OPTIMIZATION OF OFFSHORE PLATFORM DESIGN, USING THE PIONEERING SPIRIT FOR INSTALLATION

Quantitative assessment of the PS-installation possibilities, compared to the conventional installation method of the Kebabangan platform

Master Thesis

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Optimization of offshore platform design, using the Pioneering Spirit for installation

Quantitative assessment of the renewed installation method, compared to the conventional installation method of the Kebabangan platform

By

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

PREFACE

This report is written in partial fulfilment of my MSc. Offshore Engineering at Delft University of Technology. The work was carried out for, and facilitated by, Allseas BV in Delft.

The report is the result of a research on the installation of offshore platforms. Allseas is nearing the completion of Pioneering Spirit, an offshore pipe-lay and heavy lift vessel. The main question was what the advantages could be for the design of an offshore platform, when Pioneering Spirit would be used for installation. This is a broad subject and the scope needed to be defined. To narrow down the scope, a good understanding on platform design was needed. This information was gathered during my literature study.

The risk of this topic was the high-level view on the problem. I chose to go into depth on manageable parts of the problem. After discussions and analysis, three areas of interest were selected. These three areas were investigated in detail.

Normally, a platform is designed by a team of engineers. This research covered the preliminary design, but can serve as a starting point on the topic. Furthermore, future projects can be approached in the same manner to be able to see where the use of the Pioneering Spirit can result in advantages.

Acknowledgments
I would like to thank all the members of the thesis committee for their advice and guidance, in particular my supervisors Marijn Dijk, Frank Sliggers, Federico Pisanò and my chairman André van der Stap. They all helped me on their respective fields of expertise.

Further, I would like to thank my colleagues at Allseas for the enjoyable time in Delft and all the input and thoughts on my research. All colleagues were very open for discussions and in providing interesting insights.

Lastly, I would like to thank my fellow students at the university and at Allseas. They were great as sparring partners and sometimes a welcome distraction.

Ernest Pigeaud
Delft, December 2015

SUMMARY

Platform installation in the oil and gas offshore industry is a critical phase between design and "first oil". Although the topsides are becoming heavier, the demand for integrated topsides remains.

Pioneering Spirit is a vessel built by Allseas, with the purpose to lift integrated topsides and substructures. Her lifting capacity and capability is unique in the offshore industry. Consequently, the design of platforms to be installed by the Pioneering Spirit can be optimized in several areas. The identification of this specific opportunity resulted in the research question of this MSc. thesis:

"What are the most significant advantages in the field of platform design, when using Pioneering Spirit for installation?"

To answer this question, the Kebabangan platform was used as a case study. The comparison between a renewed optimized platform and a conventionally installed platform resulted in a quantifiable answer. All design steps, boundaries, design criteria and opportunities were mapped. By means of a Multi-Criteria Analysis all individual areas of interest were scored and weighted; comparing the installation capabilities of Pioneering Spirit to the conventional installation methods of the Kebabangan platform in a qualitative way.

The most significant potential advantages were identified in the following areas: Transport and installation (1), substructure design (2) and integrated foundation (3). These three areas were investigated more thoroughly in this research.

1. *Transport and installation*

The conventional transport and installation-scenario of the Kebabangan platform was compared to several transport and installation scenarios which can be executed by the Pioneering Spirit. Including day-rates, mobilization costs and the deferment, multiple scenarios are economically preferable. The profitable scenarios show a 30% cost reduction on average (with a maximum indicative saving of $20.000.000).

One of the main advantages is the installation of substructures with Pioneering Spirit instead of launching. Using Pioneering Spirit, items that are not able to withstand a launch operation (boat-landing, parts of the foundation) can be installed onshore, significantly reducing offshore installation time.

2. *Substructure design*

A substructure must be designed to support the topsides, therefore the substructure design is influenced by the characteristics of the topsides. For the conventional Kebabangan platform a float-over operation was used for the topsides installation. When designing the substructure with boundary conditions derived from an installation method with Pioneering Spirit, different design drivers arise. When taking these into account in the design phase, the substructure design can be optimized significantly with respect to the amount of steel. This preliminary re-design for the Kebabangan substructure showed a steel reduction of 40%, resulting in cost savings of approximately $30.000.000.

This reduction is a combination of the decreased amount of temporary steel required for a launch operation, and the decreased amount of structural steel for the substructure itself, as without a float-over operation a less wide substructure will suffice.

3. *Integrated foundation, suction anchor*

The conventional foundation technique (skirt piles) was compared to other possibilities using Pioneering Spirit. At Kebabangan, the soil properties allow for suction anchors to be installed. The use of suction anchors instead of conventional skirt piles results in large savings in the transport and installation phase, up to $7.000.000.
This is mainly induced by the time saving component. The installation of a skirt pile takes one to two days, whereas conventionally 12 skirt piles are required. The four required suction anchors can be installed simultaneously within a day.

The three investigated areas on platform design are the first steps in design optimization for “Pioneering Spirit platform installation”. This preliminary research achieved a total initial saving in the order of $50.000.000, testing the optimization on the Kebabangan case study. The findings show great potential for Pioneering Spirit and Allseas.

To generalize the advantages, it is recommended to asses more case studies with the optimization method as applied in this research. Furthermore, in future case studies, the workability in the transport and installation phase should be incorporated. As a next step, the results of the quantitative research should be substantiated numerically.

Table of Contents

1 INTRODUCTION

1.1 Background

All over the world offshore platforms are being installed to get the hydrocarbons out of the ground from beneath the seabed. These platforms all have their own unique features and locations and need a tailor-made installation method, e.g. tow-out, launching, float-over or modular lifting.

Due to rules and regulations, it is becoming common practise that offshore platforms need to be removed when they are no longer in production. Therefore, there is a growing market demand for the decommissioning of offshore platforms. Currently, this is a complex and costly operation, as the structure is often decommissioned in multiple modules, where topsides and substructures need to be dismantled at the site location.

Recently, Allseas has come up with an alternative for decommissioning of offshore structures, with the design and construction of the Pioneering Spirit (PS). The PS has greater lift capacity than the existing heavy lift vessels today. Furthermore, it enables possibilities in decommissioning larger and heavier platforms in a unique way. Instead of modular decommissioning, as is commonly done at the moment, the PS is capable of lifting topsides as a whole, resulting in major reductions in terms of costs and time.

This development raises the question whether the PS can also provide advantages in the **installation phase** of offshore platforms, and subsequently in the **design phase**, as the design is highly dependent on the installation procedure. This research investigates the potential optimization of platform design that can be achieved by using the PS for the installation of an offshore platform.

1.2 Scope and objective

As the subject has a wide range of possibilities, the scope of this research is narrowed down.

The objective is to come up with an integrated and optimized platform design, while using the PS for installation. The goal is to present quantitative results of the advantage that can be achieved by using the PS for platform installation.

"What are the most significant advantages in the field of platform design, when using Pioneering Spirit for installation?"

A platform design is a complex combination of the design of several sections, which are all interdependent. An overview is given in Figure 1-1, showing a typical offshore platform.
An offshore platform is divided in three sections:

- Topsides: Topsides design is strongly dependent on the composition of the hydrocarbons in the ground, pressure, depth, wanted production rate, etc. The weight of the topsides is determined by these properties.
- Substructure: The substructure has the purpose to keep the topside above the water level at all times. It must withstand all environmental influences as well as the weight of the topside and its own weight. The installation method of both the topside and the substructure influences the shape of the substructure.
- Foundation: The foundation secures the substructure to the seabed and ensures that the connection between the seabed and the substructure is able to resist the loads on the topside and substructure.

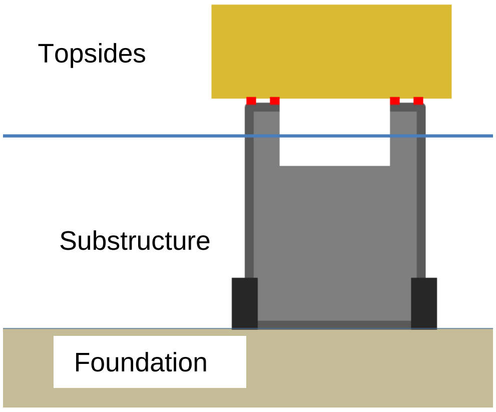


Figure 1-1: Offshore platform

To narrow the scope for this research, a preliminary design is made for such a platform, while using the full potential of the PS. The potential advantages for all separate sections of the platform will be investigated qualitatively. For the most promising advantages, a quantitative assessment will be carried out.

1.3 Methodology

The methodology of this research is explained in this section. To reach the objective, the following steps are taken:

To investigate the advantages of an optimized platform design by using a new installation method, first the conventionally used methods need to be investigated. The platform will be divided into three sections: Topside, substructure and foundation. Conventional installation methods are investigated for each section. To get a thorough understanding of the drive behind the conventional design of a section, general installation requirements and boundaries are addressed.

Thereafter, the capabilities and boundaries of the PS will be investigated. Its characteristics will be described and the new possibilities for platform installation are investigated. Based on this, a suitable case study can be selected.

A case study is carried out to be able to quantify the potential optimization of the PS. An existing platform will be selected, to which the PS can be compared while it is being used in its full potential. The design of the conventionally installed case study will be investigated, followed by the optimized design with the PS installation method.

The advantages that result from this comparison are qualitatively analysed by means of a Multi-Criteria Analysis (MCA). The highest scores in the MCA are the most promising areas for potential optimization.

The most promising areas thereafter are quantitatively assessed, again comparing it to the case study. Optimizations for the platform design for the most promising areas will be presented.

1.4 Report structure

The background of this research, scope and objectives and methodology is presented in this Chapter. Below, the structure for the remainder of the report is presented.

- In Chapter 2 the general approach of offshore platform design is described. Also, the dimensions and boundaries of the PS are defined.
- In Chapter 3 the case study is executed. The requirements and boundaries of the case study are provided and the conventional design and installation method as applied is discussed. In this chapter, preliminary potential advantages of the PS are pointed out. The case study is used in a later stage to be able to quantify potential advantages.
- Chapter 4 contains the MCA. The comparison method, the selected criteria and the results are presented here. The outcome is a ranking of the most promising areas for optimization of the platform design.
- These most promising areas are quantitatively assessed in Chapter 5, resulting in a detailed calculation of the cost-savings that can be obtained by using the PS for platform installation.
- The conclusions and recommendations of this research are presented in Chapter 6.

Note. Within this report numbers with decimals are indicated by a comma and a dot is used as the thousand separator.

2 OFFSHORE PLATFORM DESIGN

2.1 Introduction

This section introduces the general approach of platform design, describing the importance of the installation phase and how decisions in installation method influence the final design. Following, the capabilities and boundaries of the PS are described.

2.2 Offshore platform design – general approach

The design of an offshore platform starts with a hydrocarbon reservoir. The knowledge regarding the amount of hydrocarbons in a reservoir, the composition and pressure leads to the required process-installations to process the hydrocarbons. The capacity of process-installations correlates with the size of the process installations. All the process-installations must be housed on the topsides (together with living quarters, helideck, etc.) With this, the main weights and dimensions of the process-installations are known. Subsequently, the initial required dimensions and weights of the topsides can be estimated (left-hand flow chart in Figure 2-1).

