	48 × Siemens 3.6-107
Nysted (Rødsand I)	166	2003	Denmark	Gravity	6-10	72 × Siemens 2.3
Bligh Bank (Belwind)	165	2010	Belgium	Monopile	-	55 × Vestas V90-3MW
Horns Rev 1	160	2002	Denmark	Monopile	-	80 × Vestas V80-2MW
Ormonde	150	2012	United Kingdom	Monopile	-	30 × REpower 5M
Longyuan Rudong Intertidal Demonstration	150	2011 (phase 1)	China	High Rise Pile Cap	-	21 × Siemens 2.3-93;

	TOTAL MW	YEAR COMISSION	COUNTRY	TYPE OF FOUNDATION	DEPTH (m)	TURBINE
Princess Amalia	120	2008	Netherlands	Monopile	-	60 × Vestas V 80-2MW
Donghai Bridge *	102	2010	China	High Rise Pile Cap	-	34 × Sinovel SL3000/90
		2011		High Rise Pile Cap	-	1 × Sinovel SL 5000
				High Rise Pile Cap	-	1 × Shanghai Electric W3600/116
Lillgrund	110	2007	Sweden	Gravity	4 - 13	48 × Siemens 2.3-93
Egmond aan Zee	108	2006	Netherlands	Monopile	-	36 × Vestas V90-3MW
Kentish Flats	90	2005	United Kingdom	Monopile	-	30 × Vestas V90-3MW
Barrow	90	2006	United Kingdom	Monopile	-	30 × Vestas V90-3MW
Burbo Bank	90	2007	United Kingdom	Monopile	-	25 × Siemens 3.6-107
Rhyl Flats	90	2009	United Kingdom	Monopile	-	25 × Siemens 3.6-107
North Hoyle	60	2003	United Kingdom	Monopile	-	30 × Vestas V80-2MW
Middelgrunden	40	2001	Denmark	Gravity	3 - 6	2MW Bonus B76/2000
Vindpark Vänern	30	2012	Sweden	Gravity		10 x WWD 3MW
Thorntonbank Phase 1	30	2009	Belgium	Gravity	13 - 20	6 x 5MW Repower
Sprogø	21	2009	Denmark	Gravity	10 - 16	7 x Vestas V90 - 3.0 MW
Kemi Ajos I & II	15	2008	Finland	Gravity	0 - 8	10 x 3 MW
Avedore Holme	10,8	2011	Denmark	Gravity/Near shore	2	3 x 3,6 Siemens SWT 3,6 120

A2. LIST OF OFFSHORE WIND FARM PROJECTS

	TOTAL MW	STATUS	COUNTRY	TYPE OF FOUNDATIO N	DEPTH (m)	TURBINE
Gwynt y Môr	576	Under Construction	United Kingdom	Monopile	13 - 30	170 x 3, 6
Bard Offshore	400	Under Construction	Germany	Tripile	40	80 x 5 MW
Anholt	400	Under Construction	Denmark	Monopile	14 - 17	111 x 3.6
Thorntonbank phase III	188	Under construction	Belgium	Jacket	12 - 18	18 x 6.15 MW
Thorntonbank Phase 3	110,7	Under construction	Belgium	Jacket	12 - 20	18 x 6.15 MW
Datang Laizhou Wind Farm Phase III	49,5	Under Construction	China	Gravity/Near shore	1	33 x 1.5 MW
Kårehamn	48	Under construction	Sweden	Gravity	6 - 20	16 x 3 MW
Codling Windpark	1000	Consent Authorised	Ireland	Not decided	-	Not decided
Albatros	345	Consent Authorised / On hold	Germany	Gravity	40	69 x 5 MW
Norther / North sea power	310 - 470	Consent authorised	Belgium	Not decided	12 - 25	Not decided
Tromp Binnen	295	Consent Authorised	Netherlan ds	Gravity	-	Not decided
Blekinge Offshore	1000 - 2500	Consent application submited	Sweden	Not decided	10 - 30	Not decided
RENTEL (Vlaanderen)	300-500	Consent application submited	Belgium	Not decided	22-30	Not decided
Erie Wind Energy	>1000	Concept / Early planning	Canada	Not decided	15 - 22	Not decided
Hornsea	>1000	Concept / Early planning	United Kingdom	Not decided	25 - 36	Not decided
South Korea	>1000	Concept / Early planning	South Korea	Not decided	-	Not decided
Gwynt y Môr	576	Under Construction	United Kingdom	Monopile	13 - 30	170 x 3, 6

A3. LIST OF WIND FARMS WITH GBF

	TOTAL MW	YEAR COMISSION	COUNTRY	TYPE OF FOUNDATION	DEPT H (m)	DISTANCE TO SHORE (km)
Nysted II (Rødsand II)	207	2010	Denmark	Gravity	6 - 12	8,8
Nysted I (Rødsand I)	166	2003	Denmark	Gravity	6 - 10	10,8
Lillgrund	110	2007	Sweden	Gravity	4 - 10	7
Middelgrunden	40	2001	Denmark	Gravity	3 - 5	2
Kemi Ajos I & II	30	2008	Finland	Gravity	3 - 8	2,6
Thorntonbank Phase 1	30	2009	Belgium	Gravity	12 - 27	26
Vindpark Vänern	30	2012	Sweden	Gravity	3 - 13	7
Sprogø	21	2009	Denmark	Gravity	6 - 16	10,6
Kårehamn	48	Under construction	Sweden	Gravity	6 - 20	3,8 km
Albatros	345	Consent Authorised / On hold	Germany	Gravity	40	110
Tromp Binnen	295	Consent Authorised	Netherlands	Gravity	23 - 28	65

APPENDIX B

Wind farms and future solutions review

Appendix B1. Operational and under construction wind farms

Operational

Nysted II (Rødsand II)

Nysted I (Rødsand I)

Lillgrund

Middelgrunden

Thorntonbank Phase 1

Vindpark Vänern

Sprogø

Under construction

Kårehamn

Nysted II (Rødsand II)

(Denmark)

Project data

Country: Denmark

Year of commission: 2010

Total installed capacity: 207 MW

Number of turbines: 90

Distance from shore: 8,8 km

Water depth: 6-12 m

Investment: 446 M€

Investment per MW: 2,15 M€

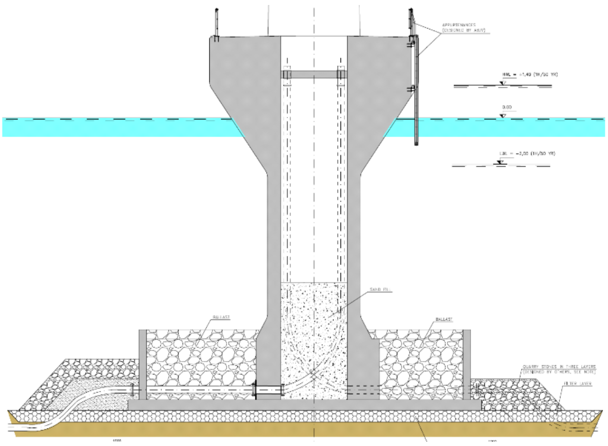
Location of the wind farm (wikimedia)

1. General Information

Nysted II is nowadays the largest offshore wind farm with gravity-based foundations. It is placed 9 km away from Nysted (Denmark), and near its predecessor Nysted I. Nysted II started its commercial operation in 2010.

2. Foundation design

The foundations of Nysted II are not very different from the Nysted I ones, and were designed as gravity based foundation with hexagonal shaped base with pockets to be filled with ballast when placed on the seabed. The hollow shaft have constant diameter and on the top the foundation they have a conical shape to reduce the ice loads. The base have 16 m diameter and the height is up to 22m.



Cross section of the foundation (ABJV)

3. Manufacture

The foundations were produced in Poland in a quite industrialized process. The 90 foundations were finished in 12 months, which is about 4 days per foundation. The steel works took place on land in a reinforcement yard constructed specifically for the project. When the steel frame was finished, an innovative air pressure system lifted the frame and took it to the flattop barges, where the casting took place. Each of the 90 foundations required about 560 m3 of concrete and 91 tons of reinforcement bars, and weights up to 1.300 tonnes empty. A medium size concrete factory was installed close to the quayside to provide such amount of concrete.

