BETTER SHIPS, BLUE OCEANS

End report of the Gravity based wind turbine foundation Joint Industry Project (GBS WIND JIP)

MARIN Report No.	**:**	**29246-5-PO**
RVO Project No.	**:**	**TEWZ116043**
Date	**:**	**March 2019**
Version	**:**	**1.0**
		Final Report

End report of the Gravity based wind turbine foundation Joint Industry Project (GBS WIND JIP)

MARIN order No. : 29246
MARIN Project Manager : E.J. de Ridder

Number of pages : 30

Ordered by : GBS WIND JIP

RVO project No. : TEWZ116043

Reported by : Ir. E.J. de Ridder
Reviewed by

Version	Date	Version description
1.0	March 2019	Final report

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REVIEW OF TABLES AND FIGURES

1 PROJECT DATA

Project Number	TEWZ116043
Project Title	Gravity based wind turbine foundation joint industry project
Applicant	Stichting Maritiem Research Instituut Nederland
Additional applicant	ECN part of TNO, Vuyk Engineering Rotterdam (Vuyk), Witteveen+Bos, Deltares, MARIN
Contact person Applicant	Erik-Jan de Ridder
Project Period	01-07-2016 t/m 31-12-2018
Date of this report	March 2019

2 PROJECT SUMMARY

The objective of the GBS WIND JIP was to improve the engineering methods of transport and installation of gravity based wind turbine foundations. So that this will lead to more effective and safer operations with better workability and optimised logistics.

The following sub objective were defined and reached as follows:

- To understand cost drivers in GBS design and fabrication: This objective was reached by the developed ECN install model for the GBS, and the case study performed in WP 1 and 4
- To understand the operational limits of GBS transportation under tow: This objective was reached for the tow condition, by the extensive model tests in MARIN's model basin and the full scale bridge simulation with the tug captains
- To understand the loads and motions of a GBS during transport and installation in order to optimise the (number of) vessels and equipment used: This objective was reached by the extensive model tests in MARIN's and Deltares model basins, and the full scale bridge simulation with the tug captains. Next to this detailed time domain simulation models were run for a matrix of environmental conditions, which can be used to determine workability for different locations.
- To develop a simplified suction model to predict motion behaviour for the GBS near the seabed: During the project it became clear, that the lowering of the GBS is going very slow, which means that this can be assumed to be a stationary process of a changing added mass.
- To develop a method to predict workability of a GBS installation in moderate waves: This is explained in detail in handbook by Vuyk Engineering Rotterdam and Bureau Veritas(BV)
- To include supply chain logistics in the installation planning and cost analysis. ECN part of TNO performed a detailed cost analyse for different case study's consisting of different concepts of GBS installation and construction methods. From this study it followed that eventually, the overall GBS LCOE is higher by 5-7% than in monopile case.
- Capitalising on opportunities for mass production of GBS within a centralised construction dock: This was part of the case studies performed by ECN part of TNO

3 INTRODUCTION OF THE GBS WIND JIP

As a result of the Paris convention it is expected that there will be a large increase in offshore wind energy capacity in the next decades. One expected trend is that larger wind turbines will be placed further offshore in relatively larger water depths.

For example, in the Netherlands the next generation wind turbines may be placed in water depths of 40 m. The future plans for “IJmuiden far” are an example of this development.

For remote areas new concepts are under development which aim for low installation cost and good workability in offshore environments. For larger wind turbines at larger water depths a Gravity Based Structure (GBS) foundation can be a feasible and cost effective option. To reduce the overall cost of offshore wind energy it is needed to optimise the fabrication, transport and installation process of such GBS constructions.

A better understanding of the towing and installation of such large concrete structures is required. This includes aspects such as towing stability, tug handling, operational logistics, hydrodynamic response in waves and bottom interaction during the placement on the bottom. At present the installation of GBS structures is carried out in civil engineering (e.g. tunnels and storm barriers) and in the oil and gas industry. These installations are typically done in the summer season. For the large scale at which wind turbine parks will be developed the industry needs better tools to be able to work in higher seas and still conduct safe operations.

In the past a lot of attention has been given to the towing and installation of large GBS constructions for the oil and gas industry. This was mostly done in low waves due to safety considerations.

Figure 3-1: Previous oil and gas industry using GBS

To achieve an economically feasible concept it is expected that the wind turbine industry needs to install the GBS construction in slightly higher sea states. This requires a better understanding of the motions and loads in waves during towing and installation of the GBS. This leads to better designs and safer working methods

In 2016, in an attempt to improve the design and engineering tools for the installation of gravity based wind turbine foundations, a Joint Industry Project (JIP) was launched by five entities: ECN part of TNO, Vuyk Engineering Rotterdam (Vuyk), Witteveen+Bos, Deltares, MARIN. Since April 2018 ECN has been acquired by TNO.

The main objective of the GBS WIND JIP is:

To improve the engineering methods of transport and installation of gravity based wind turbine foundations. This will lead to more effective and safer operations with better workability and optimised logistics.

The work plan consists of five technical work packages (WP).

- WP 1: Base case design:
- WP 2: Transportation:
- WP 3: Installation:
- WP 4: Logistics with ECN's planning tool:
- WP 5: Recommended practice:

The WPs were assigned to the project partners respectively. However, as it is a Joint Industry Project it was expected that all parties involved regularly gave constructive feedback to each other.
At the start of the project a basic design of a GBS will be designed based on a selected offshore location. The base case design will then be used in the remaining work packages to identify the most critical aspects during towing and installation of the GBS. Finally the lessons learned will be summarized in a recommended design and analysis methodology. This outcome can then be used by the participants of the JIP for new GBS offshore wind turbine foundation designs as shown graphically in Figure 3-2.

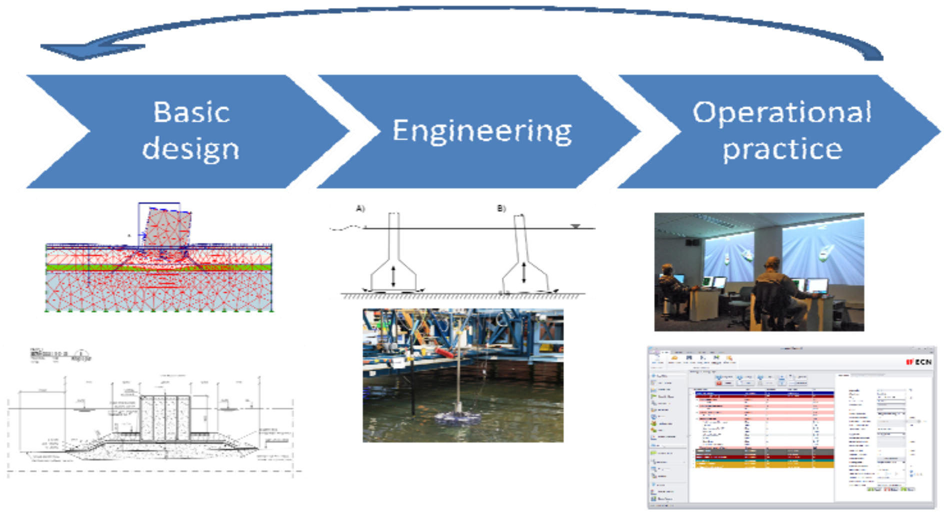


Figure 3-2 Overview of the project approach

4 OBJECTIVES OF THE GBS WIND JIP

To achieve an economically feasible concept for the transport and installation of a GBS, it is expected that the wind turbine industry needs to install the GBS construction in slightly higher sea states. This requires a better understanding of the motions and loads in waves during towing and installation of the GBS. This leads to better designs and safer working methods

The objective of the GBS WIND JIP was to improve the engineering methods of transport and installation of gravity based wind turbine foundations. So that this will lead to more effective and safer operations with better workability and optimised logistics.