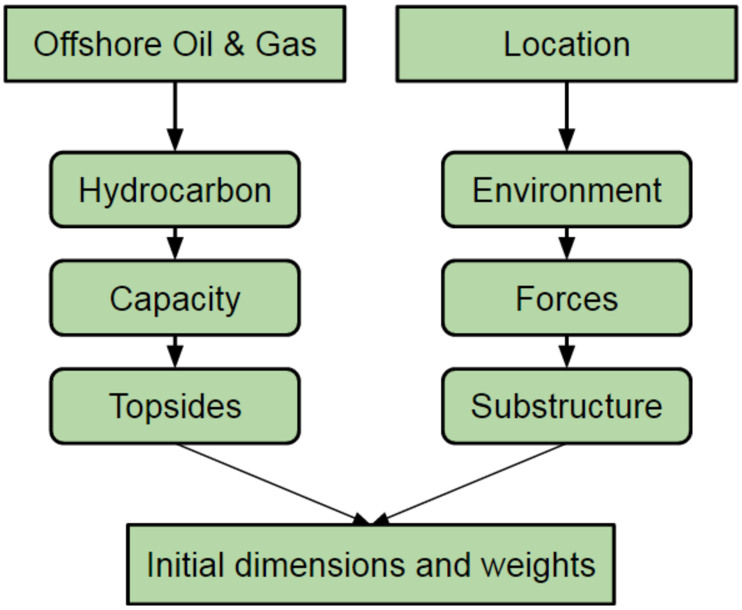


Figure 2-1: General approach offshore platform design

A substructure is needed to support the topsides and to protect the topsides from environmental influences like waves. At the reservoir location the water depth and the environmental conditions (waves, current and wind) will attack the substructure and the topsides. The substructure will have to withstand the weight of the topsides as well as the forces induced by the environment. With these requirements for the substructure, the initial dimensions and weights can be determined (right-hand flow chart in Figure 2-1).

The different sections of the offshore platform are described below. The existing conventional installation methods are presented.

For each offshore platform, the topsides and substructure need to be constructed, transported, installed and commissioned. The type of installation of both sections is interdependent.

2.2.1 Topsides

When installing the topsides, the weight is of great importance. Commonly used installation methods for topsides are single lift, modular and float-over installation. Each method has its own range of lifting capacity.

Single lift installation
In Figure 2-2 a single lift topsides installation is shown. The topsides are lifted entirely by a crane vessel and positioned on top of the substructure. Smaller integrated platforms may be installed by single lift. The lifting capacity of the crane vessel is limiting. When using single lift, the commissioning of the platform is done relatively easy.

Figure 2-2: Single lift topsides installation
(adapted from [1] (2015))

Modular installation
When the weight of the topsides exceeds the lifting capacity of a crane vessel, the topsides can be divided in multiple smaller units. These units can then be installed individually. In Figure 2-3 a unit is being installed by a crane. When dividing the topsides in smaller units, a smaller crane can be used. A drawback of this installation method is the commissioning of the topsides after installation. All the units have to be connected offshore.

Figure 2-3: Modular installation topsides
(adapted from [2] (2015))

[1] http://www.offshore-technology.com/projects/carina/carina5.html
[2] http://www.chevronunitedkingdom.com/news/latest/2015-06-23-clair-ridge-modules-installed.aspx

Float-over
A float-over operation (refer to Figure 2-4) is a method that can be applied when the weight of the topsides exceeds the crane vessels capacity. The topsides are positioned on a barge. The barge is then manoeuvred between the legs of the substructure. When in position, the barge is ballasted and the topsides is set on the legs of the substructure. Using a float-over allows for heavy integrated topsides installation, reducing the commissioning time offshore compared to the modular installation. A drawback of this method is the design of the substructure is strongly influenced by this operation method. This is further explained below.

Figure 2-4: Float-over installation topside
(adapted from [3] (2015))

2.2.2 Substructure

The substructure installation method is dependent on its weight and dimensions. Substructures can be divided in three types: artificial islands, bottom-founded structures and floating structures. Depending on the water-depth a suitable type is chosen. Artificial islands are used in very shallow water (10 meters) and floating structures for deep water (400 meters and deeper). In this research only bottom-founded structures are considered.

Commonly used installation methods for bottom-founded substructures are ‘lifting from barge’ or ‘launch’. The selection of installation method is directly related to the weight and dimensions of the substructure.

Lift from barge
Substructures lying on a barge can be lifted by a crane vessel. The barge can be towed away and the substructure can be lowered into the water. In Figure 2-5 a substructure is lifted from a barge. The substructure will be lowered and moved from a horizontal to a vertical position and put in to place on the seabed. The crane vessel must be capable to lift the weight and be able to move the substructure into its final position. Relatively small substructures can be installed with this method.

[3] http://www.coscoht.com/floatover_successful.php

Figure 2-5: Lift from barge
(adapted from [4] (2015))

Launch
A launch operation requires a special kind of barge. The substructure is positioned on a barge on skid tracks. The barge is then ballasted in such a way, that the barge will tilt. The substructure then starts to slide and substructure is “launched” into the water (Figure 2-6). Pre-installed buoyancy tanks keep the substructure from sinking. A crane vessel fills the buoyancy tanks and installs the substructure. When a substructure is too large or too heavy for a crane vessel to be lifted from a barge, this launch operation can be used. However, the substructure needs skid tracks and buoyancy tanks. This is steel that is only needed for the installation, and has no function thereafter. During a launch operation impact loads may occur, the substructure needs to cope with these loads.

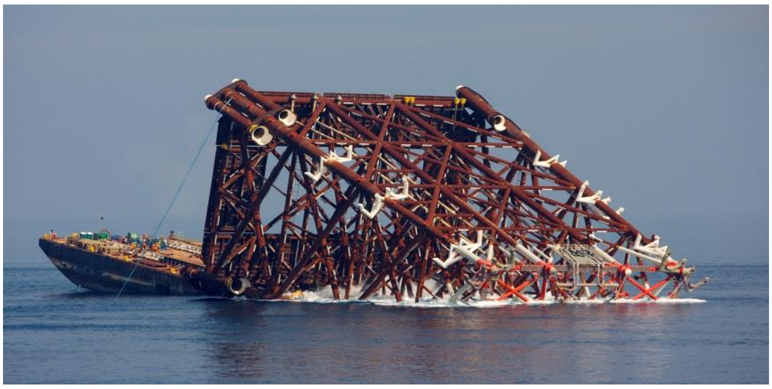


Figure 2-6: Launch, required from
(adapted from [5] (2015))

2.2.3 Foundation

The foundation forms the connection between the platform and the seabed. The platform needs to be secured to the seabed to assure the substructure will not move, flip or sink into the seabed. The topsides and the substructure are exposed to environmental impacts. The foundation must cope with these environmental impacts and the weight of the platform. The way of founding the substructure is dependent on the soil composition at the platform location and the forces the foundation has to deal with. There are two foundation types discussed within this research: skirt piles and suction anchors.

[4] http://www.scaldis-smc.com/oilandgas.php
[5] http://www.businesswire.com/news/home/20150302006538/en/McDermott-Awarded-Wellhead-Jacket-Deck-Umbilical-Project

Skirt piles
Skirt piles are relatively long thin piles installed by a hammer into the seabed. Usually there are several piles needed per leg of the substructure to deliver the needed bearing capacity. Figure 2-7 shows a skirt pile sticking above the water line and a crane vessel with a hammer that will drive the pile to target depth. The connection between the soil and the wall of the skirt pile creates a friction force that keeps the pile in-place when loaded by topsides weight and environmental influences.
A drawback of this foundation type is that driving of skirt piles is a time-consuming task (1-2 days per pile, 8 to 12 piles).

Figure 2-7: Skirt pile with hammer above and under water
(source (Brasfond, 2015))

Suction anchor
A suction anchor is a can that is positioned underneath a substructure (Figure 2-8). When the suction anchor is positioned on the seabed, pumps on top of the suction anchor start pumping water out of the suction anchor (arrow Q in Figure 2-8). Due to the under-pressure inside the suction anchor, it pulls itself into the seabed. The dimensions of the suction anchors depend on the soil strength and the required bearing capacity. Suction anchors are large structures underneath the substructure that have to be installed simultaneously with the substructure. Because all suction anchors are installed at the same time and no hammering process is needed, the installation time is reduced. However, not all soil types are suitable for suction anchors.

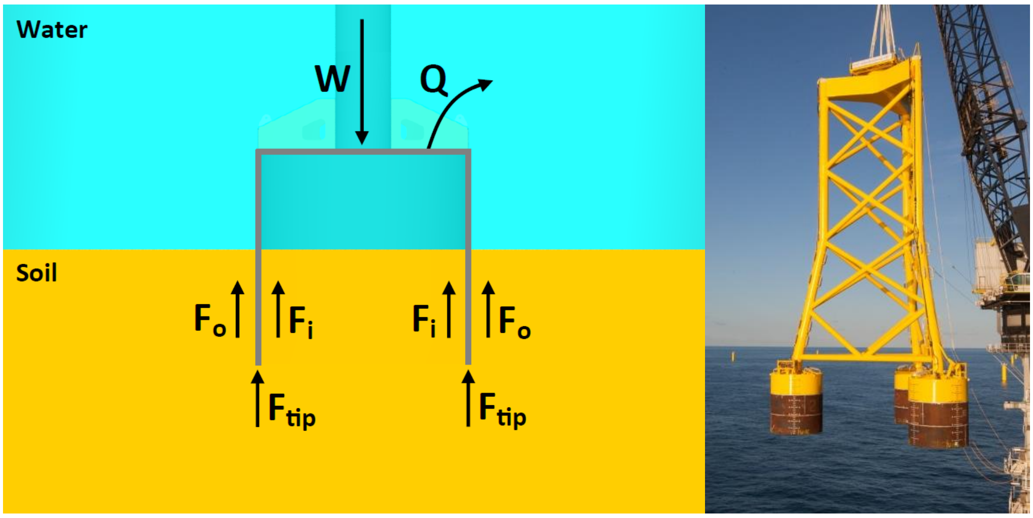


Figure 2-8: Working principle of a suction anchor
(adopted from [6] (2015))

[6] http://www.offshorewindindustry.com/news/first-suction-bucket-jacket-complete

2.2.4 Interdependency of platform-sections

The described topsides, substructure and the foundation types are interdependent. The dependency relates to the installation method. Decisions made on the topsides installation influence the substructure design and installation. For example: When the topsides are installed by a float-over, automatically the substructure needs to cope with an extra boundary condition: The substructure design must allow a float-over operation. This results in a gap in the substructure enables a barge with the topsides to manoeuvre into place.

An extra block is added to the general scheme (refer to Figure 2-1) showing that the transport and installation type influence the final design.

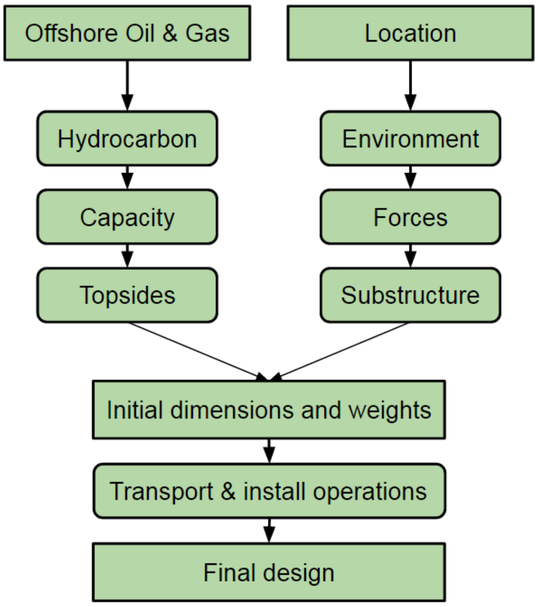


Figure 2-9: General approach offshore platform design I

2.3 Pioneering Spirit: A step-change in the offshore industry

The PS is a unique vessel in the offshore industry. The PS is able to lay pipes, install offshore platforms and decommission offshore platforms. Within this research the focus is set on the lifting capacity of the PS, therefore the pipe-lay capabilities are not discussed.

The main lift capabilities and boundaries will be discusses in this section. A more detailed overview of boundaries and capabilities is provided in Appendix B. The PS can be split up in three sections. First, the overall boundaries of the PS are discussed and thereafter the two lifting tools on board are explained.

2.3.1 PS main boundaries

The PS is the largest vessel in the world with respect to water displacement. With this, the vessel can be trimmed conveniently, which can improve the workability and stability of the vessel during operations. Due to its dimensions the vessel has very limited access in harbours and docking places. Therefore the transfer from and to quays has to be done with additional barges. The balance between the capabilities and the limitations of the PS must be investigated, to be able to use its capabilities as effective as possible. In Figure 2-10 and Table 2-1 the main dimensions are summarized.