Steel frames (ABJV)

Concrete casting on barge (ABJV)

Foundation manufacture (Aarsleff)

4. Transport

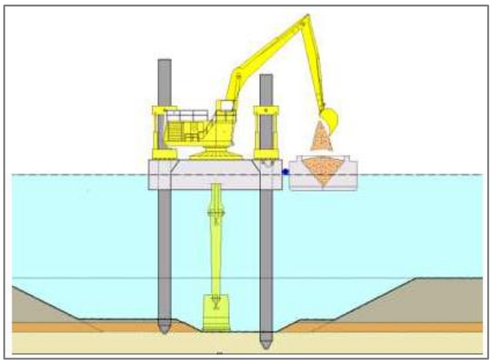
The foundations were towed to the final emplacement about 100 nautical miles (182 km) away in a 24 hours trip. Each 3 weeks average, a barge with 6 foundations could start the trip to Rødsand.

Foundations transport (ABJV)

5. Seabed preparation

The seabed had to be prepared before lowering the foundations. Firstly, it was dredged from 32.000 to 60.000 tonnes of sand and clay. This corresponds to a depth of excavation of 1.1 - 2 m in average. The excavation equipment was GPS controlled and consisted in a large backhoe on a pontoon, and a vessel to store the dredged material. CPT tests were carried out. When a sufficient bearing capacity layer was reached, a levelling frame was lowered down. Then, the frame was filled with crashed stone in order to create a flat layer with only 3 cm of tolerance. Divers observed all the process and levelled the layer with a beam.

Seabed preparation (ABJV)



Seabed preparation (ABJV)

6. Foundation Installation

The crane EIDE barge 5, specifically adapted to this project and capable of lifting up to 1.450 tons, is placed carefully near the barge, and the lifting equipment, which is different than in Nysted I, is assembled. Then, the crane lifts the foundation and from 12 to 18 hour later the foundation is in position. Divers are required for the process.

Some foundations were so heavy, that the barge had to be ballasted to sink some centimetres the foundations so that EIDE barge 5 could be able to lift them. After the foundation is placed, up to 900 tonnes of stones in the base and 300 tonnes of sand in the hollow shaft rise the weight of the foundation up to 2.700 tonnes. As scour protection, about 120 m3 of ballast in two layers were established around each foundation.

Foundation lowering down (ABJV)

7. Turbine Installation

The turbines are shipped from the port of Nybord, chosen due to its closeness to the blades manufacture location and the difficulties to be transported on land. The vessel SEA POWER, carried three rotors at a time

Turbine installation (EON)

Companies involved

Design: COWI (Denmark)
Manufacture: ABJV (Denmark)
Seabed preparation: Peter Madsen Rederi (Denmark)
Installation: Eide Contracting (Denmark), A2SEA (Denmark); Peter Madsen Rederi (Denmark)
Main contractor: ABJV (Denmark)
Electrical line: Norddeutsche Seekabelwerke (Germany), JD contractor (Denmark), Peter Madsen R.(Denmark)
Operator: EON (Germany)

Main vessels used

Seabed preparation: Large backhoe on barge
Foundation Installation: “Eide Barge 5”
Turbine Installation: “Sea Power”
Cable installation: “Nostag 10” and “Henry P. Lading”
Substation: “Rambiz”

Nysted I (Rødsand I)

(Denmark)

Project data

Country: Denmark

Year of commission: 2003

Total installed capacity: 166 MW

Number of turbines: 72

Distance from shore: 10.8 km

Water depth: 6-10 m

Investment: 269 M€

Investment per MW: 1.62 M€

Nysted I wind farm (Wikimedia)

1. General Information

Nysted I is nowadays the second largest offshore wind farm with gravity-based foundations. It is placed 10 km away from Nysted (Denmark). The first foundation was installed in May 2003 and only three months later, all the turbines were erected. In December 2003, the wind farm started commercial operation.

2. Foundation design

The foundations of Nysted I were designed as gravity based foundation with hexagonal shaped base with pockets to be filled when placed on the seabed. The hollow shaft have constant diameter and on the top the conical shape reduce the ice loads.

3D view of the foundation (Tech Marine)

3. Manufacture

The foundations were cast on-board flattop barges at Swinoujscie Port, in Poland. Each of the 73 foundations require about 540 m3 of concrete and 91 tons of reinforcement bars, and weights up to 1.300 tones. A medium size concrete factory was installed close to the quayside to provide such amount of concrete.

Foundations manufacture (Dong Energy)

4. Transport

After produced in the barges, the foundations were towed to the final emplacement 100 nautical miles (182 km) away in a 24 hours trip.

Foundations transport (Dong Energy)

5. Seabed preparation

The seabed had to be prepared before lowering the foundations. Firstly it was dredged from 0.5 to 9.5 m of lose sand and mud. The excavation may have been carried out with a large GPS controlled backhoe on a vessel, and lowering a steel frame that would be filled with crashed rock and levelled by divers, in the same procedure than Nysted II and Lillgrund.

6. Foundation Installation

The crane EIDE barge 5, specifically adapted to this project and capable of lifting up to 1.450 tonnes, lifted the foundations from the barge, and laid it accurately on the seabed.

The lowering was carried out in two steps. Firstly, the foundation was lowered above its final location, and after checking the position, the crane lowered the base the last centimetres.

After that, the open boxes at the bottom of the foundation were filled with pebbles and gravel, to achieve a total weight up to 1.800 tons. Then, the foot and the surroundings meters of seabed were covered with large stones.

Lowering a foundation (DONG Energy)

7. Turbine Installation

The turbines are shipped from the port of Nybord, chosen due to its closeness to the blades manufacture location and the difficulties to be transported on land.

The vessel Ocean Andy, that can carry four turbines at a time, transported the turbines in 4 main parts: lower tower, upper tower, nacelle and rotor.

Crane Eide Barge 5 (DONG Energy)

Rotor installation (DONG Energy)

Companies involved

Design: COWI (Denmark)
Manufacture: Aarsleff (Denmark) and Ballast Nedam (Nederland)
Seabed preparation: Peter Madsen Redery (Denmark)
Installation: Eide Contracting (Denmark), A2SEA (Denmark)
Main contractor: Aarsleff (Denmark); Ballast Nedam (Denmark)
Electrical line: Mika (Switzerland), Peter Madsen Rederi (Denmark) and JD contractor (Denmark)
Operator: DONG Energy (Denmark)

Main vessels used

Sea preparation: Peter Madsen´s Vessels
Foundation Installation: "Eide Barge 5"
Turbine Installation: "Sea Energy" / "Ocean Ady"
Cable installation: "Atlantis" and "MS Honte"
Substation: "Rambiz"

Lillgrund

(Sweden)

Project data

Country: Sweden

Year of commission: 2007

Total installed capacity: 110 MW

Number of turbines: 48

Distance from shore: 7 km

Water depth: 4-10 m

Investment: 200 M€

Investment per MW: 1,82 M€

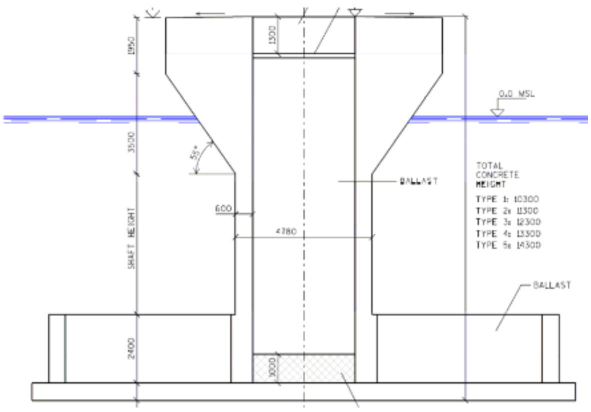
Location of the wind farm (wikimedia)

1. General Information

Lillgrund is nowadays the third largest offshore wind farm with gravity-based foundations. Its 48 turbines of 2.3 MW each provide 110 MW of installed capacity. It is located in the region of shallow waters of Öresund, between Denmark and Sweden. Lillgrund started its commercial operation in 2007.

2. Foundation design

The foundations of Lillgrund were design with the same concept used in Nysted I and II, especially in Nysted I whose foundation are very similar. As in these projects, they are gravity based foundation with hexagonal shaped base with pockets to be filled with ballast when placed on the seabed. The hollow shaft have constant diameter and on the top the foundation have a conical shape to reduce the ice loads. The base have 16 m diameter and the height is up to 22m.