To reach this objective the following sub-objectives are defined:

- To understand cost drivers in GBS design and fabrication
- To understand the operational limits of GBS transportation under tow and/or partly lifted
- To understand the loads and motions of a GBS during transport and installation in order to optimise the (number of) vessels and equipment used.
- To develop a simplified suction model to predict motion behaviour for the GBS near the seabed.
- To develop a method to predict workability of a GBS installation in moderate waves
- To include supply chain logistics in the installation planning and cost analysis.
- Capitalising on opportunities for mass production of GBS within a centralised construction dock

5 APPROACH OF THE GBS WIND JIP

The described goals of the GBS WIND JIP were achieved by using:

- Experimental verification by model tests in state-of-the-art test facilities.
- State-of-the-art numerical calculations.
- Industry experience from the market leaders.

The project was set-up as a Joint Industry Project (JIP) which has the following advances:

- Strong cooperation between the different partners (industry and research) and the sponsors to solve an industry wide problem.
- It offers a route to carry out expensive research and development but spread the costs over a number of interested parties.
- A good spreading of the development knowledge between the participating companies with their own expertise.

The project duration was 2½ years. During the project meetings with the participants were held each half year, were the developed knowledge was shared and discussed with the participants. Furthermore a project website was available were all the deliverables were distributed on. The following companies participated in the GBS WIND JIP:

Table 5-1: Project partners and participant

Partner/Participant	Type of company	Contribution
MARIN	Research institute	Hydrodynamic expert
Deltares	Research institute	Soil Expert
ECN	Research institute	Logistical expert
Vuyk	Engineering Company	Marine expert
Witteveen+Bos	Maritime engineering company	Design expert
Deme	Installation contractor	Expert in offshore installation
Besix	Building company	Expert in building large concrete structure
Saipem	Installation contractor	Expert in offshore installation
Jan de Nul	Installation contractor	Expert in offshore installation
Statoil	Energy company	Wind farm operator
Strukton	Installation expert	Installation expert, and performed the installation of the 1st GBS wind farm where the installation was done with Tugs (Blyth Wind farm)
Bureau Veritas	Classification company	Contribution to the handbook and regulation and classification expert
ALP Maritime	Tug company	Tug operation expert and delivering tug captains for the simulator
Monobase Wind	Engineering company	Engineering company and developer of a GBS foundation

6 PROJECT RESULTS AND DISCUSSION

The project was divided in three work packages:

Table 6-1: Summary overview of WPs and deliverables

WP	Task	Contractor	deliverables
1	Base case design and case study, environmental conditions	ECN,	ECN-X--17-003.pdf
		Witteveen+bos	WG93-1-17-013.598-rapd-WP1 Base case design GBS-signed.pdf
		Vuyk	180063LKl16405 - Stability GBS.pdf
2	**Investigation the transport of the GBS foundations**		
2.1	Identify existing methods	MARIN, Vuyk	Input delivered by means of Workshop
2.2	Towing resistance & course stability	MARIN	Model test report: 29246-1-BT&OB_Complete FINAL.pdf, Simulation report: 29246-3-PO GBS WIND JIP Workability Study v2_0.pdf
2.3	Tug capacity and operational practice	Vuyk, MARIN	29246-MSCN-v01.pdf
3	**Investigation the installation of the GBS foundations**		
3.1	Identify existing methods	MARIN, Vuyk	Input delivered by means of Workshop
3.2	Motion response and hydrodynamic loads	MARIN, Vuyk	Model test report: 29246-1-BT&OB_Complete FINAL.pdf, Simulation report: 29246-3-PO GBS WIND JIP Workability Study v2_0.pdf
3.3	Seabed interaction	Deltares	1230903-003-HYE-0001-r-Installation of gravity based wind turbine foundations_signed.pdf Model test data (on FTP Server)
3.4	Operational installation practice	MARIN, Vuyk	29246-MSCN-v01.pdf
4	**integrated project logistics and cost calculation**		
4.1	Step by step description of installation method	Vuyk	Input delivered by means of Workshop
4.2	Installation planning of GBS for wind turbines	ECN, Witteveen+bos,	First version of the installation tool has been delivered
4.3	Cost of energy analysis	ECN, Witteveen+bos	TNO 2018 R11606 GBS JIP Case Study Report - final draft.pdf
5	Recommended design and analysis methodology.	All parties	16405-R01B_Draft - WP5 GBS Wind JIP handbook 2019.pdf
6	Project management	MARIN	MARIN Report 29246-5-PO_End report GBS Joint Industry Project.pdf

6.1 WP 1: Base case design

The work conducted in WP1 is the generic design of the GBS. To determine this generic design a first estimation of loads was made based on the foreseen GBS location. With this first load estimation a rough dimension was determined which was used for a preliminary load analysis. Based on the results of the load analysis an optimization of the GBS dimensions was made based on geotechnical stability calculations.

For the general design of the GBS a reprehensive location in the North Sea and the German Bight was chosen. This means that a certain water depth and corresponding metocean condition is applied so that it becomes a realistic North Sea condition.

For the generic designs of the GBS a fictive water depth of 35 m is implemented, this is a depth which corresponded with the encountered depths at the foreseen locations. From this depth it’s expected that the use of a GBS can be concurrent to the use of a monopile.

For the structural elements (i.e. walls or floors) assumptions of the thickness were made based on expert judgment and workability. No specific attention was given to the structural design of the GBS since it was assumed not to be relevant for this JIP.

The “bases case” GBS is a self-floating GBS which is sailed to the final location where it is immersed. Based on the stability calculations of the “base case” the dimensions of a non-floating GBS were estimated and used for the logistics and costs comparisons in WP4.