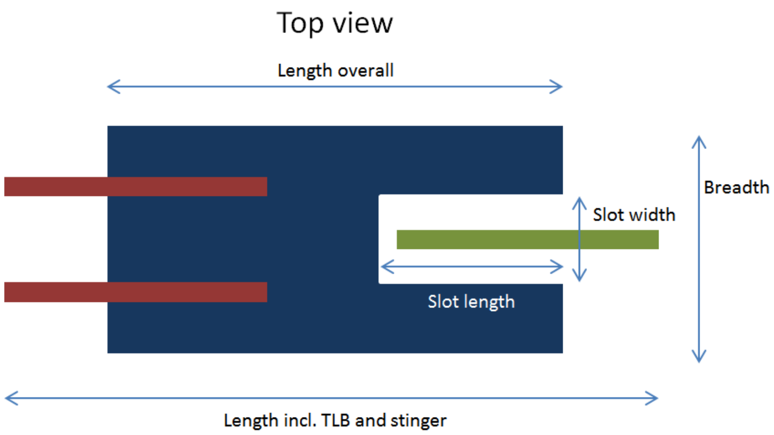


Figure 2-10: Main dimensions of the PS

Parameter	Amount	Dimension
Length overall (hull body)	382	[m]
Length overall (incl. TLB and stinger)	477	[m]
Breadth (hull body)	124	[m]
Sloth width	59	[m]
Slot length	122	[m]
Displacement @Draft (T)=12m	379.000	[ton]
Displacement @Draft$_{max}$ (T)=27m	97.200	[ton]
Topsides lift capacity	48.000	[ton]
Jacket lift capacity	25.000	[ton]

Table 2-1: Main dimensions of the PS (source (Allseas, 2015))

2.3.2 Jacket Lift System

The Jacket Lift System (JLS) installs the substructure. In Figure 2-11 the JLS system is shown in upright position. The lift capacity, centre-to-centre (ctc) distance of the Tilting Lift Beams (TLB), amount of sledges and the freedom of movement of the sledges on the TLB are the main items of the JLS capabilities that may influence the design of the platform. (The system is not finalized yet. The most up-to-date set-up of the system is used for the research. (May 2015))
With the JLS having two parallel TLB, a strong four-legged tapered substructure will be limited in the taper angle. In the (vertical) upright position the interface between the top of the substructure and the cables of the PS need to be sufficiently strong. The locations of the substructure that are supported by the sledges on the beam must deal with all the forces in the horizontal orientation of the TLB. Compared to a launch substructure, these locations must be stronger to deal with the stresses during transport in horizontal position. In Table 2-2 the main capacities and dimensions of the JLS are given.

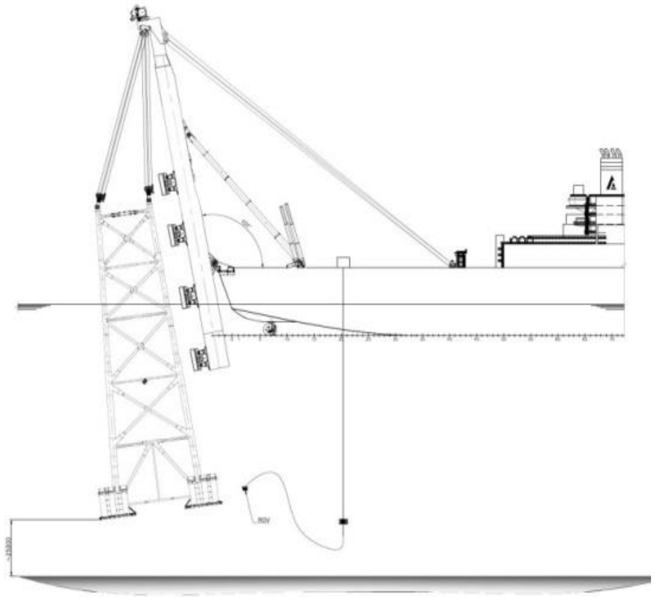


Figure 2-11: JLS upright position (source (Allseas, 2015))

Capacity and dimension JLS	Amount	Unit
JLS Safe Working Load	25.000	[t]
Main hoist full load hoisting speed	3,38	[m/min]
Length main body TLB	139,65	[m]
Minimum centre to centre (ctc) distance of TLB	21	[m]
Maximum centre to centre distance of TLB	86,25	[m]
Maximum TLB operating angle	115	[deg]

Table 2-2: Capacity and dimensions JLS (source (Allseas, 2015))

The maximum dimensions of the substructure are not set. The substructure could for example have more than 4 legs. When the TLBs are positioned underneath two legs and the extra legs are outside the TLBs the substructure could be wider than the maximum ctc-distance of the TLBs. The maximum length is not necessarily determined by the length of the TLB, but dependent on the weight distribution on the TBL. The bending moment at the outboard section of the PS need to be dealt with by the TLBs.

2.3.3 Topside Lift System

For the Topside Lift System (TLS), the slot width, lift capacity per TLS-beam, ctc-distance between TLS-beam and the outreach of a TLS-beam are all points of interest. The topsides can be installed with the so-called “heave compensating system”. This is a system that allows the PS to move due to the waves and keep the topsides completely still. This system allows the PS to install the topsides with a higher workability and less impact loads then currently applied methods.

The minimum height between the Mean Sea Level (MSL) and the lifting points needs to be 15m. This is a result from the maximum ballasting of the PS, the height of the remaining freeboard and the dimensions of the TLS-beams. The main numbers are shown in Table 2-3. Figure 2-12 shows a bow view of the system. The horizontal TLS-beams can be positioned in a lot of different ways allowing for freedom in the topside design and thus the substructure.

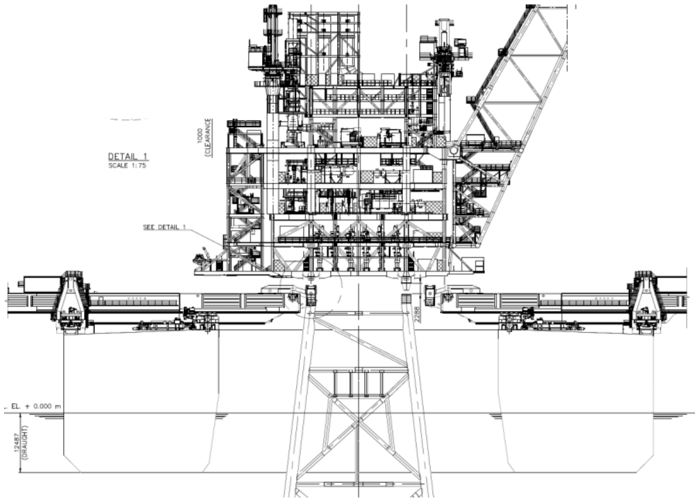


Figure 2-12: TLS bow view (source (Allseas, 2015))

Description	Amount	Unit
Maximum transport capacity forklift unit	103	[MN]
Maximum lift capacity forklift unit	74,5	[MN]
Maximum (total) vertical stroke	4	[m]
Minimum longitudinal -ctc-distance lifting points	12,2	[m]
Maximum speed Z-direction during quick lowering	0,34	[m/s]
Length lifting beam	65	[m]
ctc of lifting beams	6,1	[m]

Table 2-3: Capacity and dimensions JLS (source (Allseas, 2015))

The topsides can have all kind of dimensions. The restrictions on the topsides are the locations of the lifting points and the Centre Of Gravity (COG) of the topsides.

The TLS results in boundaries for the substructure as well. The maximum dimensions must fit within the slot of the PS. The lifting points must be at least 12,2 meters apart from each other to be able to position the lifting points of the TLS beams.

2.4 Case study selection

Designing a platform for installation with the PS from scratch is time-consuming and complex. Evaluating whether a design is promising compared to other up-to-date technologies and standards can give useful insights in potential gain. Designing from scratch in a fictive place and environmental conditions does not show if a design is viable. To be able to compare the final design a reference case is needed. For this reason, a case study is selected for comparison purposes. When comparing the “PS platform design” to an existing platform, the advantages and disadvantages can be assessed.

The internal offshore platform database at Allseas is used to choose a suitable platform for the case study.
The Kebabangan platform (KBB) is selected to serve as a case study in this research. This platform has been installed late-2014 with a float-over operation, a launched tower and skirt piles. The platform has the dimensions and weight that match the capacity of the PS. The platform is installed recently, so applied techniques are up-to-date, meaning a fair comparison can be made between the conventional installation method as applied and the renewed installation method as possible by the PS.

3 CASE STUDY

3.1 Introduction

To come up with a new design for a PS-installed platform at the case study location, the requirements and boundary conditions at the location are needed. This chapter describes the environmental and boundary conditions, subsequently the motives of the (conventional) case study design and thereafter the optimized design for the PS-installation method.

The general design scheme is extended (as shown in Figure 3-1) and in this form used to investigate the design philosophy for the Kebabangan platform as existing. Thereto, the design requirements and boundary conditions are required as input (the reservoir properties and the environmental influences).

Following the input, the installation method and the platform design are described in 3.3.

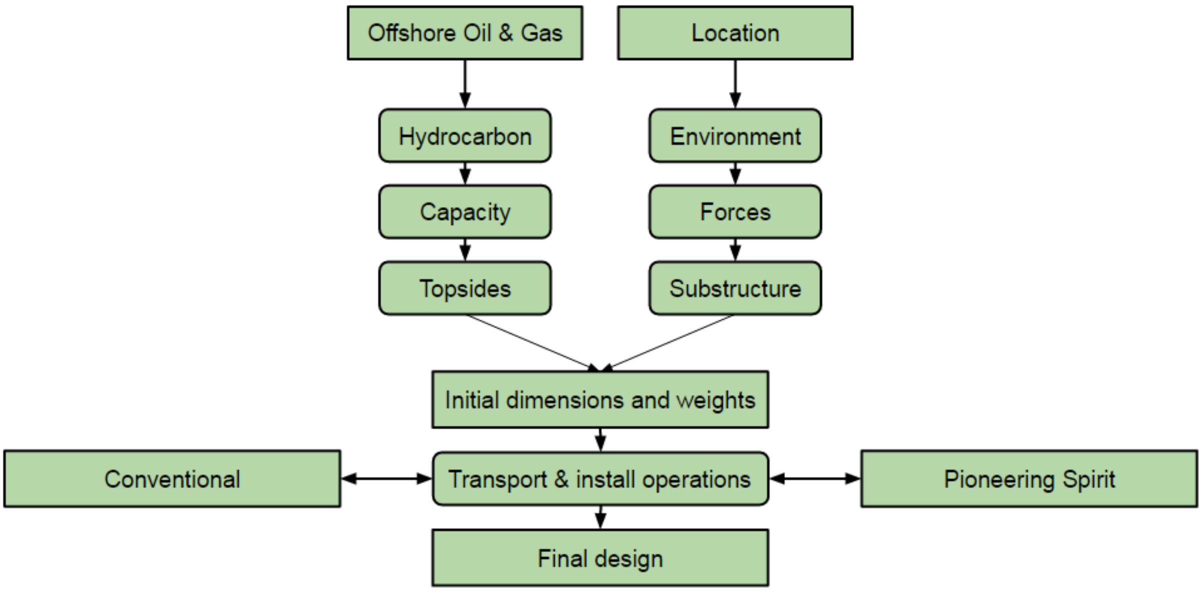


Figure 3-1: Design scheme offshore platform II

3.2 Kebabangan Platform

3.2.1 Design requirements - Hydrocarbon

The design requirements for the KBB platform are based on the production of the Kebabangan oil and gas field. The production numbers are used as input data for this research.

It was found that the hydrocarbons from the field are mainly gas. The design of the platform shall have a daily capacity of (OET, 2014):

- 825 million standard cubic feet of natural gas;
- 80,000 barrels of crude oil; and
- 22,000 barrels of condensate, per day.