Cross section of the foundation (Vattenfall)

3. Manufacture

The foundations were produced in the same port used for the manufacture of Nysted foundations: Swinoujscie, Poland. The foundations were cast directly on barges.

Foundation manufacture (Vattenfall)

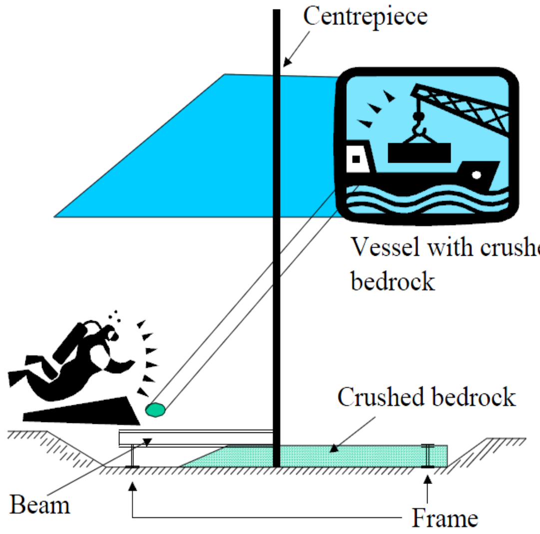
4. Transport

The foundations were towed to the final emplacement. Up to four foundations could be carried at a time.

Foundations transport (Vattenfall)

5. Seabed preparation

The seabed preparation started during the foundation casting in Poland. In the first step, it was dredged about 2.5 m on average of sand and clay. The excavation was carried out by a GPS controlled backhoe on a vessel. When a sufficient bearing capacity layer was reached, a levelling frame was lowered down. Then, the frame was filled with crashed rock in order to create a flat 30 cm layer. Divers observed the process and levelled the crashed rock using a beam. A centrepiece was used to facilitate the positioning. No compaction of the layer was done.



Seabed preparation (Vattenfall)

6. Foundation Installation

The crane barge "EIDE barge 5", the same used for the installation of Nysted I foundations and capable of lifting up to 1.450 tons, was used to lift the foundations and put it in their positions.

After the foundation was placed, more dredging was done to place the J-tubes. Then, the surroundings of the foundations were filled with filter rock to prevent scour and J-tubes were fitted.

After this step was finished, it was placed ballast rock both in the pocket and in the shaft, in order to rise the weight of the foundations. A concrete slab was cast on the top of the foundations.

Foundation installation (Vattenfall)

7. Turbine Installation

The turbines are carried by the vessel SEA POWER from the port of Nybord, chosen due to its closeness to the blades manufacture location and the difficulties to be transported on land. The interface between the tower and the foundation is very important. Some problems had to be solved to ensure the verticality of the tower.

Horizontality problem (Vattenfall)

Companies involved

Design: COWI (Denmark), IMS (Germany), NIRAS (Denmark)
Manufacture: Hochtief Construction (Germany), E. Pihl & Sons (Denmark)
Seabed preparation: Peter Madsen Rederi (Denmark)
Installation: Eide Contracting (Denmark), Hochtief Construction (Germany), A2SEA (Denmark)
Main contractor: Vattenfall Europe (Denmark)
Electrical line: ABB(Sweden), Boskalis (Sweden), Baltic offshore (Sweden)
Operator: Vattenfall (Sweden)

Main vessels used

Seabed preparation: Large backhoe on barge
Foundation Installation: “Eide Barge 5”
Turbine Installation: SEA POWER
Cable installation: “GRÄVLINGEN " "NAUTILUS MAXI" "CS Pleijel"
Substation: “Samson”

Middelgrunden

(Denmark)

Project data

Country: Denmark

Year of commission: 2001

Total installed capacity: 40 MW

Number of turbines: 20

Distance from shore: 2 km

Water depth: 4 – 8 m

Investment: 47 M€

Investment per MW: 1,17 M€

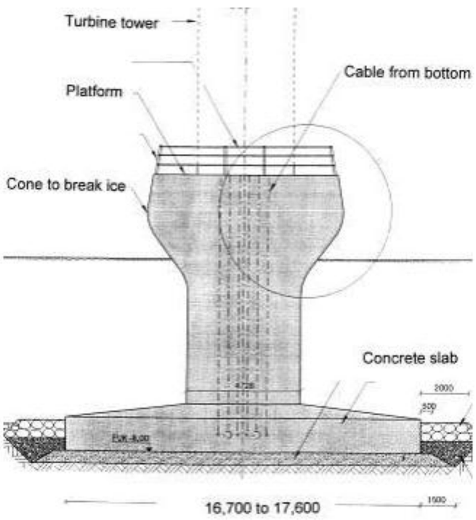
Location of the wind farm (Siemens)

1. General Information

Middelgrunden is one of the biggest gravity-based foundation offshore wind farms. It is placed only a few km away from Copenhagen (Denmark), and one of its main features corresponds to its local ownership. It was commissioned in 2001.

2. Foundation design

The foundations were designed as gravity based foundations, and the main factor that affected this design is the shallow waters in the area (4-8 m average). They can be divided in 3 main parts, a 16 m diameter concrete slab, the shaft and the upper part with a conical shape to reduce the ice loads.



Elevation of the foundation (Middelgrunden)

3. Manufacture

Morberg & Thorsen manufactured the foundation in a dock of the harbour of Copenhagen. All the foundations were produced at the same time. *PERI* supplied the formworks with different shaft units and the conical shape, achieving high casting speeds. All the electrical equipment is inside before transporting.

Foundation manufacture (Power technology)

4. Transport

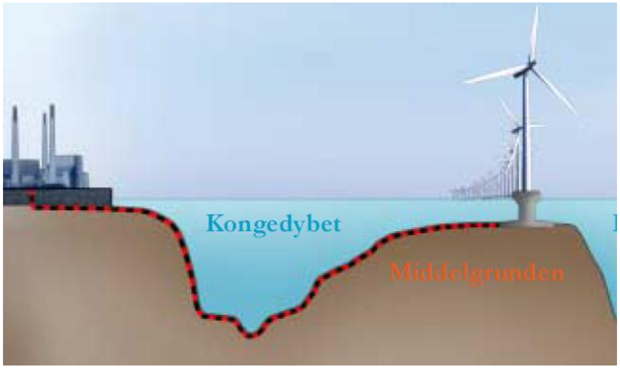
When finished, the dock was flooded and the crane barge EIDE BARGE 5 picked up the foundations and took it directly to the final emplacement. The lower part of the tower is installed on shore, so it is carried with the foundation as well.

Foundations finished (Aarsleff)

Foundation transport (Power technology)

5. Seabed preparation

The seabed preparation was much more complicated than expected and it had to be faced some problems. The sludge in the seabed reached up to 5 m, and it was almost liquid, so it had to be removed several times. Besides, it was placed a layer of rock as a cushion layer. This layer was supposed to be compacted, but again some complications were found to achieve the required compaction, so finally it was necessary to carry out several injections to ensure enough contact. Divers were necessary in the operations of placement, compaction and levelling of the compacted rock cushion.



Seabed preparation (cranebg)

6. Foundation Installation

As explained before, the barge EIDE barge 5 picked up the foundations from the dock and carried it directly to their final position. This allows savings in other heavy vessels. The barge was not capable of lifting the weight of the foundation and the tower, so it had to be transported semi submerged, with a satisfactory method. Engineers carried out very accurate calculations because the waters in this area are shallow and the foundation could have stuck in the seabed. The positioning was very accurate and the special measures planned to solve deviations in inclinations were not necessary.

Foundation installation (ABJV)

7. Turbine Installation

The lower part of the tower is installed onshore in the foundation and transported with it. The weather has an important role in the emplacement of the turbines, but when favourable conditions, the work went on day and night and in about 18 – 24 hours two turbines could been installed.