Based on the work performed in WP 1, a GBS with a diameter of 38 m is designed as presented in Table 6-2 and Figure 6-1:

Property	Value	Unit
Diameter base	38	m
Height of base	12	m
Height of cone	13	m
Diameter of shaft	8	m
Total model height	50	m
Estimated mass	11200	t
Draught	9.4	m

Table 6-2: Dimensions of base case GBS

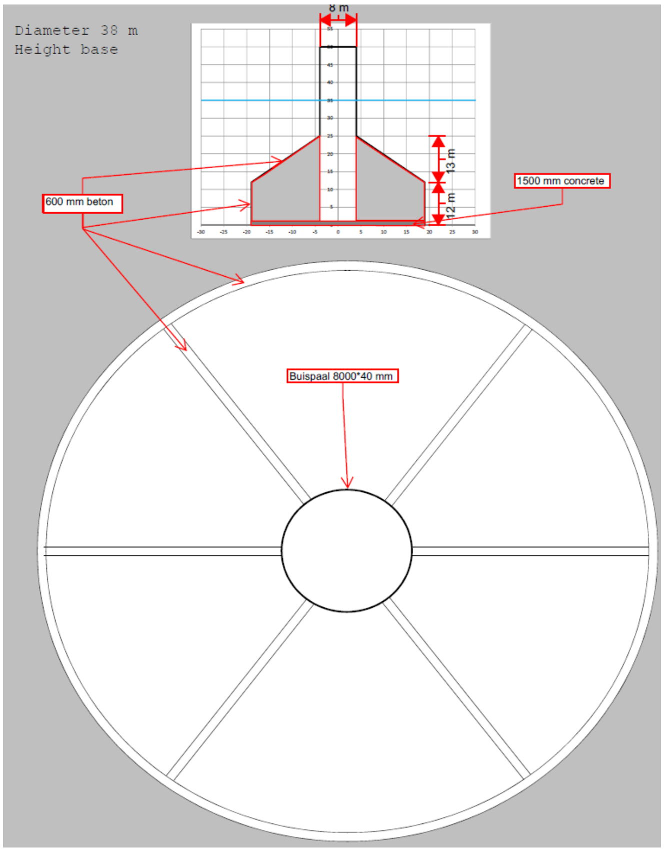
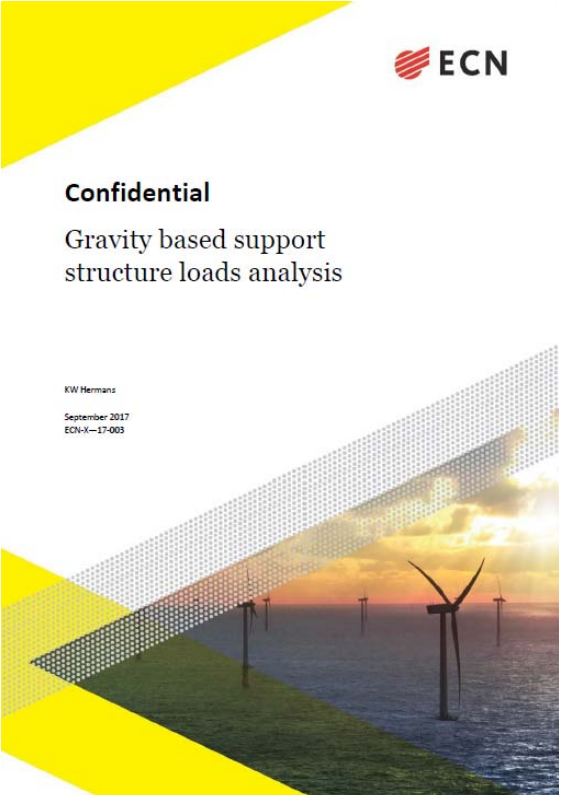
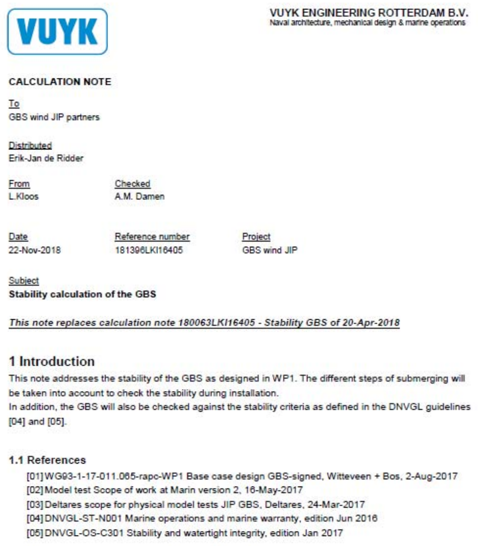


Figure 6-1: GBS design

The results of this the WP 1 were summarised in the following reports:

Report No.	Report name	Title
 	ECN-X--17-003.pdf	**Gravity based support structure loads analysis** *This report described the load due to wind and waves on the base case GBS foundation design.*
 	WG93-1-17-013.598-rapd-WP1 Base case design GBS-signed.pdf	**GBS JIP WP 1** *This report described the geotechnical design of the base case GBS foundation design.*

Report No.	Report name	Title
	180063LKI16405 - Stability GBS.pdf	**Stability of the GBS** *This report described the stability calculations for the base case GBS foundation design.*

VUYK

VUYK ENGINEERING ROTTERDAM B.V.
Naval architecture, mechanical design & marine operations

CALCULATION NOTE

To
GBS wind JIP partners

Distributed
Erik-Jan de Ridder

From: L.Kloos
Checked: A.M. Damen

Date: 22-Nov-2018
Reference number: 181396LKI16405
Project: GBS wind JIP

Subject
Stability calculation of the GBS

This note replaces calculation note 180063LKI16405 - Stability GBS of 20-Apr-2018

1 Introduction

This note addresses the stability of the GBS as designed in WP1. The different steps of submerging will be taken into account to check the stability during installation.
In addition, the GBS will also be checked against the stability criteria as defined in the DNVGL guidelines [04] and [05].

1.1 References

[01] WG93-1-17-011.065-rapc-WP1 Base case design GBS-signed, Witteveen + Bos, 2-Aug-2017
[02] Model test Scope of work at Marin version 2, 16-May-2017
[03] Deltares scope for physical model tests JIP GBS, Deltares, 24-Mar-2017
[04] DNVGL-ST-N001 Marine operations and marine warranty, edition Jun 2016
[05] DNVGL-OS-C301 Stability and watertight integrity, edition Jan 2017

6.2 WP 2: Transport of GBS

In this work package the hydrodynamic challenges during the transport of the GBS foundations was investigated. As input the GBS design from Wp1 was used. This work package was divided in the following sub work packages:

- Identify existing methods (WP 2.1)
- Towing resistance & course stability (WP 2.2)
- Tug capacity and operational practice (WP 2.3)

6.2.1 WP 2.1 Identify existing methods

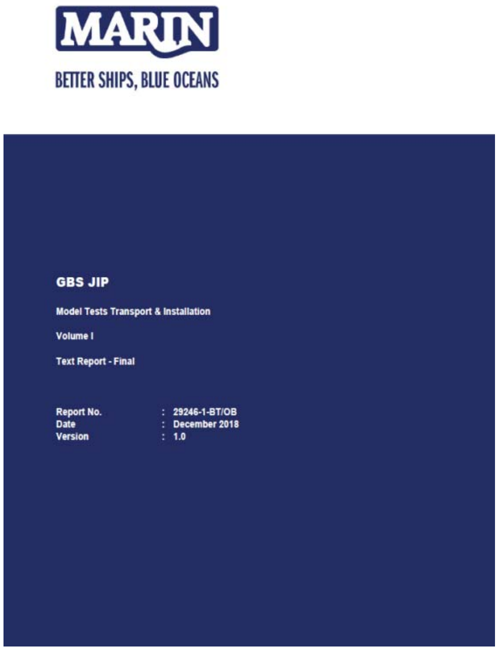
Vuyk and MARIN summarized the existing engineering methods used for the transportation of GBS's. In this WP 2.1 the method of transport was defined including the size of the tug's to be used and the characteristics of the towing lines. The outcome of this study defined the setup used in the WP 2.2 and 2.3.