3.2.2 Design requirements - Environment

The environmental conditions and associated loading is one of the most important factors in the design. To make a good comparison with the existing Kebabangan platform the environmental forces must be as accurate as possible. From a met-ocean report covering an area which is located close to the case study area, data was obtained on the environmental design conditions. The exact location of the met-ocean report is slightly in a different part of the South-China Sea, as visualised in Figure 3-2.

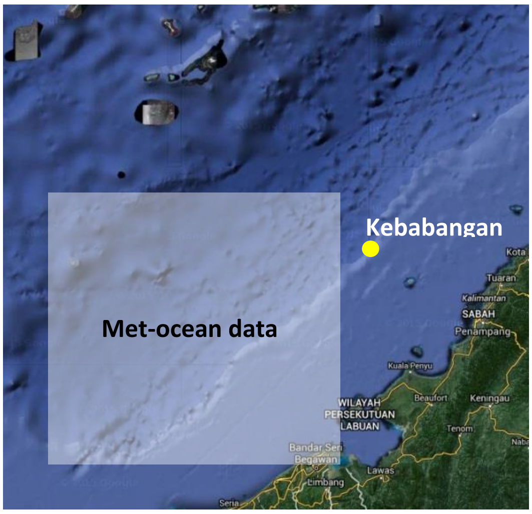


Figure 3-2: Location met-ocean data with respect to Kebabangan (source (Google Maps))

Water depth

The Kebabangan platform is located in the South-China Sea west of Borneo (Malaysia), 70 nautical miles (nm) from the coast in a water depth of 140m. In shallow water, the water depth can influence the waves. Waves are not influenced by the bottom when occurring in deep-water. Deep-water has certain characteristics, which are investigated below:

$$\frac{h}{\lambda} \geq 0{,}5$$

$$\lambda = \frac{g}{2\pi} T^2$$

With:

- λ Wave length [m]
- T Wave period [s]
- g Gravitational acceleration [m/s^2]
- h Water-depth [m]

To be able to design a platform, met-ocean data needs to be obtained for the site location. However the met-ocean data used for this research is measured in a deeper part of the South-China Sea (Figure 3-2), till a depth of 1000 m. There are a lot of factors that influence the waves (e.g. wind, morphology).
To check whether the waves get influenced by the seabed, the classification of deep water is used. The above relation is looked at. This means with a water-depth (h) of 140m, the wave period (T) can have a maximum of 13,3 sec.

Return period
The environmental design requirements for the platform design are based on a 100-year return period. During the transport and installation phase, less severe conditions are used. During transport and installation, a return period of 1 in 10 years applies, while during installation a return period of 1 in 1 year is used. A summary of the return periods per project phase is given in Table 3-1.

Project phase	**Return period**
Design (construction requirements)	1 in 100 years
Transport	1 in 100 years
Installation	1 in 1 year

Table 3-1 Return period per project phase

Waves
The waves have a large influence on the substructure. Beside the waves attacking the structure in horizontal direction, the wave height will be governing in the required deck elevation of the platform (waves hitting the deck of the topsides is not allowed).

When designing a platform the 100-year return period is used to determine the elevation of the deck. For the preliminary sizing of the legs and members the guidelines are used from “Handbook of offshore engineering” (Chakrabarti, 2006).
The maximum wave height measured is 12,0m, with a wave period of 13,1s (Table 3-2). These values are the design wave conditions, obtained from the met-ocean data.

	$H_{significant}$	T_z	T_1	T_p	H_{max}	T_{ass}
Return Period	[m]	[s]	[s]	[s]	[m]	[s]
1 year	3,5	6,9	7,6	12,2	6,8	12,2
10 years	4,9	4,9	7,4	8,2	12,7	9,4
50 years	5,9	7,8	8,6	13,0	11,2	13,0
100 years	6,3	7,9	8,7	13,1	12,0	13,1

Table 3-2: Wave return period at nearby location (source (Allseas, 2014))

Note: The waves from the met-ocean data have a period (T_p) of 13,1s. The maximum period for the deep-water classification is 13,3s (Refer to section Water depth). This means the water can be classified as deep-water. This is only one factor influencing the waves, but for the purpose of this research the wave data from Table 3-2 is used.

Current
The current has impact on the substructure. In the met-ocean report, current data is measured till 1.100m water depth. At the location of the platform the water depth is only 140m. Currents have a lower velocity when closer to the seabed. A conservative approach is used for the current at the platform location, keeping the currents the same as the ones from the met-ocean data, i.e. the data is used without degrading the velocity when approaching the seabed. The current velocities can be found between 0,74-1,27 m/s (Table 3-3). The design current velocity is chosen to be 1,27 m/s.

	Directions								
	N	NE	E	SE	S	SW	W	NW	OMNI
	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
Surface 0m	1,04	1,27	1,27	0,67	1,07	1,27	1,25	0,72	1,27
Depth 29m	1,04	1,27	1,27	0,67	1,07	1,27	1,25	0,72	1,27
Depth 79m	0,64	0,78	0,78	0,41	0,65	0,78	0,76	0,44	0,78
Depgh 111m	0,67	0,81	0,81	0,43	0,68	0,81	0,80	0,46	0,81
Depth 143m	0,60	0,74	0,74	0,39	0,62	0,74	0,73	0,42	0,74

Table 3-3: Current profile at nearby location (source (Allseas, 2014))

The current velocity is assumed not to increase. When the direction of the current is from the deeper part to the more shallow part, the coastline is perpendicular to the current direction. Meaning the water cannot go anywhere and thus the current will not increase.

Wind

The wind load is mainly attacking the topsides of the platform (i.e. the attack area of the substructure above the Mean Sea Level (MSL) is very small compared to the topsides). The force on the topsides is determined by use of the 100-years return period at 10m above MSL and averaged over 1 minute. The PS will have to install the topside with a distance of 15m between the lifting points and the substructure. The height of 10m above the MSL for the wind force estimation might need an extra factor to account for higher wind speeds at the actual elevation height of the topsides. The design wind condition is 22,8m/s (Table 3-4).

	$W_{1h,10m}$	$W_{10min,10m}$	$W_{1min,10m}$	$W_{15s,10m}$	$W_{5s,10m}$	$W_{3s,10m}$
Return Period	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]
1 year	12,9	13,8	15,4	17,2	18,6	19,2
10 years	16,0	17,1	19,1	21,3	23,0	23,8
50 years	18,1	19,5	21,7	24,1	26,1	27,0
100 years	19,0	20,5	22,8	25,4	27,4	28,4

Table 3-4: Wind return period at nearby location (source (Allseas, 2014))

Dominant directions environmental influences

For the orientation of the platform the dominant directions of the environmental influences are governing. Due to the rectangular shape of substructure and topsides the attack angle may be of great influence on the force on the platform.

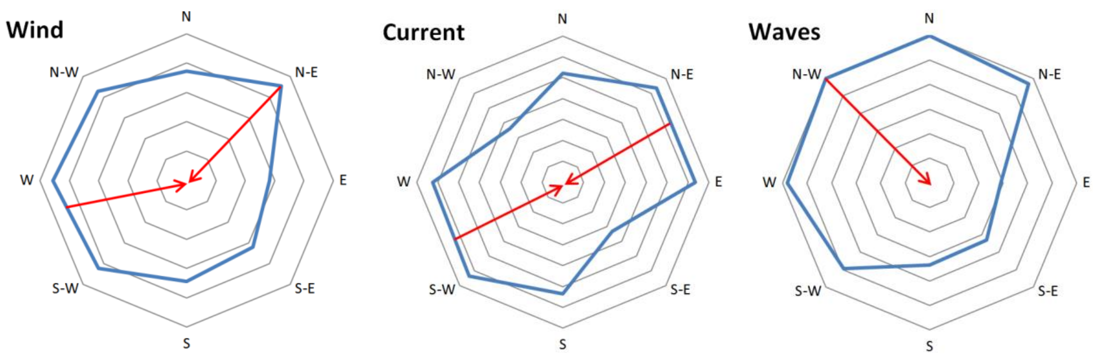


Figure 3-3: Dominant directions environmental conditions

The plots in Figure 3-3 visualise the highest measured wave height, current and wind speeds from a certain direction. The wind and current have more or less the same directions. Waves are coming in perpendicular. The attack area of the topsides and substructure influence the resulting force. A larger contact area needs to withstand a larger force. The critical load-case for the platform as a whole is investigated below.

The wind force applied on the topsides can cause a more critical load-case for the platform as a whole than when the waves impact the substructure. This than results the orientation of the complete platform is governed by the wind direction.

The design requirements are mapped, presenting the hydro carbons and the environment at the location. The initial dimensions and weights can be determined according the design scheme II (Figure 3-1). In the next section the boundaries are assessed.

3.2.3 Boundaries - Existing local construction facilities

The local construction facilities where the KBB Platform was constructed are located on West-Malaysia and Singapore. Two different yards were used for the construction of the substructure and the topsides (Figure 3-4 and Figure 3-5). The substructure was constructed at the Kencanna HL Yard in Malaysia, approximately 1100 nm from the project location (Figure 3-4). The topsides were constructed at the MMHE East Yard in Singapore, approximately 800 nm from the project location (Figure 3-5). For this research these production yards are used for a fair comparison.

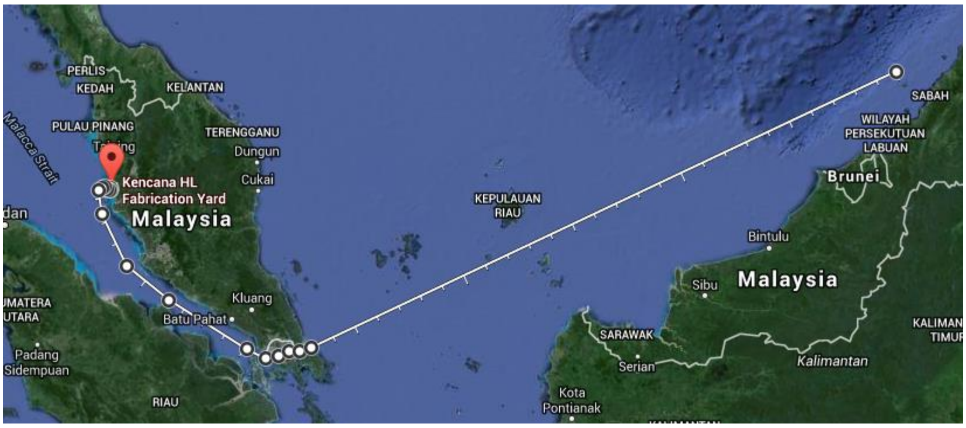


Figure 3-4: Production substructure and tow transport route, Kencanna HL Yard [1100nm] (source (Google Maps))

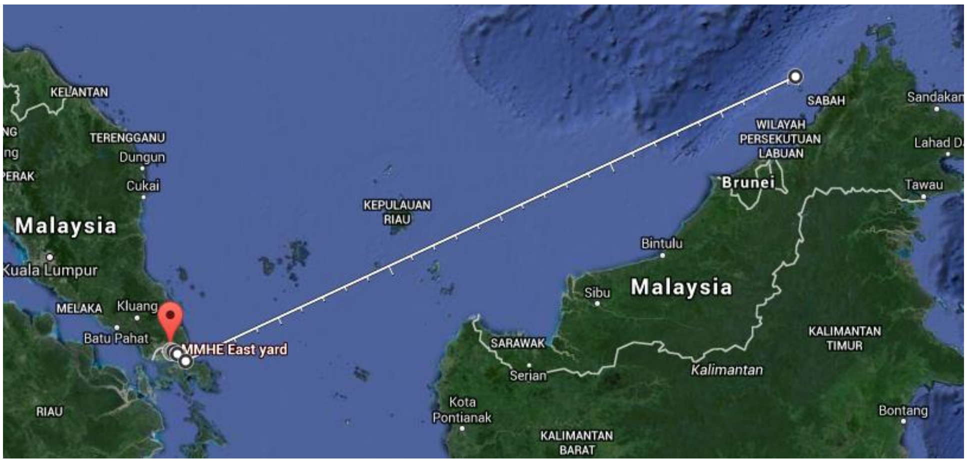


Figure 3-5: Production topside and tow transport route, MMHE East Yard [800nm] (source (Google Maps))

One other part on the case study that must be kept in mind is the temporary drill rig (tender assist) that will be used in the lifetime of the platform. Initially there will be only 6 wells drilled and further down the life time of the platform there will be 6 additional wells drilled in order to keep the desired production rate. For the new topsides design this must be kept in mind. In Figure 3-6 the conventional position of the tender assist is shown.