Turbine installation (Middelgrunden)

Companies involved

Design: COWI (Denmark), Grontmij (Netherland)
Manufacture: MT Højgaard (Denmark)
Seabed preparation: Peter Madsen Rederi (Denmark)
Installation: Eide Contracting (Denmark), Pihl (Denmark), Muhibbah Engineering (Germany)
Main contractor of the foundation: MT Højgaard (Denmark)
Electrical line: JD contractor (Denmark), NKT cables (Denmark)
Operator: DONG Energy (Denmark)

Main vessels used

Foundation Installation: "Eide Barge 5"
Turbine Installation: "MEB JB1"
Cable installation: "MS Honte" and "Henry P. Lading"

Thorntonbank I

(Belgium)

Project data

Country: Belgium

Year of commission: 2009

Total installed capacity: 30 MW

Number of turbines: 6

Distance from shore: 26 km

Water depth: 12 – 27 m

Investment: 150 M€

Investment per MW: 5 M€

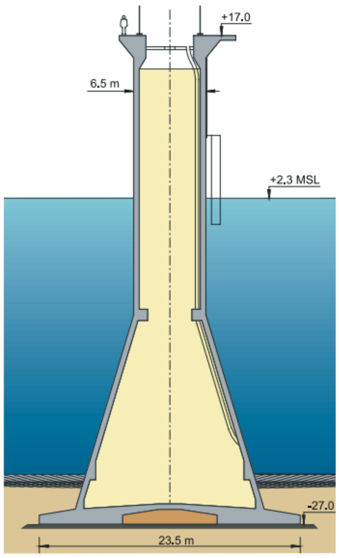
Foundation (National geographic)

1. General Information

Throntonbank I is one of the most interesting offshore wind farms from a technical point of view, due the gravity based foundation chosen and the important depths (up to 27 m). It has to be mentioned that the next phases were carried out with jackets foundations. It is placed 26 km away from Belgium, and it was fully commissioned in 2009.

2. Foundation design

The foundations were designed as gravity based foundations, with the shape of an Erlenmeyer flask. They can be divided in 3 main parts, a 23.5 m diameter concrete slab, a conical hollow shaft and a constant diameter shaft. The design comply with the basis of a big base surface to provide enough friction and distribute the loads on the seabed, trying to reduce the horizontal surface to decrease the horizontal loads and trying to minimize the structural weight and achieve the weight necessary ballasting later the hollow shaft. The concrete slab thickness varies from 0.7 to 1,5 meters. Furthermore, the thickness of rest of the foundation is 0.5 meters, but it rises in the joint section between the conical and cylindrical part, and in the top of the foundation.



Cross section (COWI)

3. Manufacture

MBG manufactured the foundation onshore in about six months. Climbing formworks were used, provided by *DOKA*. The conical shapes complicated the casting process and therefore rose the costs. The concrete used had C45/55 compression strength, environment class ES4, consistency S3 and cement type CemIII HSR 42.5 LA. Cement ratio of 450 kg/m3 and w/c factor of 0.36. The empty weight is 2800 – 3000 tonnes with 215 tonnes of steel (200 kg of steel per cubic meter of concrete) and 32 prestressed cables.

Foundation manufacture (left: Wikimedia, right: DEME)

4. Transport

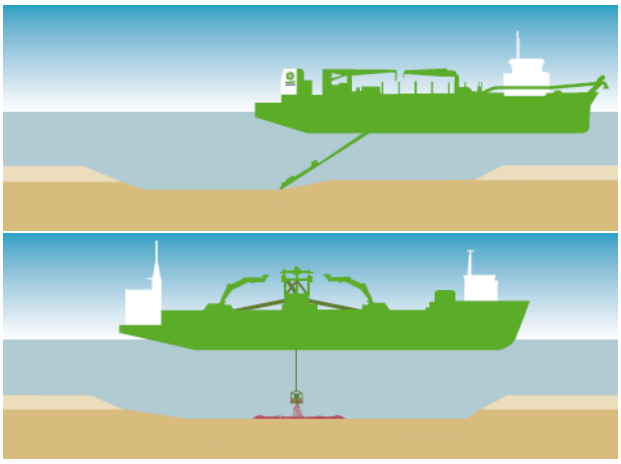
The foundation finished is transported onshore from the construction site to the quay by means of SPMTs (self-propelled modular transporter). Then, the heavy lift vessel RAMBIZ lifted the foundation and transported it partially submerged directly to the final location.

Foundation transport (left: DEME, right: Scaldis)

Foundation transport (IMC)

5. Seabed preparation

The seabed was prepared in two steps. Firstly, the first layer of loose sand was dredged. On average 7 m of sand were dredged in a surface of 50x80 m (90.000 m3 on average per foundation). This sand was disposed nearby in order to reuse it later as ballast. Then, two layers of crushed rock were laid as foundation bed by means of a fall pipe vessel. The thicknesses of these layers were about 1,3 m both. The first layer consisted in a filter layer (0-63mm) and the next was a gravel layer (10-80mm). An accuracy of 5 cm was required in order to ensure the horizontality.



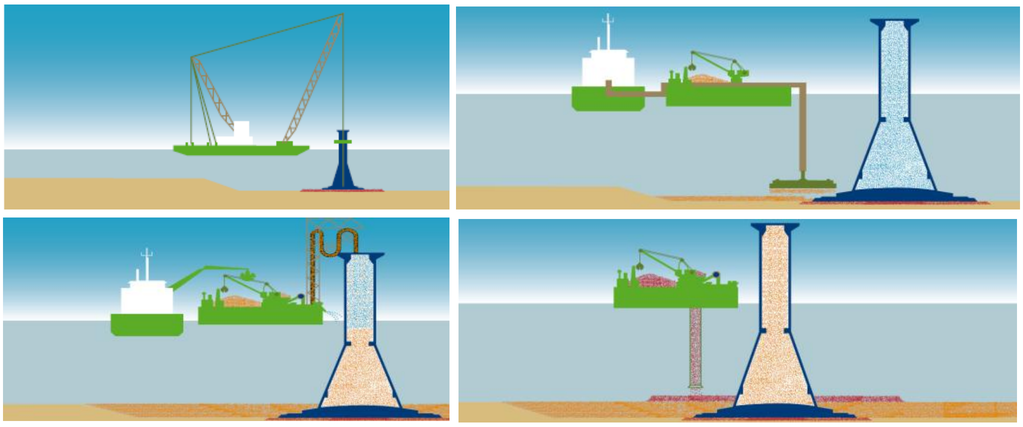
Seabed preparation (DEME)

6. Foundation Installation

As explained before, the heavy lift vessel RAMBIZ picked up the foundations in the quay and carried it semi submerged directly to their final position. This allows savings in other heavy vessels but the high dependency in this vessel is risky. Applying highly accurate positioning systems, the foundation is sunk slowly. Two days were required from the hoisting in the quay to the final emplacement.

Then the foundation pit was backfilled with up to 60.000 m3 per pit. The hopper dredger “Jade River” re-dredged the stockpiled sand and pumped it to “Thornton I”, a multipurpose pontoon that controlled the spreading of the sand. A similar operation was carried out to fill the foundation hollow with 2000 m3 of sand on average. The main difference is that the material was dredged and pumped by “Vlaanderen XXI” in this case.

Finally, “Thornton I” installed the scour protection in two separate layers of rocky material supplied by “Vlaanderen XXI”: one filter layer (0-120mm) of 0.6m thickness, and one armour layer (20% of 5-40 kg and 80% of 200kg) of 0.7m thickness.



Foundation installation (DEME)

Foundation installation (DEME)

7. Turbine Installation

This work was carried out by *GeoSea*. “Vagant” transported all parts of one foundation and the jack pontoon “Buzzard” served as stable platform. Sixty people worked permanently in turbine transport and assembly.

Companies involved

Foundation Design: COWI (Denmark)
Foundation Manufacture: MBG (Belgium)
Seabed preparation: Dredging International (Belgium)
Foundation Installation: Scaldis Salvage & Marine Contractors (Belgium)
Turbines installation: Geosea (Belgium)
Main contractor of the foundation: THV Seawind (Belgium)
Electrical line: VSMC (Holland)
Operator: C-Power (Belgium)

Main vessels used

Seabed preparation: Large backhoe on barge
Foundation Installation: “Eide Barge 5”
Turbine Installation: “Sea Power”
Cable installation: “Nostag 10” and “Henry P. Lading”
Substation: “Rambiz”

Vindpark Vänern

(Sweden)

Project data

Country: Sweden

Year of commission: 2012

Total installed capacity: 30 MW

Number of turbines: 10

Distance from shore: 7 km

Water depth: 3 – 13 m

Investment: 60 M€

Investment per MW: 2 M€

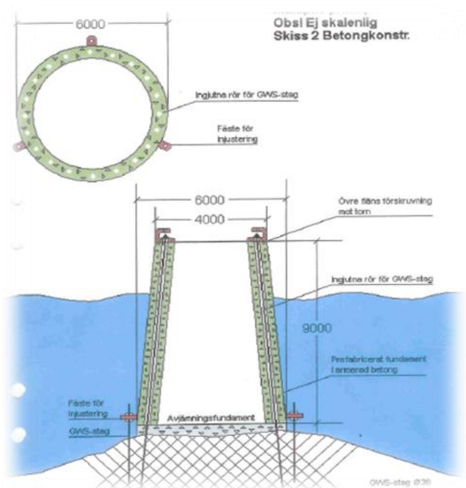
Location of the wind farm (wikimedia)

1. General Information

Vindpark Vänern is a wind farm installed in Vänern, the biggest lake in Sweden. Despite the fact that the foundations used were gravity base foundations, they are quite different from the ones used in the sea, due mainly to the lower environmental loads. Vindpark Vänern is placed 7 km away from the shore, and it was fully commissioned in 2012.