6.2.2 WP 2.2 Towing resistance & course stability

The towing resistance and course stability was determined with different methods from simple engineering tools to complex model tests. From the model tests it followed that Vortex Induced motions (VIM) can occur during transport. Therefore different towing velocity's were tested in the model basin. The simple numerical simulations cannot predict this VIM behaviour. Therefore a force time series was extracted from the model test, and was applied to the numerical model. In this way the VIM behaviour could be modelled during the simulator training. In this work package the following tools were used:

- Diffraction calculation for one GBS foundation
- Transportation model tests for one GBS foundation in MARIN's shallow water basin.
- Time domain simulations for the GBS foundation in which the complete transport can be simulated. This model was used in the simulator training with the operational tug captains described in WP 2.3.

The results of the model tests performed in WP 2.2 were summarised in the following report:

Report No.	Report name	Title
 BETTER SHIPS, BLUE OCEANS GBS JIP Model Tests Transport & Installation Volume I Text Report - Final Report No. : 29246-1-BT/OB Date : December 2018 Version : 1.0	29246-1-BT&OB_Complete FINAL.pdf	**GBS JIP Model tests transport & installation** *This report described the transport and installation tests performed with the GBS foundation*

6.2.3 WP 2.3 Tug capacity and operational practice

Vuyk in cooperation with Strukton and BV produced rough method statements and defined the equipment needed. For example they defined the type of Tugs to be used and the towing line requirements, taking into account Marine Warranty needs (Guidelines) and their experience.
An interactive bridge simulator model was prepared, including the floating GBS and 3 coupled tugs. MARIN organised a 5 day workshop, in which several aspects of the transport and installation operation were demonstrated and discussed. The tugs in the bridge simulator model were operated by tug captains. The tug models were controlled from desktop set-ups, including radio communication, radar and electronic map. The objective of the workshop was to give operational personnel the opportunity to review and comment on the operational procedures. Furthermore, different towing arrangements were simulated and the operational people gave feedback on which approach is most optimum from their point of view. The feedback was then used in the final design of the procedures. Furthermore, the optimum towing arrangement and operational limits were determined based on the outcome of the bridge simulations.

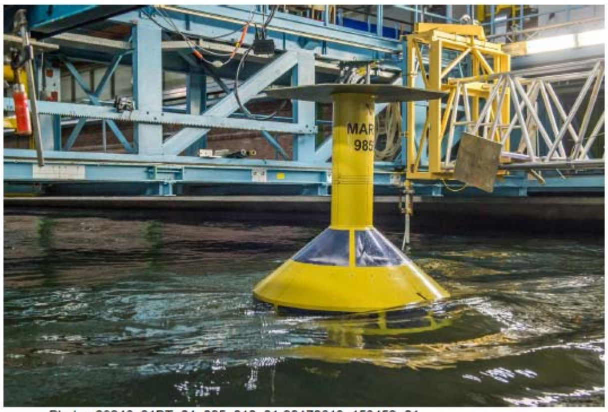
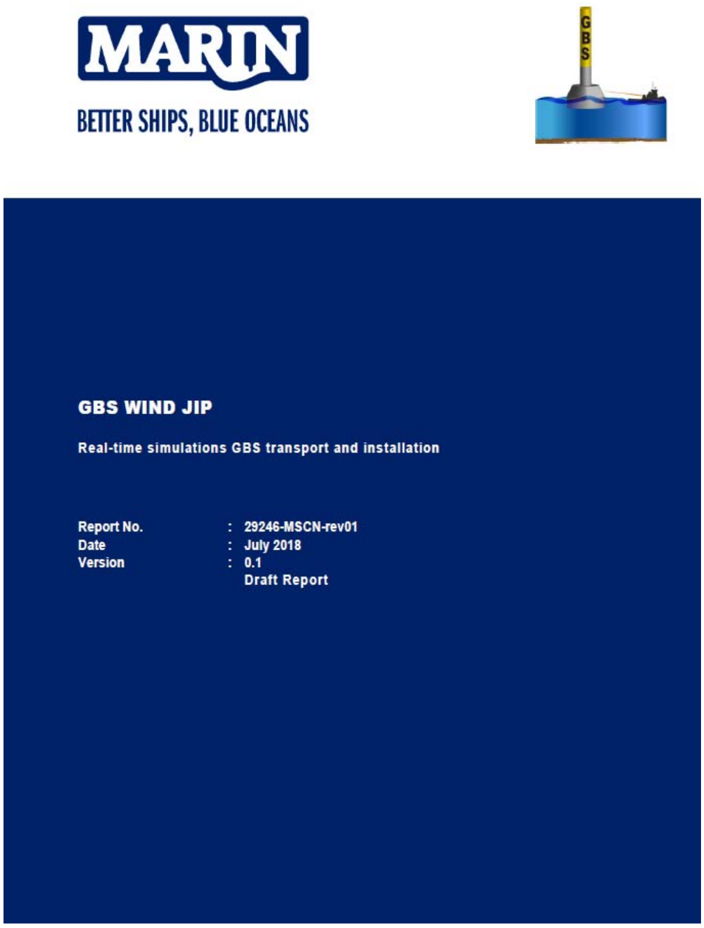


Photo: 29246_01BT_04_005_010_01-20170613_153452_01

Figure 6-2: Model tests for the transport of a GBS as part of the GBS WIND JIP

Figure 6-3: Bridge simulations for the transport of a GBS as part of the GBS WIND JIP

The results of the Real-Time simulations performed in WP 2.3 were summarised in the following report:

Report No.	Report name	Title
 MARIN BETTER SHIPS, BLUE OCEANS GBS WIND JIP Real-time simulations GBS transport and installation Report No. : 29246-MSCN-rev01 Date : July 2018 Version : 0.1 Draft Report	29246-MSCN-v01.pdf	**GBS WIND JIP Real-time simulations of GBS transport and installation** *This report described the transport and installation simulations performed in the bridge simulator with tug captains*

6.3 WP 3.3: Installation of a GBS

This work package investigated the hydrodynamic challenges during the installation of the GBS foundations. As input the GBS design made in WP1 was used. This work package was divided in the following sub work packages:

- Identify existing methods (WP 3.1)
- Motion response and hydrodynamic loads (WP 3.2)
- Seabed Interaction during installation of a GBS (WP3.3)
- Operational installation practice (WP 3.4)

6.3.1 WP 3.1 Identify existing methods

Vuyk, Deltares and MARIN summarized the existing engineering methods used for the installation of GBS's. For this rough method statements were made with respect to the lowering/touchdown methods as well as the positioning methods. Next to this the equipment needed was defined. MARIN made a summary of the different methods used (ranging from simple calculations to complex model tests) during the engineering phase of GBS installation which was basis of the tools used in the remaining sub WP'2.