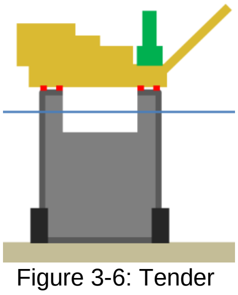


Figure 3-6: Tender assist position (green)

Summary

In Table 3-5 the environmental conditions and boundary conditions for the platform design are summarized. In order to make a fair comparison, the environmental conditions are assumed the same for the conventional and the optimized platform.

Summary Environmental conditions KBB	**Used for KBB platform**
Waves H_{max} T_p *Dominant direction*	 12,0 m 13,1 s N-W
Wind (10m +MSL) *Dominant direction*	22,8 m/s W, N-E
Current *Dominant direction*	1,27 m/s N-E E, S-W W
Distance to substructure construction location	1.100 nm
Distance to topsides construction location	800 nm

Table 3-5 Summary environmental conditions for South Chinese Sea

3.3 KBB Platform Design: Conventional installation method

3.3.1 Introduction

In this section, the KBB platform design is described, as it is installed using the conventional method in late-2014.

The reservoir properties and the environment are investigated. A design was made to reach the required capacity as determined in 3.2.1. The initial dimensions and weights of the Kebabangan platform are known and shown in Table 3-6.

KBB	Amount	Unit
Topsides		
Weight	17.000	[ton]
Substructure		
Height	149	[m]
Foundation	**Type**	
Method	Skirt piles (12x)	-

Table 3-6: Initial dimensions KBB Platform (source (Allseas, 2015))

The next step is determining the most suitable transport and installation method for the entire platform (Figure 3-7). The requirements, boundaries and interdependency between the three platform sections (topsides, substructure and foundation) must be taken in to account.

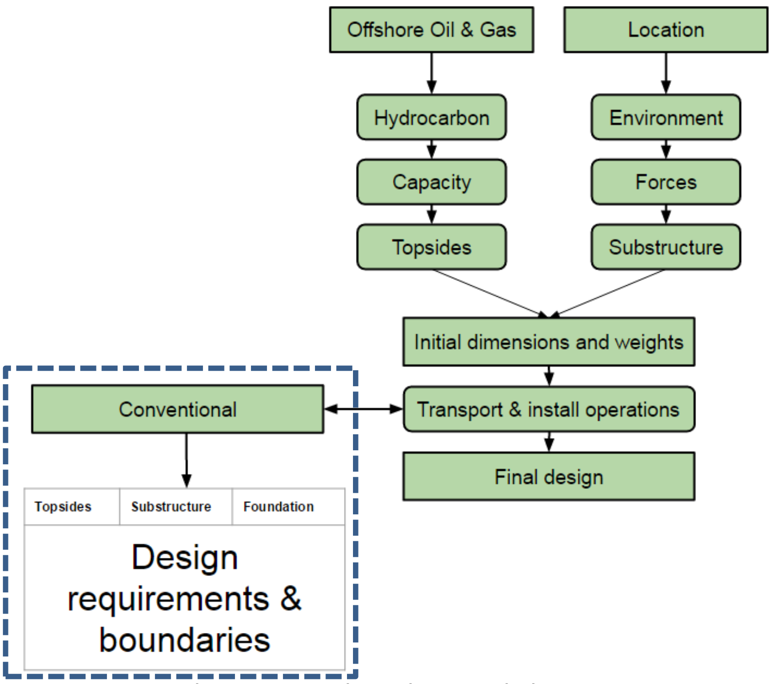


Figure 3-7: Design scheme Kebabangan

3.3.2 Transport and installation method

The available installation methods are explained in Section 2.2. The installation method of the topsides, substructure and foundation will be assessed in this section as well as the interdependency leading to the final design.

Topsides

The installation method of the topsides is determined by their weight. The topsides of the case study weigh 17.000ton. To install the integrated topsides at Kebabangan, a float-over operation is used to be able to install the integrated topsides. A semi-submersible vessel is used to transport and install the topsides (Figure 3-8). Due to the width of the vessel the topsides needed to be even wider. This results in stretched topsides.

Figure 3-8: KBB's float-over operation;
vessel Xiang Rui Kou (adapted from [7] (2015))

Substructure

As a consequence of the selected installation method for the topsides, the substructure design has a gap that allows for a float-over operation. Correspondingly the substructure's dimensions are influenced. The float-over requirement causes the substructure to be wide. Due to the widening, the substructure has dimensions and a weight that influence the installation method for the substructure.

A launch operation (launch barge shown in Figure 3-9) is used to transport and install the substructure. In the design of the substructure, additional launch runners and buoyancy tanks are required for the launch. As this installation method induces large impact loads on the substructure during operation, less robust components of the substructure need to be installed after the launch.

Figure 3-9: KBB's substructure on launch barge;
barge Intermac 650 (adapted from [8] (2015))

[7] http://www.coscoht.com/floatover_successful.php
[8] http://www.mcdermott.com/SiteCollectionDocuments/Solutions-Platong-Imperial.pdf

Foundation
The foundation is realised by the use of skirt piles, installed by a crane vessel (Figure 3-10). As explained in 2.2.3, skirt piles are relatively long thin piles installed by a hammer into the seabed. In general, there are three piles required per corner leg of the substructure. (The crane vessel is also used for the positioning of the substructure on the seabed.)

Figure 3-10: KBB's used crane vessel; vessel DB101
(adapted from [9] (2015))

Vessels
The installation methods described above need support and supply vessels. The launch barge (Figure 3-9) needs tugs to tow the barge (also shown in the figure). The skirt piles must be transported to the installation location as well. The total fleet (and thus the operation method) is also dependent on the vessel available at the South-China Sea.

A total amount of 16 vessels was needed for the conventional transport and installation method. The complete overview of the vessel used for the installation of the platform at KBB is shown in Table 3-7.

No	Vessel	Type	Activity
1	Tower launch barge	Intermac 650	Launching barge
2	Crane vessel	DB101	Upending and positioning substructure
3	Pile barge	400 Class Teras003	With crane vessel pile installation
4	Conductor barge	300 Class Teras 337	Delivering of the conductors
5	Boat-landing barge	250 Class Teras 251	Installing boat-landing with crane vessel
6	Asset barge	300 Class Intermac 408	
7	Supply/crew boat	--	
8	Topsides float-over vessel	Xiang Rui Kou	Float-over operation for topsides
9 - 16	Tugs (8x)	Range: 65-200MT	Assistance

Table 3-7: List of vessels used conventional installation method at KBB (source (KPOC, 2014))

[9] http://www.shipspotting.com/gallery/photo.php?lid=1039721

3.3.3 Final design

The design scheme can be expanded with the conventional final design (Figure 3-11).

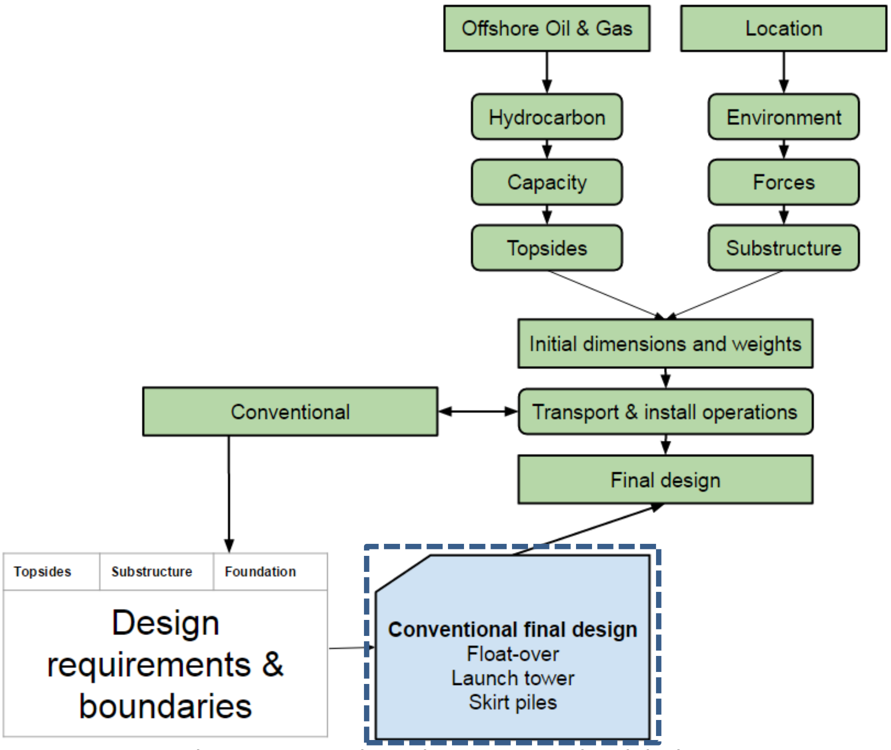


Figure 3-11: Design scheme, conventional design

The dimensions and weight of final design is shown in Table 3-8.

KBB	Amount	Unit
Topsides		
Weight	17.000	[ton]
Area	97x30	[m^2]
Height	32	[m]
Width float-over gap	46	[m]
Substructure		
Weight	12.300	[ton]
Area – at seabed	70x48	[m^2]
Area – at top substructure	70x22	[m^2]
Height	149	[m]
Foundation	**Type**	
	Skirt piles	

Table 3-8: Final dimensions and weight conventional design (source KPOC (2015))

The final orientation of conventional design is known as well. From Table 3-8 it can be seen that it is a stretched platform. This means the attack area differs with respect to the direction of the environmental influences. In Figure 3-12 the orientation of the conventional design is shown.

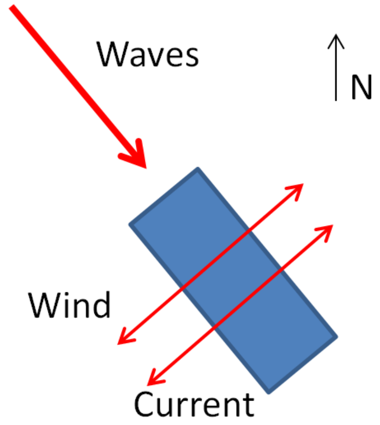


Figure 3-12: Orientation conventional design

3.4 KBB Platform Design: Pioneering Spirit installation method

3.4.1 Introduction

The design philosophy of the conventional installed platform is described in Section 3.3. The question arises where the PS will have the advantage compared to the conventional installation method. In section 2.3 the boundaries and capabilities of PS are given. Together with the requirements given in section 3.1, a new platform can be designed for installation with the PS.

Installing a platform with the PS will influence the design of the entire platform. Every choice in the new design is again interdependent.

3.4.2 Transport and installation method

The Pioneering Spirit will be deployed in the transport and installation phase of the platform. As became clear in the description of the conventional transport and installation methods (Section 3.3), all phases and platform sections are highly interdependent and influence the design of the different sections. Resulting, there are many areas in which the PS used for transport and installation can generate advantages. Rough preliminary advantages are:

Topsides
The PS can perform the transport and installation of the topsides, reducing the number of boundaries and therewith the influence on the design of the topsides.

Substructure
The PS can perform the transport and installation of the substructure. As the PS is also used for the installation of the topsides, less specific boundary conditions are influencing the substructure design. Using the PS, results in less critical interdependency. The substructure design is less influenced by the topsides design.

Foundation
The PS can perform the transport and installation of the foundation, influencing the selection process of the type of foundation to be applied. The controlled substructure installation with the PS will result in more foundation types to be possible (e.g. suction anchors), as the installation is less fiercely.

Vessels

Aside from the PS, there are two barges needed for the transfer of the topsides and the substructure from the quay to the PS. These barges require two tugs for manoeuvring. Dependent on the foundation type that is selected, an additional barge and tugs may be needed (e.g. skirt piles).