2. Foundation design and installation

The design of the foundation has not been used in other gravity-based foundations, so it is interesting. The foundation corresponds to a hollow conical shaped foundation made of several rings of precast concrete that are anchored by steel bars to the rock in the seabed of the lake.



Cross section of the foundation (Vindpark Vänern)

Foundation manufacture and installation (Vindpark Vänern)

Companies involved

Developer: Vindpark Vänern (Sweden)
Foundation Manufacture: PEAB (Sweden)
Seabed preparation: -
Foundation Installation: -
Turbines installation: -
Main contractor of the foundation: -
Electrical line: -
Operator: Vindpark Vänern (Sweden)

Main vessels used

Seabed preparation: -
Foundation Installation: -
Turbine Installation: “West Wind (formerly Shuttle II))
Cable installation: -
Substation: -

Sprogø

(Denmark)

Project data

Country: Denmark

Year of commission: 2009

Total installed capacity: 21 MW

Number of turbines: 7

Distance from shore: 10,6 km

Water depth: 6-16 m

Investment: -

Investment per MW: -

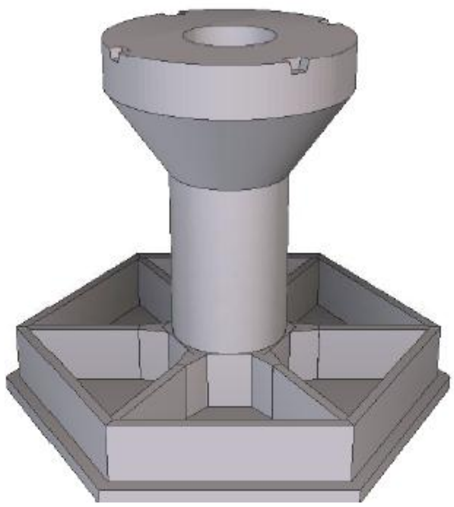
Wind farm (WAG)

1. General Information

The wind farm of Sprogø consists in seven turbines of 3 MW each located about 10 km from the shore of Sprogø, Denmark. The wind farm has many similarities with Nysted I and II and it started its commercial operation in 2010.

2. Foundation design

The foundations of Sprogø are similar than the Nysted I ones, and they were designed as gravity based foundation with hexagonal shaped base with pockets to be filled with ballast when placed on the seabed. The hollow shaft have constant diameter and on the top the foundation, they have conical shape to reduce the ice loads. The base is 29 - 22 m diameter and the height is up to 22m.



Left: 3D outline (Niras). Right: foundation scheme (ABJV)

3. Manufacture

The foundations were produced at Swinoujscie Port, in Poland, at the same time than the foundations of Nysted II (Rødsand II). The foundations were cast on-board one single giant pontoon. Each foundation weights up to 2000 tonnes empty.


Left: Steel frames (Niras). Right: foundation Construction (ABJV)

4. Transport

The foundations were manufactured directly on-board a pontoon so when they were finished, they were towed to the final emplacement about 100 nautical miles (182 km) away in a 24 hours trip.

Wind farm (WAG)

Wind farm (WAG)

5. Seabed preparation

The seabed had to be prepared before lowering the foundations. Firstly, a large backhoe on a pontoon dredged the first layer of clay and loose sand. When a sufficient bearing capacity layer was reached, a levelling frame was lowered down. Then, the frame was filled with crashed stone in order to create a flat layer with high accuracy. Finally, the frame was removed. Divers observed all the process and levelled the layer with a beam.

Seabed preparation (ABJV)

6. Foundation Installation

The crane EIDE barge 5, is placed carefully near the barge, and the lifting equipment is assembled. Then, the crane lifts the foundation and from 12 to 18 hour later the foundation is in position. Divers are required for the process.

After that, the pockets of the foundation were filled with pebbles and gravel, to achieve the weight needed to withstand the loads. Then, the foot and the surroundings meters of seabed were covered with large stones, avoiding the scour effect. This operation cost 850.000 euro.

Foundation installation (ABJV)

7. Turbine Installation

The turbines were transported to the location without assembling the blades. *A2SEA* and their vessel SEA POWER carried out the installation of the elements of the turbine.

Turbine installation (ABJV)

Companies involved

Design: COWI (Denmark)
Manufacture: ABJV (Denmark)
Seabed preparation: -
Installation: Eide Contracting (Denmark), A2SEA (Denmark); Peter Madsen Rederi (Denmark)
Main contractor: ABJV (Denmark)
Electrical line: Peter Madsen Rederi (Denmark)
Operator: Sund & Baelt Holding

Main vessels used

Foundations transport: “Giant 4”
Seabed preparation: Large backhoe on barge and split barge
Foundation Installation: “Eide Barge 5”
Turbine Installation: “Sea Energy”

Kårehamn

(Sweden)

Project data

Country: Sweden

Status: Under Construction

Project capacity: 48 MW

Number of turbines: 16

Distance from shore: 3.8 km

Water depth: 8 – 21 m

Stated project cost: 120 M€

Investment per MW: 2,5 M€/MW

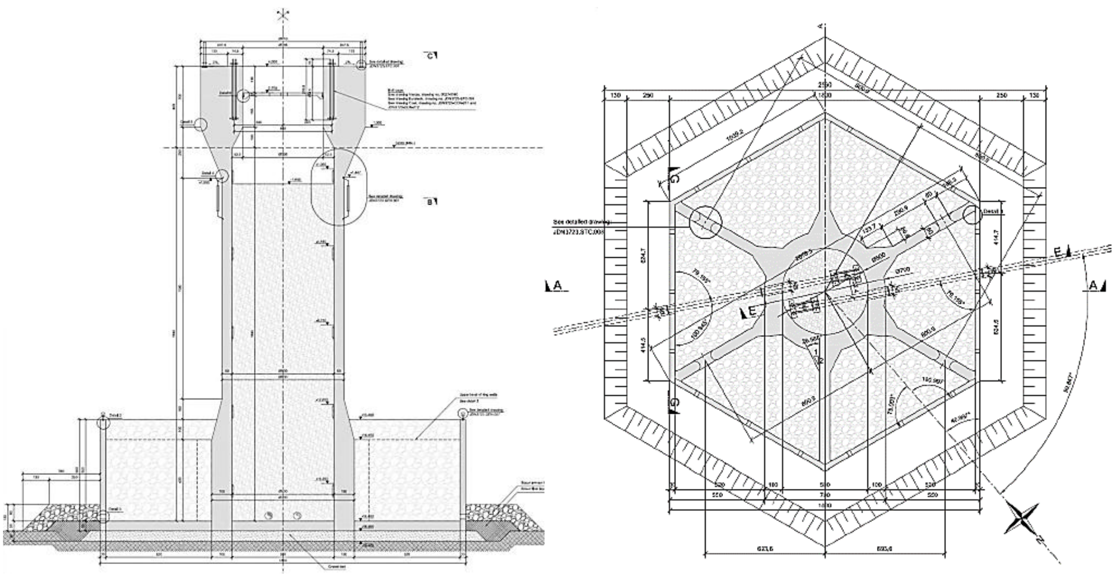
Foundations transport (Maritime journal)

1. General Information

Kårehamn is an offshore wind farm under construction in the Baltic Sea in Sweden. In May 2013, all the foundations have already been installed so in some months it is expected to start its commercial operation.