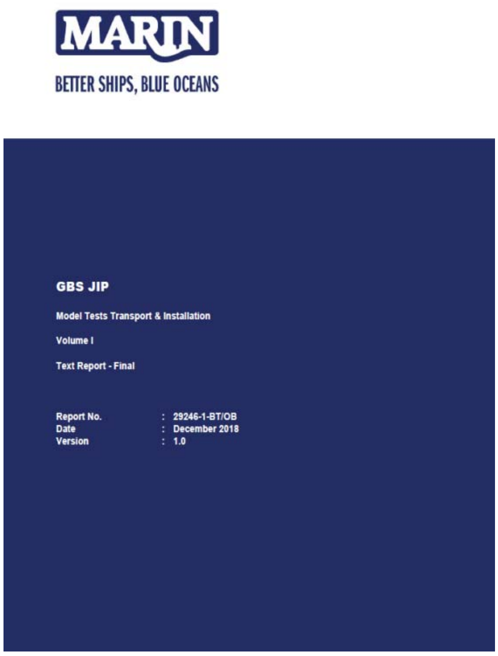
6.3.2 WP. 3.2 motion response and hydrodynamic loads

The full installation of the GBS was determined with different methods from simple engineering tools to complex model tests. From the model tests it followed that the installation of the GBS by means of tugs's moored on simplified DP (Dynamic positioning) could be posisble. However from the simulation it followed that when a full DP system was used it was difficult to keep the GBS within the required location during installation. Therefore the workability simulations were performed with a setup were the tugs are moored to the seabed by means of an anchor.

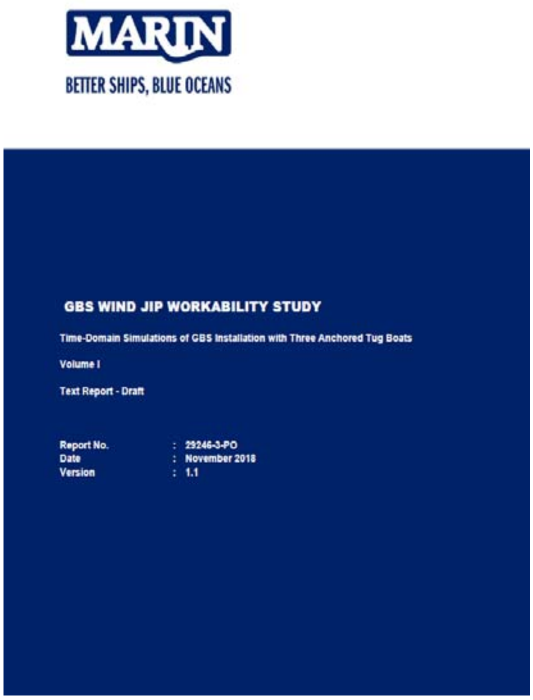
In this work package the following tools were used:

- Diffraction calculation for one GBS foundation
- Installation model tests for one GBS foundation in MARIN's shallow water basin.
- Time domain simulations for the GBS foundation in which the complete installation can be simulated. This model was used in the Simulator training with the operational tug captains

The results of the model tests performed in WP 3.2 were summarised in the following report:

Report No.	Report name	Title
	29246-1-BT&OB_Complete FINAL.pdf	**GBS JIP Model tests transport & installation** *This report described the transport and installation tests performed with the GBS foundation*

The results of the workability simulations, performed in WP 3.2 were summarised in the following report:

Report No.	Report name	Title
	29246-3-PO GBS WIND JIP Workability Study v1_1.pdf	**GBS WIND JIP workability study** *This report described the workability simulations for the installation phase of a GBS wind turbine foundation*

6.3.3 WP 3.3 Seabed interaction during installation

This work package 3.3 focused on the last phase of the installation process, just before and after the touchdown moment. The GBS is lowered to the seabed and is installed on a pre-installed gravel bed. This is a particularly critical moment where the seabed, the GBS, and the marine operation all come together. The main objectives of the scope were:

- Investigate the effect of a permeable pre-installed filter layer on the motions of the GBS during the lowering phase of the installation (Series A).

- Determine the motions of the GBS and the deformation of the filter layer during inclined and non-inclined touchdown of the GBS (Series B).

- Asses the stability of a water ballasted GBS installed on the seabed under 1 year storm Conditions (Series C).

An example of the touchdown of the GBS on the filter layer as measured during the model tests at Deltares model basin is shown in Figure 6-4:

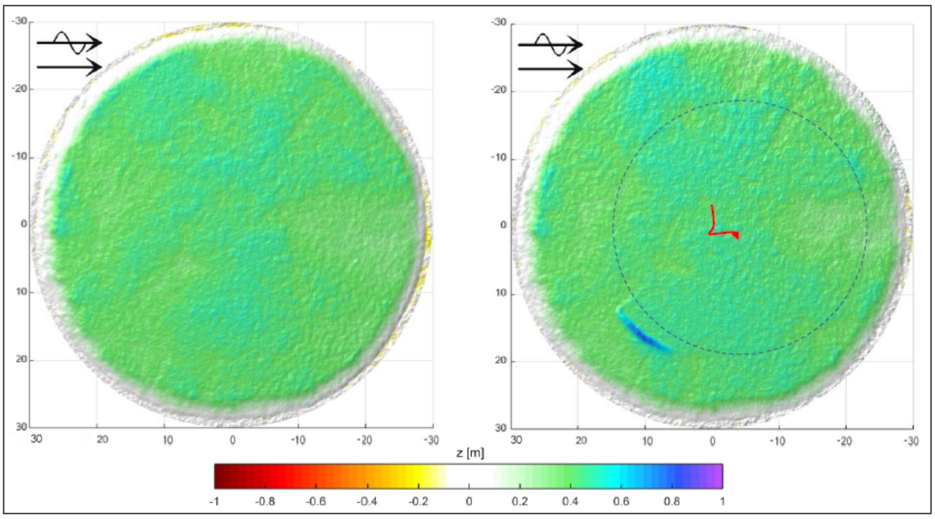
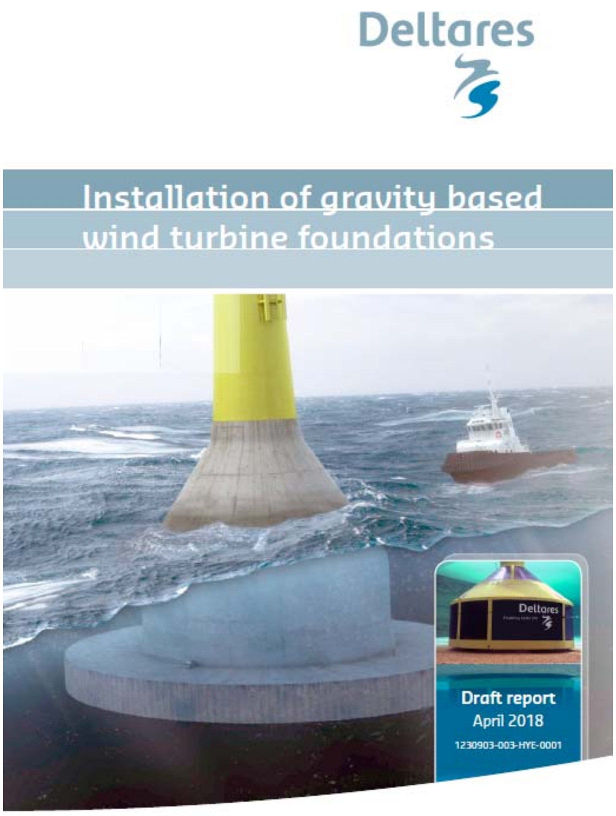


Figure 3.71 2D-visualizations of the filter layer using stereo-photography measurements. Left: pre-installed filter