No	**Vessel**	**Type**	**Activity**
1	Lift vessel	PS	Topsides and substructure installation
2	Topsides barge/vessel		Topside from quay to PS
3	Substructure barge		Substructure from quay to PS
4	Conductor barge	(300 Class Teras 337)	Delivering of the conductors
5 – 9 (11)	Tugs 4x (+2x)	Range: 65-200MT	Assistance
(12)	(Foundation barge)		(Transfer foundation parts)

Table 3-9: List of vessels used PS installation method (source KPOC (2015))

The conventional fleet consists out of 16 vessels. Table 3-9 shows a fleet variation of 9 to 12 vessels (dependent on the foundation type, i.e. suction anchors versus skirt piles).

3.4.3 Final design

The final design of the platform, when it is installed with the PS, will probably differ from the conventionally installed platform design. The main differences are listed below:

- Topsides have more freedom in design, i.e. the topsides design will be less stretched.
- The influence of the topsides design on the substructure is smaller, i.e. the substructure can be more compact (avoiding the float-over gap).
- The foundation is less exposed to impact loads, resulting in possibly integrated foundations types.

These differences show that there are many potential advantages for platform design, when using the PS for transport and installation. In this research, the advantages are further investigated and quantified.

The capabilities and boundaries of both the conventional installation and the PS installation must be compared (refer to the updated design scheme in Figure 3-13). Doing so, will provide a clear overview where the advantages may lay.

In practice, an entire team of specialists is needed for a platform design. For this research, the focus was set on the most impacting aspects of the platform design. A qualitative analysis is executed to limit the quantitative assessment to this focus area.

The qualitative analysis is described in Chapter 4. Thereafter, in Chapter 5, the quantitative assessment is executed to investigate the possible savings for the KBB Platform. The quantitative assessment compares the conventional method with the PS method for the Kebabangan Platform, mapping the most promising areas for optimization.

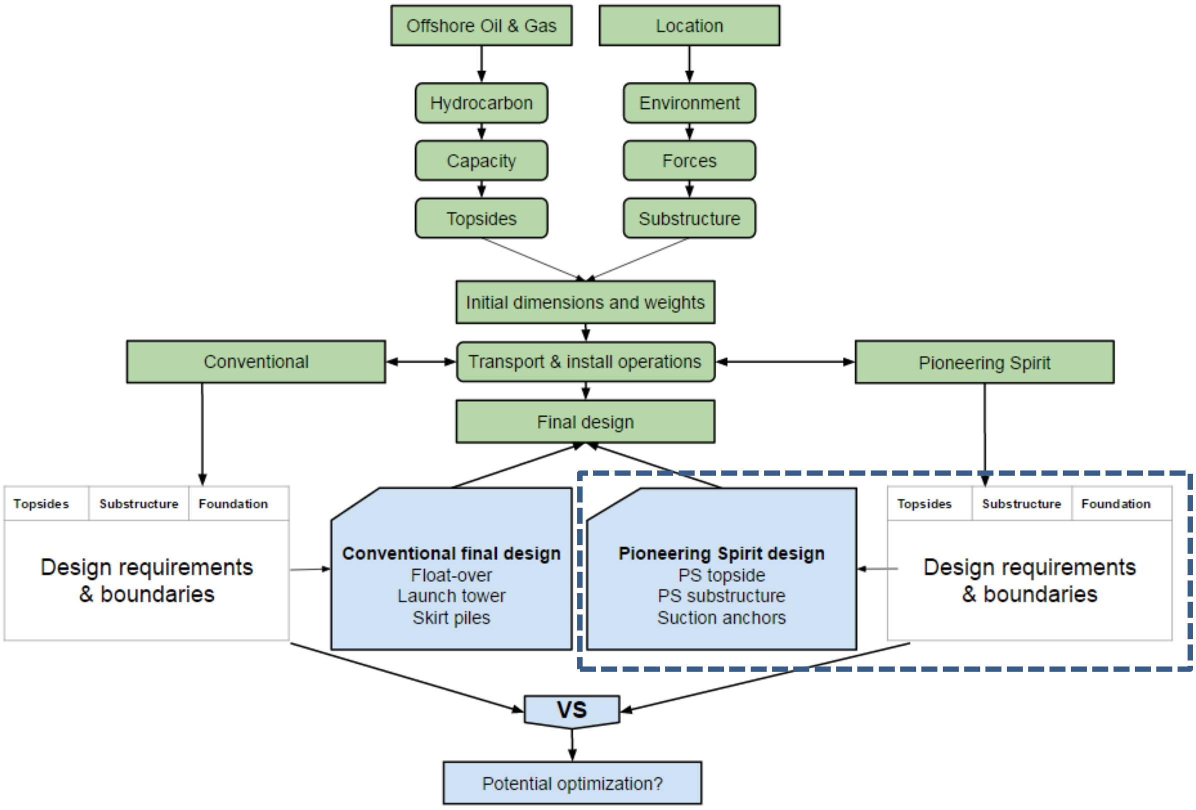


Figure 3-13: Design scheme IIII, potential optimization

4 ASSESSMENT OF MOST PROMISING AREAS

4.1 Introduction

In this chapter, all areas of potential optimization for platform design, using the Pioneering Spirit for transport and installation, is investigated qualitatively. To enhance creativity and ensure all possibilities are considered, a brainstorm session was performed in an early stage. Thereafter, to structure the assessment of most promising areas, a Multi-Criteria Analysis (MCA) was performed. Several criteria were defined, to which the different project phases and platform sections were compared. From this, the most promising areas for optimization were determined.

This chapter elaborates on the criteria that are used in the MCA, the scores of the different sections and phases on these criteria, and finally presents the results of the MCA.

- Brainstorm [Section 4.2]
- Multi Criteria Analysis [Section 4.3]
- Conclusions [Section 4.4]

4.2 Brainstorm session

In the early beginning of this research, a brainstorm session was held. The purpose was to gain an ‘out of the box’ view on the design. When working with an existing platform it is very easy to hold on to a traditional (more conventional) design. The brainstorm session was performed with fellow offshore students, having limited but sufficient knowledge of the subject. By executing the brainstorm session in a casual environment, it was possible to set the conventional restrictions aside and generate some creative ideas. During the brainstorm several ideas came up, not all involving a complete structure. Nevertheless, some fruitful insights were obtained, regarding the possibilities of the PS installation method. A brief description of the most promising outcome from the brainstorm session is presented below, informally named “Suck-it-up”. The full brainstorm session-minutes can be found in Appendix F.

“Suck it up”-concept

The idea is based on the concept that when suction anchors are used as a foundation method, no time-consuming pile driving is necessary. Extending the advantage of time-saving at the site-location, the idea is to place a hose in the outer legs of the substructure (shown in the sketch in Figure 4-1). Doing so, the pump can be located on the PS or possibly on a separate barge. By connecting the pump to the hoses, the suction anchors can be installed. This can result in major time-savings. Normally expensive underwater pumps and corresponding complex operations with Remotely Operated Vehicles (ROV) are needed to install suction anchors. By the use of hoses this will not be necessary.

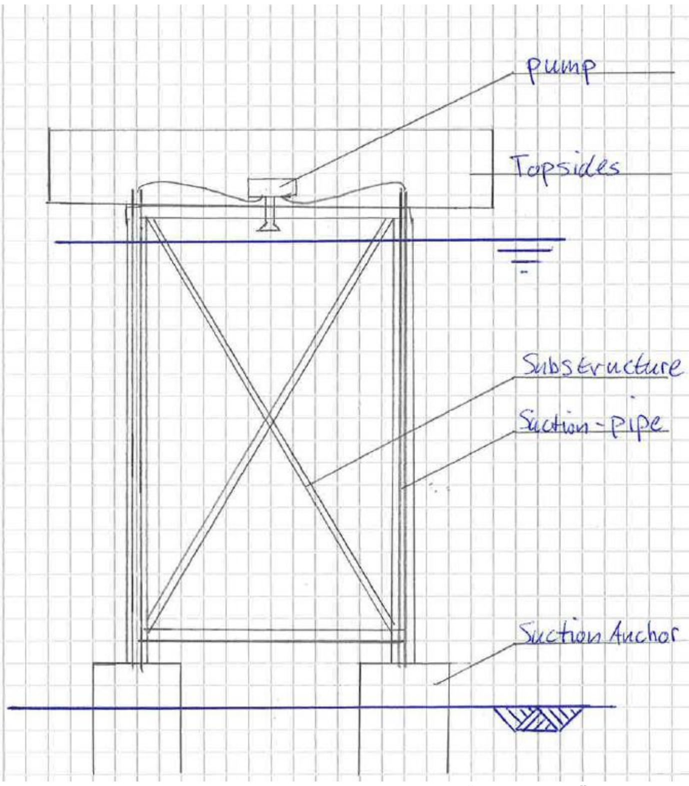


Figure 4-1: Brainstorm session result, “Suck it up”

From the brainstorm session, all kind of promising areas for optimization came to light. However, due to the dependency and interaction of all individual parts of a platform, it was not immediately clear what the most promising areas for optimization are. A design decision on the topsides can have consequences on the design of the substructure, positive as well as negative. A structured approach is needed. Thereto, an MCA was executed.

4.3 Multi-Criteria Analysis

4.3.1 Introduction

A Multi-Criteria Analysis (MCA) allows for a qualitative comparison of the interdependent potential areas for optimization. The advantages of the PS installation method shall be compared to the conventional installation method used at Kebabangan.

In the MCA, the potential areas will be scored for different criteria. These criteria are assigned different weight factors. As the sections of an offshore platform are very different from each other, the MCA is performed for each *section* individually: topsides, substructure and foundation.

For each section, it is investigated in which phase of the realisation of the platform lies the most potential. After the design the platform will go through four *phases*: Construction, transportation, installation and commissioning. The offshore platform sections and phases will be scored against criteria where optimization is expected.

- Sections [4.3.2]
- Phases [4.3.3]
- Criteria [4.3.4]

In Figure 4-2, the sections and phases are visualised.

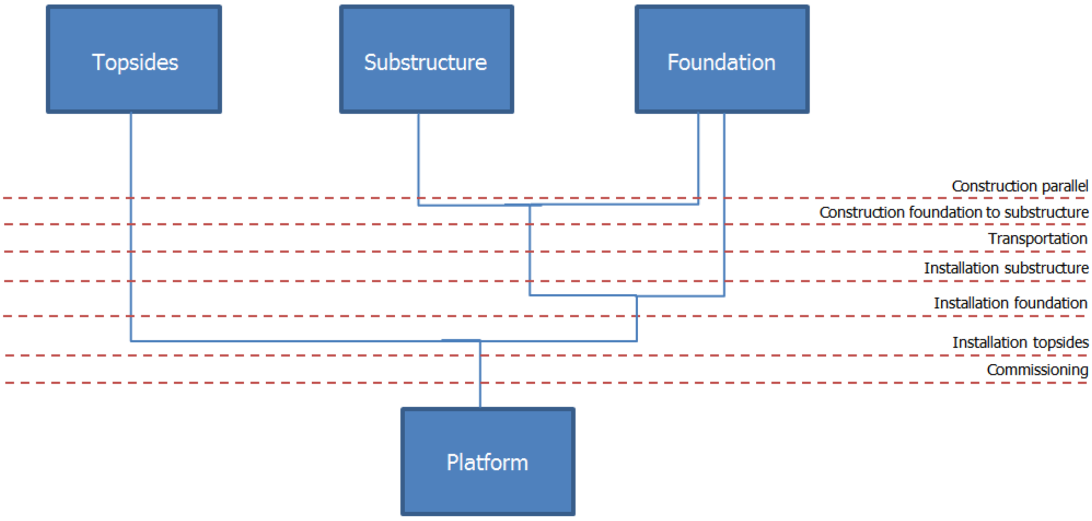


Figure 4-2 Three sections of an offshore platform

4.3.2 Promising areas for optimization per section

The platform is divided in the same sections as described in Section 2.2. These parts have influence on and interaction with each other, so any optimization in one part can result in a (dis)advantage on another part. The potential areas of optimization are denoted for the different sections of the platform below:

Topsides
The topsides are the factory and living area of the platform. It must be protected against environmental influences. Within topsides, besides process facilities, the crew's safety must be guaranteed. The greater the capacity needed for the field, the bigger and heavier the topsides shall be. The installation method is more or less determined by the weight of the topsides. Nowadays the (integrated) topsides that weigh more than 12.000 ton, are installed with a float-over. The conventional topsides of the Kebabangan field weigh 17.000 ton, consequently a float-over operation is needed. At a float-over there needs to be a big span between the permanent support points of the topsides (the distance needs to be larger than the width of the float-over vessel). The temporary support points are mainly needed for transport as well as for installation and thereafter the temporary lift points are no longer needed. Commonly these temporary support points are not necessary at (structural) ideal locations. Extra structural steel is therefore needed to guarantee the structural integrity. When installing with the PS optimization in this area can be promising.