2. Foundation design

The foundations are quite similar than the Nysted I ones and they were designed as gravity based foundations with hexagonal shaped base with pockets to be filled when placed on the seabed. The hollow shaft have constant diameter and on the top the conical shape reduce the ice loads.



Foundation design (Jan de Nul)

3. Manufacture

Jan de Nul manufactured the foundations in the harbour of Zeebrugge (Belgium) on two pontoons. The cast was carried out in four steps: base plate, walls of the ballasting pockets, shaft and ice cone. All the foundations have been finished in about 4 months. 10,000 m3 of concrete C45/55 CemIIIA LA S4 has been poured. Some section has up to 435 kg/m3 of reinforcement.

Foundation manufacture (Left: RBS Formworks. Right: Jan de Nul)

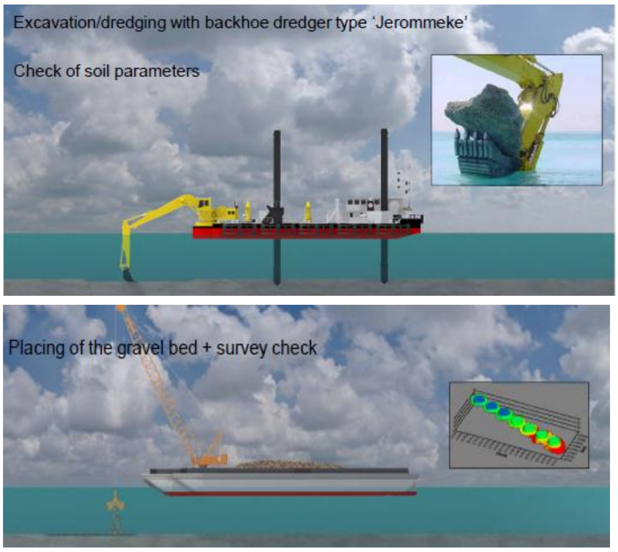
4. Transport

The foundations were towed to the final emplacement about 100 nautical miles (182 km) away in a 24 hours trip. Each 3 weeks average, a barge with 6 foundations could start the trip to Rødsand.

Foundation transport (Jan de Nul)

5. Seabed preparation

The seabed was prepared before the arrival of the foundations. A backhoe on a pontoon removed about 0.5 m of seabed. Then a layer of gravel was installed and an excavator on a pontoon equipped with a specifically designed tool levelled the gravel layer.



Seabed preparation (Jan de Nul)

6. Foundation Installation

When the foundations arrived and the seabed was prepared, the heavy lift *Rambiz*, owned by Scaldis, lifted the foundations. Then, the vessel lowered the foundations to its final position, with an accuracy of 30 cm.

The next step is ballasting the foundations in order to withstand the loads. Firstly, the shaft was filled with crude iron ore. This is a particularity of this project not used in other wind farms. Then, the compartments of the foundations were filled with crude iron ore as well and finally with a layer of heavy stones on the top.

To prevent the gravel layer erosion, a quarristone layer is installed as scour protection layer.

Foundation installation (Jan de Nul)

7. Turbine Installation

This work was carried out in May – June 2013. It will be installed 16 turbines of 3 MW each

Turbine installation (renews)

Companies involved

Foundation Design: Jan de Nul (Sweden) and COWI (Denmark)
Foundation Manufacture: Jan de Nul (Sweden)
Seabed preparation: Jan de Nul (Sweden)
Foundation Installation: Jan de Nul (Sweden) and Scaldis (Belgium)
Turbines installation: -
Main contractor of the foundation: Jan de Nul (Sweden)
Operator: EON (Germany)

Main vessels used

Seabed preparation: Large backhoe on barge
Foundation Installation: “Eide Barge 5”
Turbine Installation: “Sea Power”
Cable installation: “Nostag 10” and “Henry P. Lading”
Substation: “Rambiz”

Appendix B2. New foundation solutions

Strabag Solution

Cranefree Foundations

Gravitas Solution

GBF Solution

Strabag solution

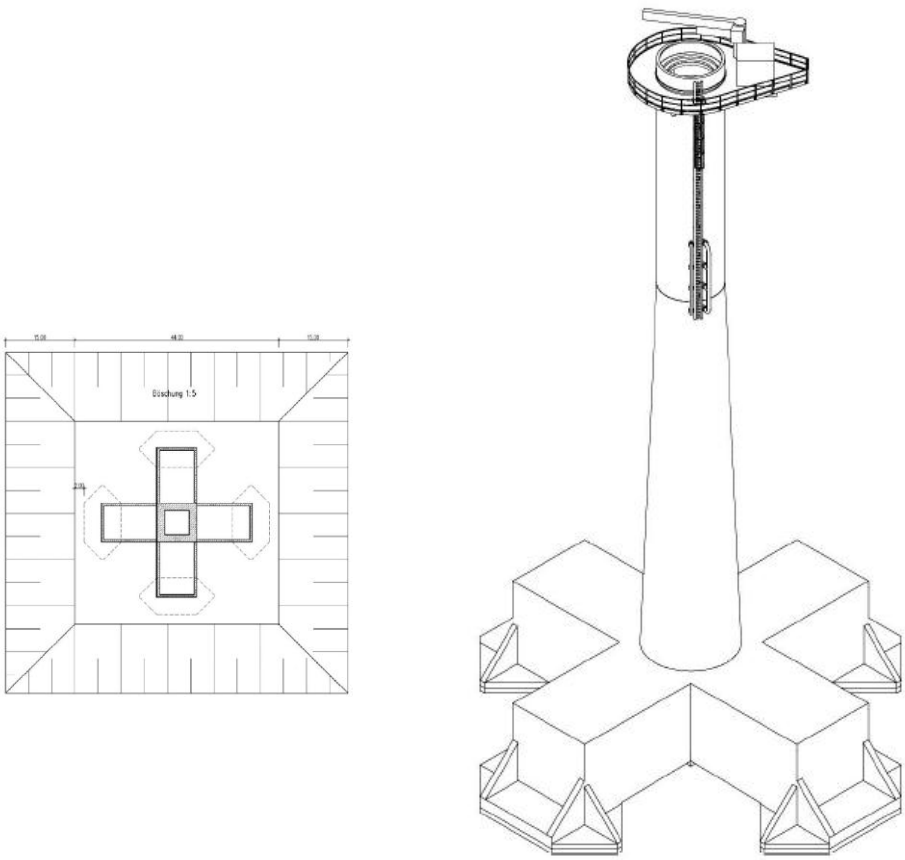
(Strabag)

1. Company Information

Strabag is a company based in Vienna that planned to invest more than 300 million euros on a factory to produce gravity based foundations and vessels for the installation. Strabag design was approved for the offshore wind farm Albatros 1, with 345 MW and a depth of about 40 m. However, Strabag has recently decided to postpone the investment in foundation and vessels due to uncertainties in the market.

2. Foundation design

The foundation has been designed as a gravity foundation with a cross-shaped base and a hollow shaft whose diameter is not constant (less diameter in the top). The cross shape in the base offers a high horizontal strength. The foundation is not buoyant.



Foundation view (Strabag)

3. Manufacture

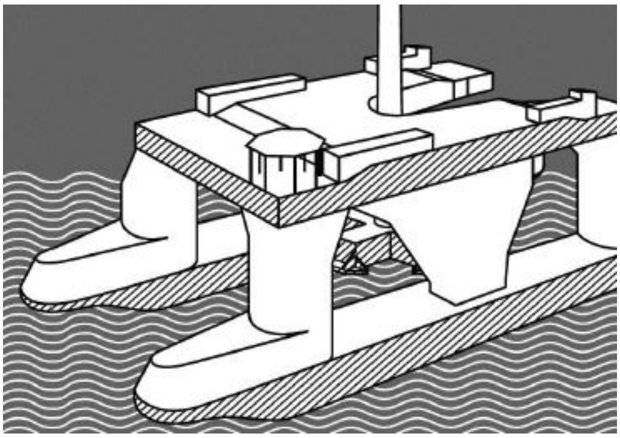
Strabag planned to produce the foundations in a quite industrialized process. The construction would take place in the port of Cuxhaven, where Strabag started to build a big factory for the foundations. The foundation weights about 5.500 tons. The reinforcement rates from 260 to 280 kg/m3, including 125 kg of prestressed steel as well.