Figure 6-4: An example of the touchdown of the GBS on the filter layer

The findings of these three different test campaigns are in the following report:

Report No.	Report name	Title
	1230903-003-HYE-0001-r-Installation of gravity based wind turbine foundations_signed.pdf	**Installation of gravity based wind turbine foundation** *This report described the last phase of the installation process, just before and after the touchdown moment*

6.3.4 WP 3.4 Tug capacity and operational practice

Vuyk in cooperation with Strukton and BV produced rough method statements and defined the equipment needed. For example they defined the type of Tugs to be used and the towing line requirements, taking into account Marine Warranty needs (Guidelines) and their experience.
An interactive bridge simulator model was prepared, including the floating GBS and 3 coupled tugs. MARIN organised a 5 day workshop, in which several aspects of the transport and installation operation were demonstrated and discussed. The tugs in the bridge simulator model were operated by tug captains. The tug models were controlled from desktop set-ups, including radio communication, radar and electronic map. The objective of the workshop was to give operational personnel the opportunity to review and comment on the operational procedures. Furthermore, different installation arrangements were simulated and the operational people gave feedback on which approach is most optimum from their point of view. The feedback was then used in the final design of the procedures. Furthermore, the optimum installation arrangement and operational limits were determined based on the outcome of the bridge simulations.

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Figure 6-5: Model tests for the installation of a GBS as part of the GBS WIND JIP

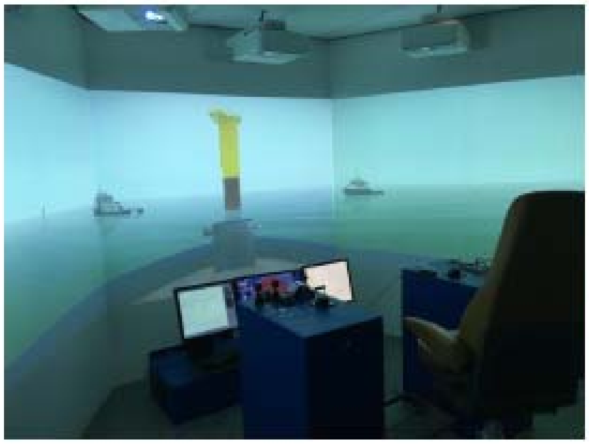
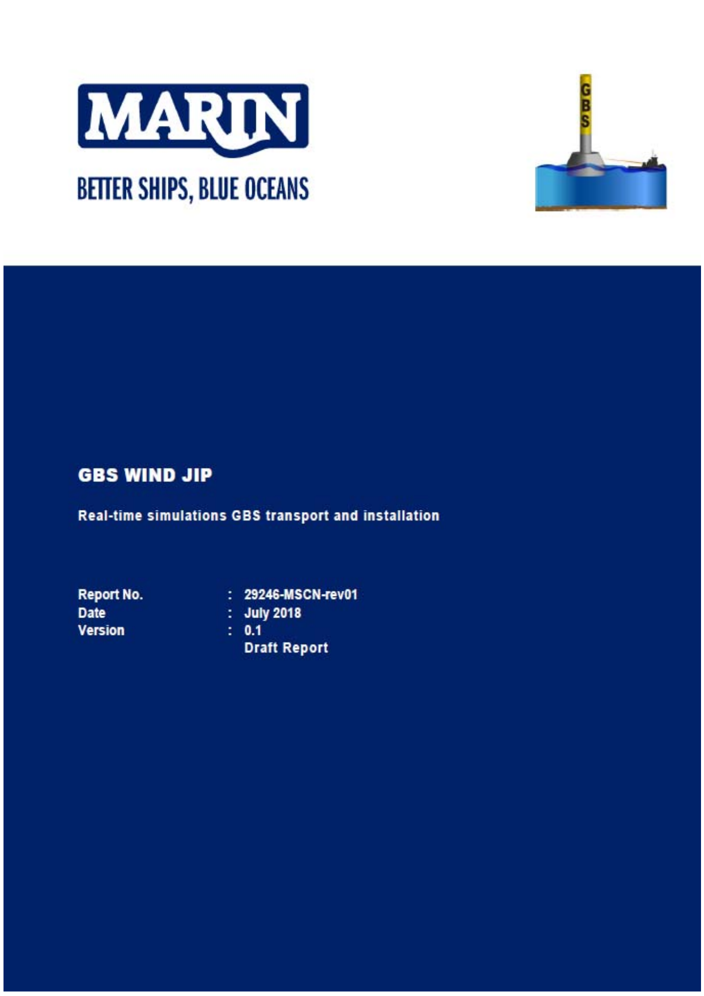


Figure 6-6: Bridge simulations for the installation of a GBS as part of the GBS WIND JIP

The results of the Real-time simulations performed in WP 3.4 were summarised in the following report:

Report No.	Report name	Title
 MARIN BETTER SHIPS, BLUE OCEANS GBS GBS WIND JIP Real-time simulations GBS transport and installation Report No. : 29246-MSCN-rev01 Date : July 2018 Version : 0.1 Draft Report	29246-MSCN-v01.pdf	**GBS WIND JIP Real-time simulations of GBS transport and installation** *This report described the transport and installation simulations performed in the bridge simulator with tug captains*

6.4 WP 4: Integrated project logistics and cost calculations

In this work package the Integrated project logistics and cost calculations during the installation of the GBS foundations was investigated. This work package was divided in the following sub work packages:

- Step by step description of installation method (WP 4.1)
- Analysis of the installation/building planning (WP 4.2)
- Cost of energy analysis (WP 4.3)

6.4.1 WP 4.1 Step by step description of installation method

Based on the outcome of WP2 and 3 Vuyk developed a step by step description of the installation method. The outcome of this study defined the setup used in the WP 4.2 and WP 4.3.

6.4.2 WP 4.2 Analysis of the installation/building planning

This task focused on the building, assembly and installation modelling of Gravity Based Support structures (GBS). The modelling was done by using the planning tool 'ECN Install' and the experience of Witteveen+Bos. During the GBS wind JIP project the planning tool 'ECN Install' was further developed and the improved version of the tool was also delivered to the JIP participants. This improved tool called ECN Install V3.1 was then used in the case study performed in WP 4.3.

6.4.3 WP 4.3 Cost of energy analysis

This work package different case studies have been performed. In the case study's, different cases of GBS installation are compared with the monopile reference case:

- Floating GBS tow-out (from dry-dock).
- (~30% lighter non-floating) GBS on installation vessel (from quayside).
- Tow-out with pre-installed turbine based around the Monobase concept. Tow out will be from dry-dock.

All cases are evaluated for a 600 MW wind farm consisting of 60 x 10 MW wind turbines at the 'Borssele' location with 'Damen Verolme Rotterdam' as installation port.

The study consists of two parts: installation modelling using ECN Install V3.1 and a Levelized Cost of Energy calculation using ECN OWECOP LCoE. The results of this study give insight into the duration of the installation, the importance of different types of delays and the required resources for a wind farm with GBS foundations.
Based on the results obtained in the case study report, the study has delivered the following outcomes:

- Constructing 20 GBS at a time in a drydock has a higher risk compared to construction on the quay. A delay of one of the GBS construction processes will impact the whole batch and increase the total construction costs.
- The foundation installation times for the GBS cases are longer than the monopile reference due to the low speed of towing (maximum 4 knots) and extended installation operations (lowering and ballasting) with limited weather windows (less than 1.5m significant wave height).
- Tugboats have an advantage in terms of costs per day compared to jack-up vessels or heavy lift vessels. However, the advantage gets eliminated or even negative due to much longer transportation and installation duration.