Substructure
The main function of the substructure is to protect the topsides from the environmental influences of the sea and let the topsides have a connection with the seabed and the wells. The design of the substructure strongly depends on the topsides and its design. Conventionally the topsides had to be installed by a float-over operation, meaning the substructure has to have a gap (of approximately 46m) in the middle, to enable the float-over vessel to manoeuvre between the legs before lowering the topside.
Launching the substructure with the conventional installation method, requires a lot of temporary and extra steel. A reduction of the amount of steel in the substructure is a point of interest when looking into optimization of the platform, by means of using the PS.

Foundation
The majority of the tower-like substructures are supported by driven piles. These piles are generally being installed with a hammer. This is a time-consuming part of the platform installation. Roughly one pile requires one or two days. At the conventional Kebabangan platform, every corner needed three piles, resulting in a time-period of some 12-24 days. Vessels capable of installing these piles have a

certain day-rate. The PS is expected to have a high day-rate, meaning that reducing the foundation installation time is desirable. Thereto, assessing different types of foundation can be interesting for optimization. The total weight of the platform is less critical when using the PS, meaning (partly) pre-install the foundation is an area of interest for optimization.

4.3.3 Promising areas for optimization per phase

The time period from the final design to when the first oil is produced consist of several phases that have to be completed. Within these phases, optimization may be realised as well. The phases are briefly described below, denoting the potential areas of optimization:

Construction
During the construction-phase of the topsides, substructure and foundation there are two main ways for optimization. Firstly, total cost savings can be achieved by reducing the amount of steel on the sections. Secondly, the time it takes to construct may be reduced. The two are correlated. If the structure is built with a minimized amount of steel, it is plausible that fewer welds are needed. On the downside, minimizing the amount of steel can lead to a more complex structure, resulting in:

- More difficult welds;
- More working hours;
- Bigger segments;
- Special equipment.

The balance between complexity and steel reduction should be investigated for every individual (part of the) structure.

Transportation
The transportation-phase starts with loading the structure from the quay to a transport vessel, transporting it to the site location and having the platform section ready for installation. How the transportation-phase is done is related to the distance between the yard and the location where the wells are drilled. Getting the sections at the designated location can be done in numerous ways, depending on the type of structure (e.g. a spar or a TLP). The distance for the topsides is nearly 800 nautical miles (nm) and for the substructure (tower in the case of Kebabangan) it was almost 1100 nm. With the loaded speed of the PS of 11,8 knots (kts), it will take respectively 3 and 4 days. With the expected high day rate of the PS ($1.000.000-1.500.000,-) it might be an idea to tow the sections (topsides and/or substructure) during transport on a barge and put them on the PS at open sea, if environmental conditions are not too harsh.

Some of the transportation methods cannot be used all year round due to the weather (i.e. have limited workability).

Installation
The installation-phase (getting the structure from its transportation position to its final position) has three key design aspects: The first one is the installation window. For offshore operations the weather window in which the operation can be done is of great importance. The sea state and wind influence the operation tremendously. Improving the workability in the installation will enlarge the chance of installing in time and create larger weather windows. Second, the time needed for installation. Getting the structure into place quicker is more convenient so a smaller weather window will suffice. Third, when using a different installation method the platform can be shaped differently. The design is less restricted by the installation method. Naturally, the PS will have certain limits as well (refer to Section 2.3).

Commissioning
In the case study (Kebabangan) the topsides are integrated, so the hook up and pre-commissioning of different modules is avoided. This will not change when it would be installed with the PS. The commissioning of the substructure in the conventional method required decoupling of the buoyancy tanks and installing of the boat-landing. The commissioning time may be reduced when the PS is used for installation.

4.3.4 Criteria

To determine which part of the structure or process gives the greatest potential for optimization, all sections and phases are analysed using several criteria. The criteria are explained below.

All criteria have been assigned a weight factor, varying from “1” to “5”, where “5” means that the PS has great potential compared to the conventional method as applied at KBB, and 1 means that minimum difference is expected.

Time

There are two sides on the time topic. First, the day rates of ships (especially the PS) and employment rates of workers in the offshore industry can be quite high. When an operation can be done quicker, it will save the operator a lot of money. Second, the time between start construction and first hydrocarbon is also very critical. Producing oil/gas as quick as possible means the cash flow for the operator begins earlier as well.
So a time-saving will result in profit for both. Thus, time is an important focus area for optimization.

Amount of steel

Reduction in the amount of steel is in general a great advantage. Of course less steel means lighter, cheaper and most likely a shorter construction-time. Normally the weight of the structure determines the way of installation and the size of the installation vessel. Using the PS this issue is not governing. Therefore, the steel reduction is the main focus area in this analysis.

Workability

The workability is focused on the transport- and installation-phases. For these phases the sea-state is important. When the topsides and/or the substructure can be transported and installed at higher sea-states, the weather-windows will be wider and the platform can be in operation earlier. Also, ships will be idling less by waiting on the workable weather-window, resulting in cost-savings for ship use.
In the commissioning- and construction-phase the focus will be on whether weld and rig areas are easy accessible.

Safety

Safety is an important aspect in the offshore industry. Some operations have higher risks than others. Eliminating or reducing risks due to a change in design or operation would therefore be an important optimization.

Development costs

The above-mentioned areas of focus can all be brought down to costs. The type of costs not yet discussed is the development costs. If the boundaries and possibilities of installation with the PS are well-mapped, the design of a platform might be done faster. So investing in the development may result in advantages further down the installation method.

4.3.5 Analysis

For each section of the platform, a separate MCA was done. The scores that are given in the MCA are assigned to the PS method-advantage relative to the conventional method. Thus, the score represents the expected room for optimization in the design, when using the PS for installation, called “potential optimization”.

The weight factors for each criteria are determined using the so-called ‘pair-wise comparison’ method. All criteria are compared to one another, rating their relevance. The results of the determination of the weight factor for each criterion are shown per section in Table 4-1, Table 4-2 and Table 4-3.

Topsides	Time	Steel	Workability	Safety	Development cost
time	0	0	1	1	0
steel	1	0	1	1	1
workability	0	0	0	1	0
safety	0	0	0	0	0
development cost	1	1	1	1	0
	2	**1**	**3**	**4**	**1**

Table 4-1: Weight factors for the criteria, for MCA topsides

Substructure	Time	Steel	Workability	Safety	Development cost
time	0	1	1	1	0
steel	0	0	0	1	0
workability	0	1	0	1	1
safety	0	0	0	0	0
development cost	1	1	0	1	0
	1	**3**	**1**	**4**	**1**

Table 4-2: Weight factors for the criteria, for MCA substructure

Foundation	Time	Steel	Workability	Safety	Development cost
time	0	0	0	1	0
steel	1	0	1	1	1
workability	1	0	0	1	0
safety	0	0	0	0	0
development cost	1	0	1	1	0
	3	**0**	**2**	**4**	**1**

Table 4-3: Weight factors for the criteria, for MCA foundations

With the weight factors, the potential gain per section can be determined for each phase.
The weighted scores of the MCA for the topsides, substructure and foundation are presented in Table 4-4, Table 4-5 and Table 4-6 respectively.

A complete overview of the analysis and substantiation per ranking is included in Appendix C.

Phase	Time	Steel	Workability	Safety	Development cost	**Potential gain Topsides**
weighted scores	**2**	**1**	**3**	**4**	**1**	
Construction	2	4	9	12	4	**31**
Transport	6	2	12	20	4	**44**
Installation	10	1	15	16	4	**46**
Commissioning	2	1	6	20	3	**32**

Table 4-4: MCA Topsides: weighted scores

Phase	Time	Steel	Workability	Safety	Development cost	**Potential gain Substructure**
weighted scores	**1**	**3**	**1**	**4**	**1**	
Construction	4	15	3	12	4	**38**
Transport	3	6	4	12	4	**29**
Installation	5	15	4	16	4	**44**
Commissioning	5	6	2	16	4	**33**

Table 4-5: MCA Substructure: weighted scores

Phase	Time	Steel	Workability	Safety	Development cost	**Potential gain Foundation**
weighted scores	**3**	**0**	**2**	**4**	**1**	
Construction	3	0	6	12	5	**26**
Transport	3	0	4	8	2	**17**
Installation	15	0	8	20	5	**48**
Commissioning	3	0	8	12	2	**25**

Table 4-6: MCA Foundation: weighted scores

4.4 Conclusion

The potential gain shows high scores for the transport and installation phase for all three sections. Furthermore, the construction phase of the substructure is ranked high. The high result of the foundation installation-phase is related to the positive impact on the use of suction anchors.

The high ranked phases can be incorporated in three promising areas for optimization:

1. The transport and installation process of the topsides, substructure and foundation.
2. Optimization of the substructure design.
3. Integrated foundation, using suction anchors.

The optimizations will be quantitatively assessed in the Chapter 5. This step is added to the design scheme (Figure 4-3), which now gives the complete overview of the platform optimization process.