Foundation manufacture (Strabag)

4. Transport

The foundation would be carried to its final location by means of a new vessel specifically designed for the purpose.

Foundation transport (Strabag)



Transport system (Strabag)

5. Seabed preparation

The seabed would be prepared dredging the first layer and later gravel layer installation or similar.

6. Foundation Installation

The foundation would be installed by means of the specifically design vessel. As scour protection, big bags have been proposed instead of rock armour.

Foundation installed (Strabag)

Cranefree solution

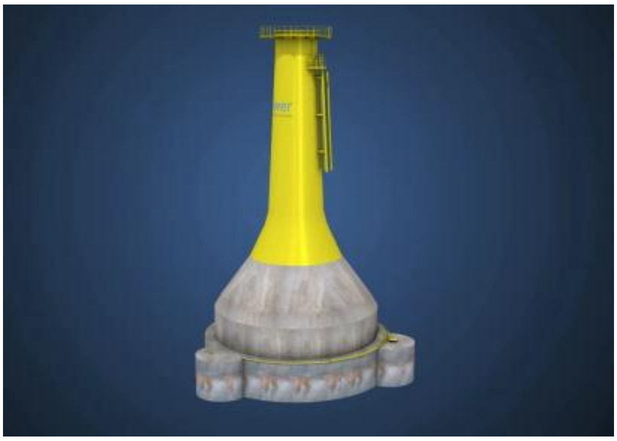
Seatower

1. Company Information

Seatower is a company that designs foundations for wind turbines and substations. Its design is based in the principles of oil and gas sector and pretends to avoid the use of heavy crane vessels and other heavy installation vessels. MT Hojgaard, leading company of offshore wind farms is the main partner of Seatower. Its design has received the ISO 9001 approval.

2. Foundation design

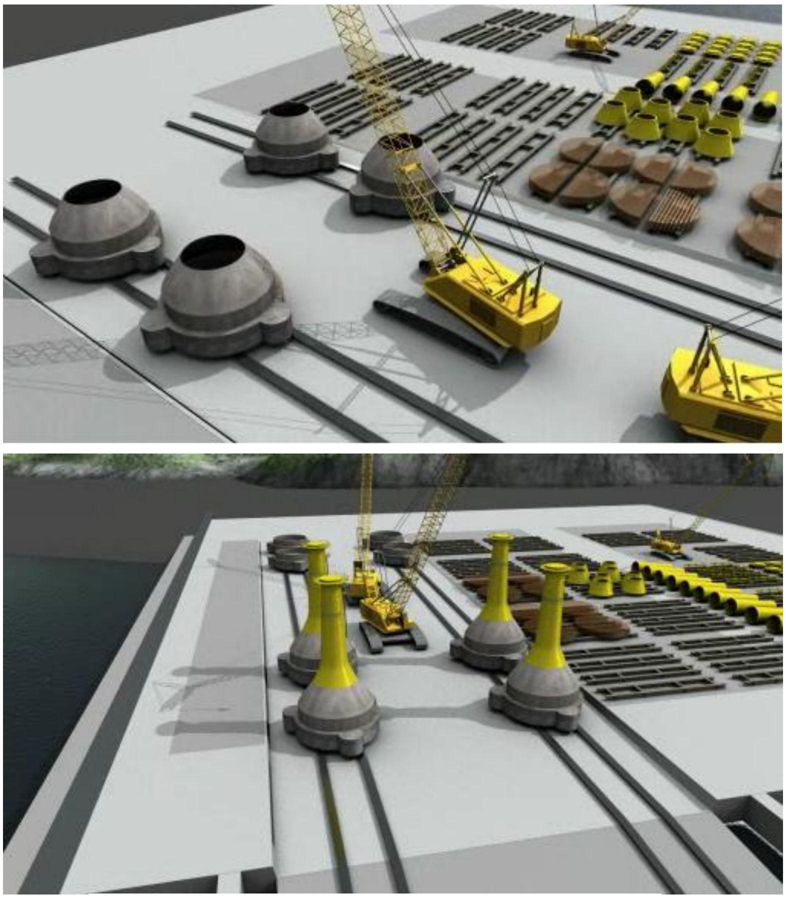
The foundation has been designed as a gravity based foundation with a hollow conical shape, designed to be buoyant and reduce the costs and risks of heavy vessels use. The main difference of the foundation is the steel skirt at the bottom, which allows the foundation to penetrate into the seabed and avoid the seabed preparation. The lower part is made of concrete and the upper part is made of steel.



Foundation view (Seatower)

3. Manufacture

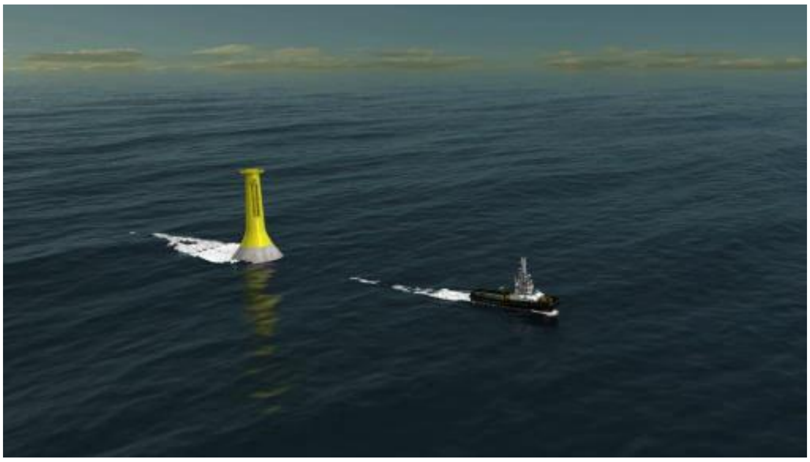
The construction of the foundations is carried out onshore in the harbour. The foundations are constructed in batches, starting with the assembling of the steel skirts. Then, the bottom slab and walls are cast. Finally, the steel tower and other elements are installed



Foundation manufacture (Seatower)

4. Transport

The foundations are buoyant, so they are towed to the final location by the same vessels that will install them. This process complies with the regulations.



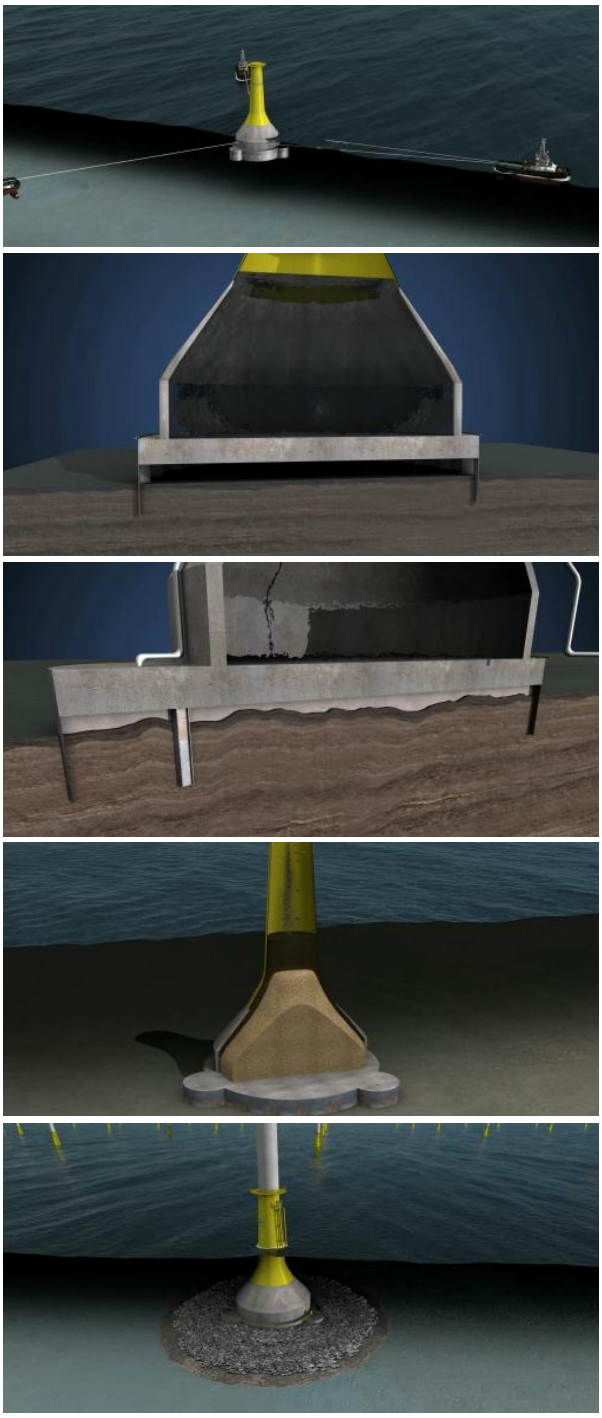
Foundation transport (Seatower)

5. Seabed preparation

According to the company, no seabed preparation is necessary, so these costs are eliminated.