- The time to transport and install a GBS with a heavy lift vessel is shorter than using the tugboats, but the costs of this vessel is much higher than any vessel used in this study. Therefore, there is no gain in the total installation costs for the lifted GBS case. Furthermore, the availability of such vessels (with a large lifting capacity >7000 mT) is very limited as well. By the time this report is being written, it is noted that only 3 vessels active in Europe can perform this type of operation.

- The LCOE of GBS are 5-7% higher compared to the monopile reference case due to:

    - higher foundation construction costs (material, indirect, and site renting); 35%, 18% and 52% for floating GBS, lifted or lighter GBS, and integrated GBS.

    - higher installation costs; 43% and 126% for floating GBS and lifted GBS

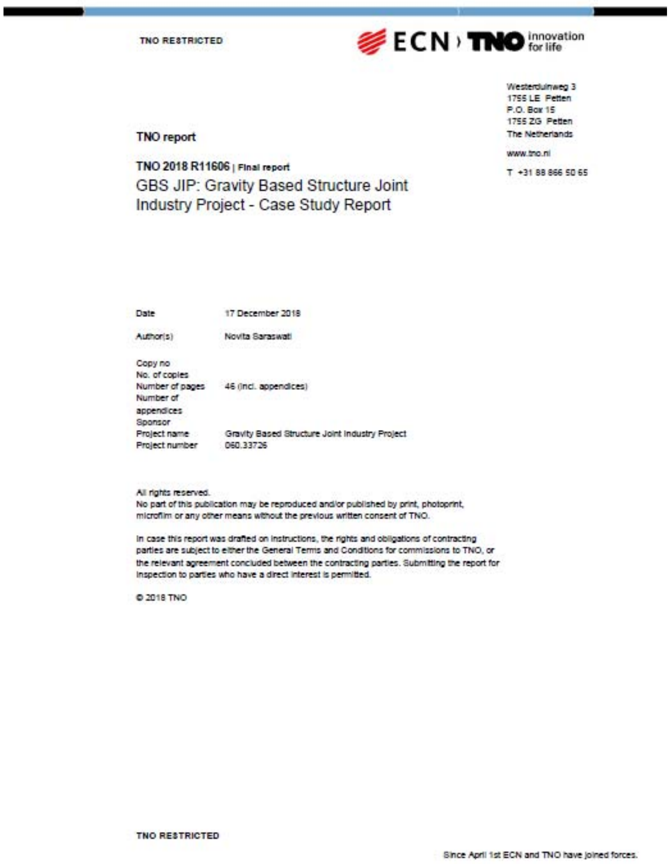
- The distance of the wind farm to the construction port will proportionally increase the sailing duration and eventually the total installation costs. The installation costs for ‘Dogger Bank’ are 39% higher than for ‘Borssele’, considering the Verolme Damen drydock from which the foundations are towed.

- There is potential cost reduction in installation, with the following options:

    - If the workability for the longer operations, such as towing, water ballasting and sand ballasting can be higher

    - If Installation is only carried out within favourable seasons (April – September)

The results of the case studies performed in WP 4.3 were summarised in the following report:

Report No.	Report name	Title
	TNO 2018 R11606 GBS JIP Case Study Report - final draft.pdf	**GBS JIP Gravity based structure Joint Industry project – Case study Report** *This report described the case study comparing the GBS foundation to a monopile foundation for different offshore wind farm locations.*

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TNO report

TNO 2018 R11606 | **Final report**
GBS JIP: Gravity Based Structure Joint Industry Project - Case Study Report

Date	17 December 2018
Author(s)	Novita Saraswati
Copy no	
No. of copies	
Number of pages	46 (incl. appendices)
Number of appendices	
Sponsor	
Project name	Gravity Based Structure Joint Industry Project
Project number	060.33726

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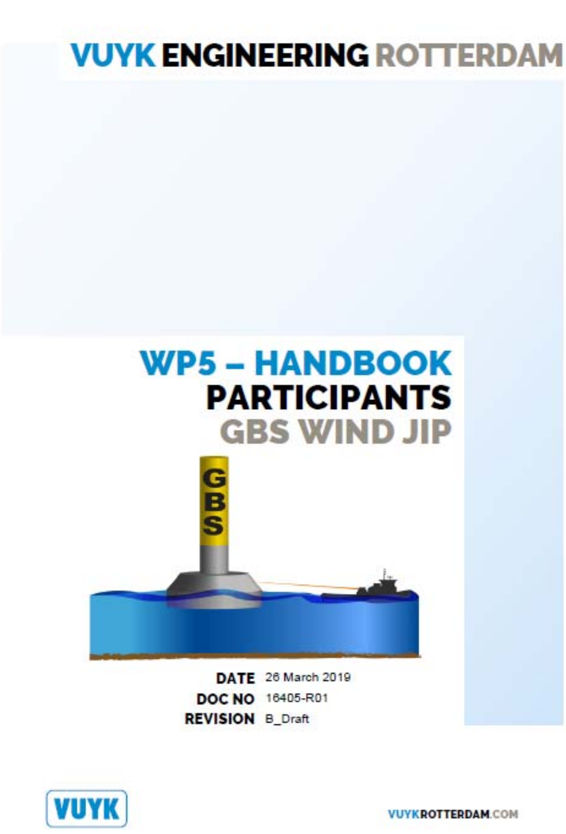
Since April 1st ECN and TNO have joined forces.

6.5 WP 5: Recommended design and analysis methodology

This work package 5 summarised the work performed in the first four work packages. This was done in such a way that the outcome can be used by the partners and participants in future GBS installation and transport projects.

The results of this work packages was summarised in the following report:

Report No.	Report name	Title
	16405-R01B_Draft - WP5 GBS Wind JIP handbook 2019.pdf	**WP 5 – Handbook participants GBS wind JIP** *This report presented a summary of the different WP's performed in the GBS wind JIP*

6.6 WP 6: Project management

In WP 6 the project was supervised and the overall progress, deliverables, milestones were monitored. Furthermore the interaction between WPs and the project meetings were organised.

Generally the project was a success. Related to the original application some changes took place:

- Timing of execution of different activities somewhat changed from original planning. As some delay during the execution of different activities was encountered, we were able to finish the project within the extended deadline.

In summary the project led to the successful development of increased knowledge in the field of transport and installation of Gravity Based wind turbine foundations.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Conclusions

The objective of the GBS WIND JIP was to improve the engineering methods of transport and installation of gravity based wind turbine foundations. So that this will lead to more effective and safer operations with better workability and optimised logistics.