6. Foundation Installation

First of all, the foundation is positioned by means of three vessels with the help of anchors. Then, hydraulic valves are opened to allow water get into the foundation, and the foundation starts lowering. When it reaches the seabed, the steel skirt penetrates into the seabed. Then, fluid concrete is pumped to fill the void under the foundation to provide a full contact between the seabed and the foundation, avoiding dredging and levelling. Then, the foundation is filled with sand. Finally, scour protection is installed to prevent erosion.



Foundation installation (Seatower)

Gravitas solution

(Gravitas)

1. Company Information

Gravitas is a consortium between *Hochtief*, Arup and *Costain*. *Hotchief* has strong marine knowledge and has participated in several offshore wind projects, while *Constain* has civil engineering and marine experience, and *Arup* is expert in marine structure design.

2. Foundation design

The foundation has been designed as a reinforced concrete ballasted gravity foundation with a hollow conical shape. It has skirt variants to suit seabed conditions and avoid or minimize the seabed preparation. The caisson is about 30 m diameter. The foundation is suitable for depths up to 60 m.

Foundation design (Gravitas)

3. Manufacture

The construction of the foundation takes place onshore and the quay does not require deep waters (10m). Each foundation would require about 3000 m3 of concrete and 900 tons of steel. Some dedicated facilities would be required, not only to build the foundation, but to provide concrete and storage spaces.

Foundation manufacture (Gravitas)

4. Transport

The foundation is self-buoyant so it has been designed to be towed to its locations by standard tugs. This eliminates the costs of heavy lift vessels and lowers the risk of availability of these vessels.

Foundation transport (Gravitas)

Foundation transport (Gravitas)

5. Seabed preparation

The foundation is expected to avoid or minimize the seabed preparation by accommodating existing slopes and sediments, and it also incorporates a skirt in order to reach a good founding layer.

6. Foundation Installation

The lowering is carried out by controlling the flux of water into the foundation, and then ballasting with sand or aggregates. An adapter ring could be used at tower interface to achieve the required verticality. Scour protection is installed to avoid erosion.

Foundation installed (Gravitas)

GBF solution

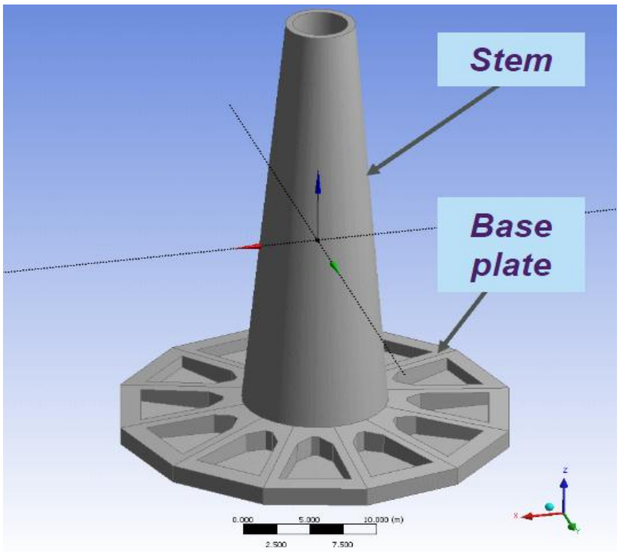
(GBF)

1. Company Information

Vinci Offshore wind is working with a consortium of Gifford, BTM Nigel Gee and Freyssinet (GBF) to create a low risk and low cost solution for gravity base foundation. The design has been selected in a competition of foundation for offshore wind farms organized by Carbon Trust.

2. Foundation design

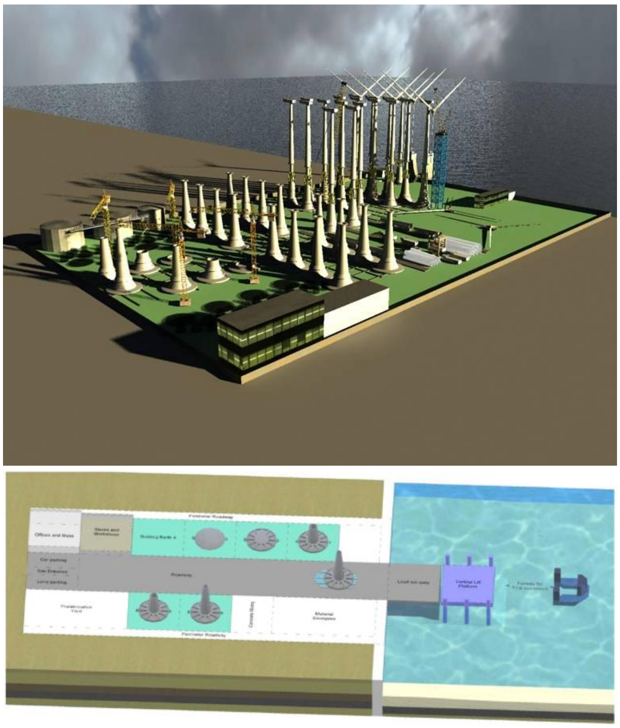
The foundation has been designed as a gravity foundation made of prestressed and passive reinforce concrete with a base plate and a hollow shaft whose diameter is not constant (less diameter in the top). The solution is suitable for depths from 20 to 60 m. The foundation is not buoyant but it has been optimized for a cost effective transport and installation process.



Foundation design (Gifford)

3. Manufacture

The foundation would be produced onshore, and would require a production facility with access to navigable water. It is expected to be produced a foundation per week, but it could be scaled up if necessary. The facility would include an area to receive materials, construction area, and a launching area. Slip forms would be used in the concrete casting process.



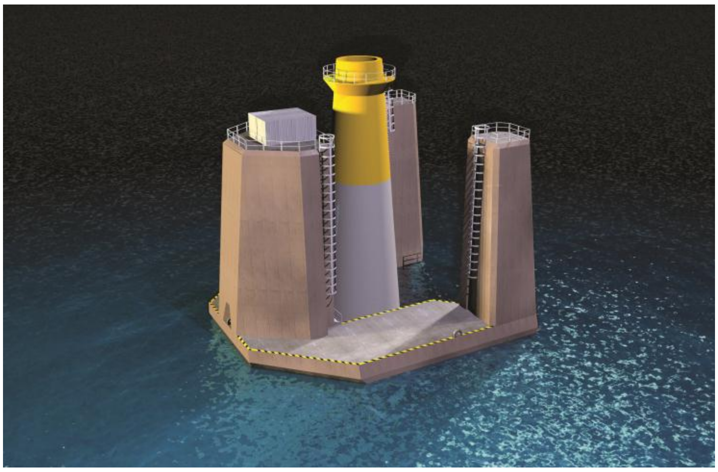
Foundation manufacture (Gifford)

4. Transport

The foundation has been optimized to be transported and installed by means of a TIB. This TIB is a semi-submersible barge that fit around the foundation shaft in order to behave as a single unit. The TIB does not have propulsive power, so it has to be towed by standard vessels, but it has a ballasting system to be submerged.

Once the foundation is finished, it is carried to a submersible barge. The barge is flooded until it reaches the seabed. Then, the TIB is positioned and flooded, to pick up the foundation, and when it is engaged, the TIB is unballasted, and both TIB and foundation are towed away.

Foundation transport (Freyssinet)



TIB with the foundation (Maritime journal)

5. Seabed preparation

There are no specifications available for the seabed preparation but in this foundation it is required and very important due to the base plate needs of a flat seabed.

6. Foundation Installation

When the TIB arrives with the foundation, it is positioned and ballasted, the foundation reaches the seabed, and the TIB is unengaged, unballasted and towed away. Sand ballast is pumped into the base and scour protection is installed around the base of the foundation.

Foundation installation (GBF)