The following sub objective were defined and reached as follows:

- To understand cost drivers in GBS design and fabrication: This objective was reached by the developed ECN install model for the GBS, and the case study performed in WP 1 and 4
- To understand the operational limits of GBS transportation under tow: This objective was reached for the tow condition, by the extensive model tests in MARIN’s model basin and the full scale bridge simulation with the tug captains
- To understand the loads and motions of a GBS during transport and installation in order to optimise the (number of) vessels and equipment used: This objective was reached by the extensive model tests in MARIN’s and Deltares model basins, and the full scale bridge simulation with the tug captains. Next to this detailed time domain simulation models were run for a matrix of environmental conditions, which can be used to determine workability for different locations.
- To develop a simplified suction model to predict motion behaviour for the GBS near the seabed: During the project it became clear, that the lowering of the GBS is going very slow, which means that this can be assumed to be a stationary process of a changing added mass.
- To develop a method to predict workability of a GBS installation in moderate waves: This is explained in detail in handbook by Vuyk Engineering Rotterdam and Bureau Veritas(BV)
- To include supply chain logistics in the installation planning and cost analysis. ECN part of TNO performed a detailed cost analyse for different case study’s consisting of different concepts of GBS installation and construction methods. From this study it followed that eventually, the overall GBS LCOE is higher by 5-7% than in monopile case.
- Capitalising on opportunities for mass production of GBS within a centralised construction dock: This was part of the case studies performed by ECN part of TNO

7.2 Recommendations

The work that has been performed in the GBS WIND JIP paved the way to explore relevant topics for future research. The recommended actions are discussed below:

- Further study focusing on reducing the costs of GBS construction is required. First challenge is to reduce the effective material costs per ton, followed by the costs of the construction site (time required), in this case the dry dock.
- The effect on costs and time of constructing GBS in smaller batches (5 or 10 maximum) should be investigated.
- For the installation aspects, the study mainly compares the workability and performance of two types of vessels – tugboats and heavy lift vessels. However, the vessel construction industry is progressing at a fast pace with a lot of potential innovative concepts and realistic designs. More installation scenarios, such as using different types of vessels like a semi-submersible barge that can carry more than 1 GBS or another way than controlled water ballast to lower the GBS, should be investigated.
- The workability for GBS installation is very limited in the chosen location. A different GBS design could have different stability and limitations during towing and installation. Further study should

include the investigation of higher workability (at least 2-2.5 metres significant wave height) to reduce delays and eventually installation costs.

- Both ballasting operations, lowering with water and filling with sand take a long time. There should be an investigation on using ballast vessels with higher ballasting rate or even two ballast vessels in the same time to reduce the operation time. The time reduction will affect the overall project duration and total installation costs.
- Installation of the lifted (lighter) GBS is highly limited by the weather conditions both with significant wave height and wind speed especially during the lifting operation. This limitation needs to be validated by a scale model and simulation, which are currently not performed in the GBS project. If the limitations taken in this study are found to be on the conservative side, then the real LCOE may also decrease.
- Some evolving input parameters such as electricity price and the price of vessels must always be re-evaluated in future studies.
- The future study also shall include the end-of-life options and de-installation and decommissioning strategy and costs for both monopile and different types of GBS since they contribute to the total lifetime costs

8 EXECUTION OF THE PROJECT

8.1 Project Evaluation and spin off

The project and the executed activities within it have been evaluated during the last few months of the project.

Evaluation of activities: the activities planned were all executed by the different project partners and led to an improved knowledge in the field of transport and installation of gravity based wind turbine foundations.

Evaluation of cooperation. The cooperation between project partners was constructive and positive. Project partners agreed to keep each other updated on further progress and use of the knowledge developed within this project. MARIN can offer its support in the operation around gravity based foundations, taking into account the results off the GBS wind JIP. ECN/TNO will use its improved Install software to advise (future) offshore wind farms on the most optimum logistical approach. The companies will use the outcome of the GBS WIND JIP to improve their service in the field of offshore wind installation.

The project execution, including the cooperation between project partners went quite smoothly while the project partners (ECN part of TNO, Vuyk Engineering Rotterdam (Vuyk), Witteveen+Bos, Deltares, MARIN) are all used to work within complex cooperation projects with often international partnerships. This experience that is present within all project partners led to a solid management of project and eased cooperation. Furthermore JIP participation meetings were held on regular bases were the latest project results and developed theory were discussed.

Generally the project was a success. Related to the original application some changes took place:

- Timing of execution of different activities somewhat changed from original planning. As some delay during the execution of different activities was encountered, we were able to finish the project within the extended deadline.

8.2 Challenges during the project

With respect to project execution, we can draw the conclusion that in general the project progressed rather smoothly. Important factors that influenced project execution are listed below:

- ¼ year extension of the project was required to finish the project. This was a result of the full scale bridge simulations which were delayed due to the availability of the tug captains and the required input needed from the model tests and the simulations.
- In the last years offshore wind has seen a large grow which made it difficult within the partners to find sufficient human resource to perform the required work for the GBS WIND JIP.

In summary the project led to the successful development of increased knowledge in the field of installation of gravity based offshore wind turbine foundations. The combined efforts of the project partners led to the expected knowledge increase and subsequent successful execution of this innovative project.

8.3 Actual costs

Within the following table the total costs per category are presented. The total budget per type of costs is compared to the actual costs made during the execution of the project.

Kostenspecificatie totaal

Wind op Zee project GBS Wind JIP
Project no.: TEWZ116043
Declaratieperiode: 01-07-2016 t/m 31-12-2018

		Kosten		Begroot		Kosten	Begroot
		Fundamenteel Onderzoel	Industrieel Onderzoel	Fundamenteel Onderzoel	Industrieel Onderzoe	Totaal	Totaal
1	**loonkosten direct personeel**	€ 0.00	€ 711,598.78	€ 0.00	€ 717,743.00	€ 711,598.78	€ 717,743.00
2	**kosten van machines en apparatuur:**						
	2a uitsluitend voor het project aangeschaft:	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
	2b niet uitsluitend voor het project aangeschaft:	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00	€ 0.00
3	**Kosten van te verbruiken materialen en hulpmiddelen:**	€ 0.00	€ 41,069.46	€ 0.00	€ 54,508.00	€ 41,069.46	€ 54,508.00
4	**kosten derden:**	€ 0.00	€ 26,850.57	€ 0.00	€ 16,000.00	€ 26,850.57	€ 16,000.00
5	**Reis- en verblijfskosten**	€ 0.00	€ 720.00	€ 0.00	€ 0.00	€ 720.00	€ 0.00
	Totaal subsidiabele kosten	€ 0.00	€ 780,238.81	€ 0.00	€ 788,251.00	€ 780,238.81	€ 788,251.00
	Subsdidiebedrag (100% FO en 60%/80% IO)	€ 0.00	€ 585,508.25	€ 0.00	€ 607,906.00	**€ 585,508.25**	**€ 607,906.00**
	Subsidiebedrag, maximaal EUR 607.906						

The actual costs are specified in detail in separately delivered cost overview. Per partner a statement is attached for the cost made in the project.

8.4 Publicity and Knowledge dissemination

Knowledge dissemination was done through:

- JIP participants meeting every ½ year.
- Through papers and presentations at conferences.
- Article in the TO 2 magazine called: Wind en Water bundelen krachten

Next to this the partners are planning several conference papers in the coming year presenting the outcome of the GBS wind JIP

The following conference presentation was given

1. *Novita Saraswati, Integrated project logistics and costs calculations for gravity based structure. EERA Deepwind 2019, Trondheim January 17th 2019.*

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