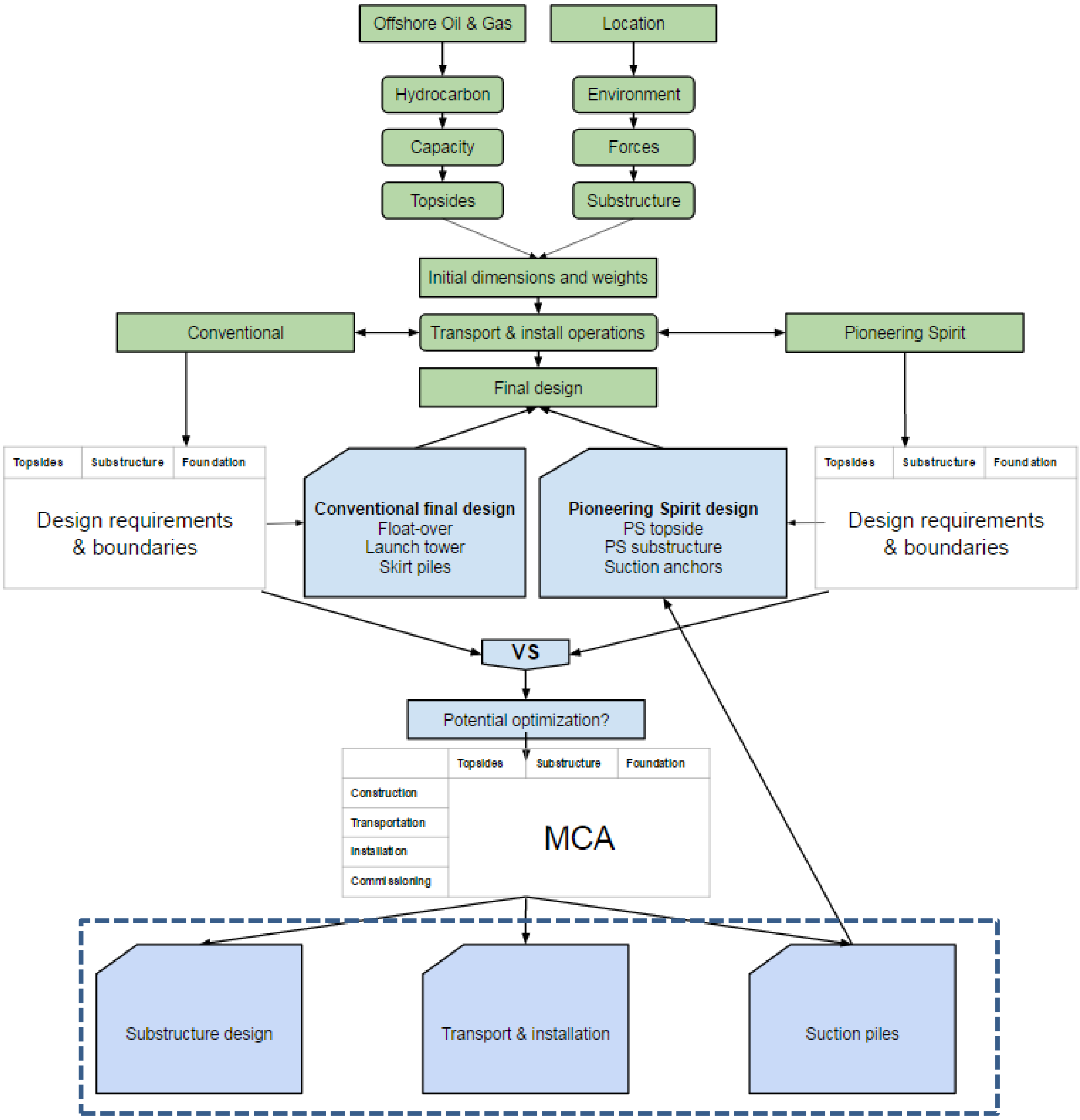


Figure 4-3: Completed platform design scheme

5 QUANTITATIVE ASSESSMENT OF THE POTENTIAL GAIN OF THE PS-INSTALLATION METHOD

5.1 Introduction

The three most promising potential areas for optimization are discussed in more detail in this chapter. A quantitative assessment is executed, using the case study data from the Kebabangan Platform (refer to Chapter 3). First, each area is quantified using the conventional method, thereafter the adjusted design as possible with the PS is assessed quantitatively. The latter is done in a relative way, comparing the saved costs to the costs as made for the Kebabangan Platform.

- The transport and installation procedure [Section 5.2]
- Substructure design [Section 5.3]
- Integrated foundation by using suction anchors [Section 5.4]

5.2 Transport and installation procedure

5.2.1 Introduction

The transport and installation procedure is considered as a potential area for optimization for each section of the platform. The conventional transport and installation scenario will be explained in Section 5.2.2. Seven new transport and installation scenarios are compared to the conventional scenario in Section 5.2.3. Here after conclusions are drawn.

Pioneering Spirit's day rate
Typically, offshore hours are more expensive than onshore hours by a factor of approximately 10 (expert opinion). Saving costs offshore is therefore the area of interest. Offshore operations cost consist of the duration of the operation, the type and amount of vessels and the associated day-rates of those vessels.

Estimations on duration, cruise velocities and day-rates are made and discussed with experts. With these estimations, a fair comparison is made between the conventional method and the PS method.

Before going into specific numbers, there is a point of discussion. The PS is a unique vessel; there is no vessel in the world with the same capabilities. That is why the “market” day-rate is not fixed. The vessel can adapt day-rates on the amount of work.

There is only one PS, so for this project it must sail to the project location. When Kebabangan is the only project near the South-China Sea and it is on the other side of the world, it might not be economically feasible to transfer the PS across the world. This is a point of discussion that is dealt by this research with the following measures.

There are two scenarios compared:
1. The conventional installation of the Kebabangan.
2. The PS installation of the Kebabangan
   a. The PS is sent to the South China Sea for multiple projects, meaning the mobilization costs are distributed over several projects.
   b. The PS is sent to the South China Sea for one project only.

The day-rate of the PS is hard to determine. The day rate of the PS is chosen conservatively at $1.000.000,-.

5.2.2 The conventional installation procedure for the Kebabangan Platform

With the information found on the conventional Kebabangan platform a hind-cast calculation is done in this section.

The conventional installation method is visualised in Figure 5-1 in chronological order. The day-rates of the vessels needed for the conventional method are given in Table 5-1. In Table 5-2 every step of the transport and installation method is presented with the accompanying duration. The cost of the entire operation is dependent on the duration of each step and the associated day-rates. Vessels can be in the field simultaneously. The total duration is the amount of days the critical path within the procedure will take, i.e. the topsides and the substructure can be transferred simultaneously on two barges, but the substructure needs to be installed before the topsides.

The cost of the procedure depends on the total time of vessels being in the field.

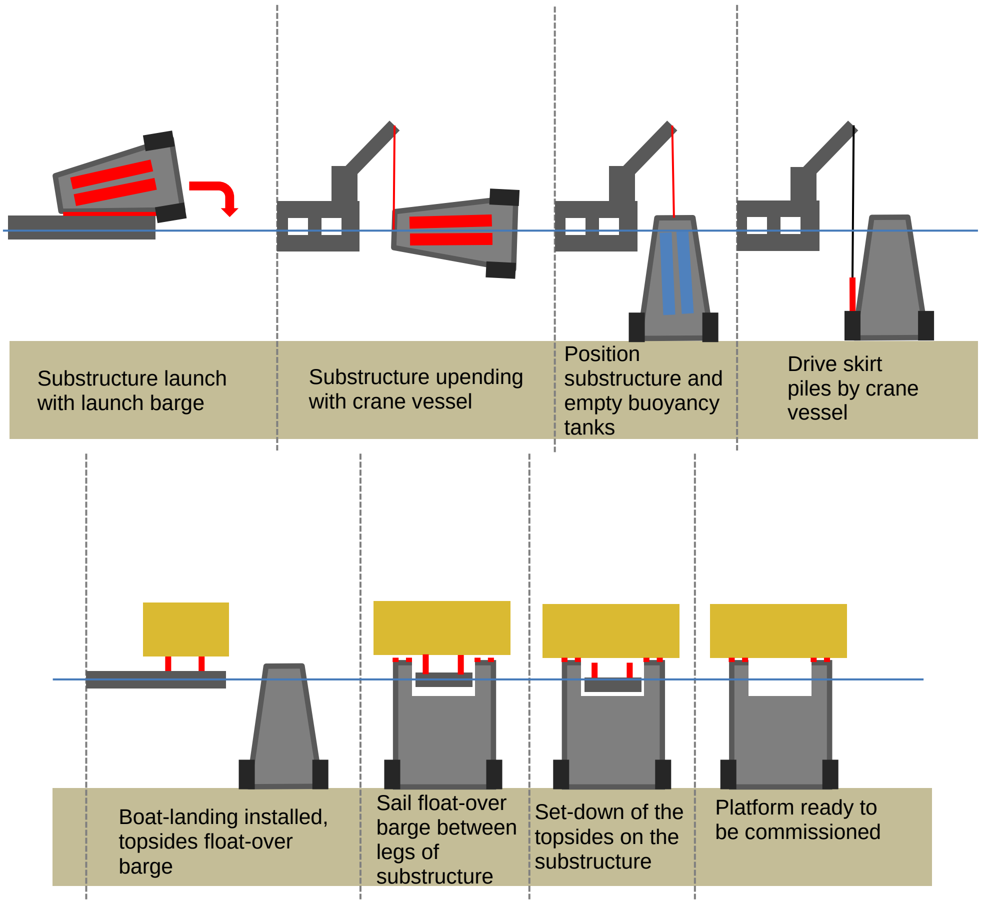


Figure 5-1: Conventional installation procedure

Vessel	Day rates [$/day]
Crane vessel	400.000
Barge	10.000
Tug	15.000
Support vessel	100.000
Semisubmersible dry dock	300.000
Launch barge	30.000

Table 5-1: Day-rates conventional procedure

Step number	Vessel	Procedure	Duration [days]	Costs [$]
1	Launch barge	Mobilisation of jacket barge	7,0	210.000
2	Launch barge	Load out jacket on barge	1,0	60.000
3	Launch barge	Sail barge to installation location	7,6	458.333
4	Launch barge	Launch jacket	0,25	15.000
5	Crane vessel	Mobilization of crane vessel	7,0	2.800.000
6	Crane vessel	Install jacket	1,0	400.000
7	Foundation barge	Mobilization foundation barge	7,0	70.000
8	Foundation barge	Sail to install location	5,6	222.222
9	Foundation barge and crane vessel	Install 12 piles	18,0	7.920.000
10	Crane vessel	Horizontally level the legs	1,0	400.000
11	Boat-landing barge	Mobilise boat-landing barge	7,0	70.000
12	Boat-landing barge	Sail to install location	5,6	222.222
13	Crane vessel and boat-landing barge	Install boat-lading	0,5	200.000
14	Boat-landing barge	Demobilise boat-landing barge	7,0	70.000
15	Crane vessel	Demobilise Crane vessel	7,0	2.800.000
16	Semisubmersible	Mobilise Semisubmersible	7,0	2.100.000
17	Semisubmersible	Load out topsides on Semisubmersible	1,0	300.000
18	Semisubmersible	Sail to float-over location	2,8	916.667
19	Semisubmersible	Float-over	2,0	660.000
20	Semisubmersible	Demobilise Semisubmersible	7,0	2.100.000
		Total installation time and cost	**31,4**	**21.990.000**

Table 5-2: Conventional installation procedure

The total duration of the of the conventional transport and installation method is 31,4 days and will cost approximately $ 22.000.000,-.

5.2.3 The PS-method for installation of the Kebabangan Platform

Within this research seven PS procedures were assessed. For the seven new procedures both scenarios with and without (de-)mobilization costs (i.e. multiple projects) are addressed, as proposed in Section 5.2.1. For mobilization, an additional 5 days one-way trip is accounted for (resulting in an additional 10 days in total for mobilization and demobilization). This is on top of the 2 days (de- and) mobilization for multiple project. When the PS has to sail all the way from the North-Sea to the South-Chinese Sea, this will take longer than 5 days. However, the PS has a lower day-rate when only sailing then when the vessel is in operation. Therefore it is justifiable to use 5 days for mobilisation and 5 days for demobilisation.

A barge is needed to transfer the sections of the platform from the quay to the PS. The transfer can be done near the production yard, but in some PS scenarios the transfer from barge to PS is done in a safe haven (water-depth 35m). In Figure 5-3 the location of the safe haven is shown at the arrow and the pin shows the location of the platform.

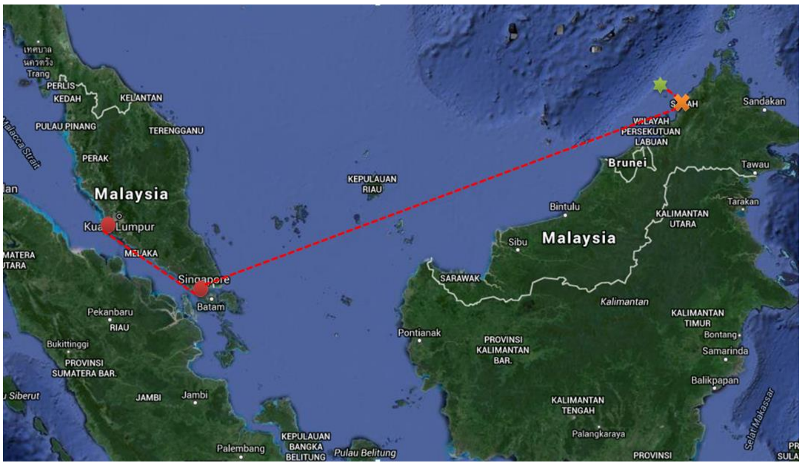


Figure 5-2: Transport overview (red dots: yards, orange cross: safe haven, green star: site-location) (source Google maps (2015))

Figure 5-3: Detail: Location safe haven, Borneo
(source Google maps (2015))

To make a reliable comparison, the same approach is used for the PS scenarios as was used for the conventional scenario.

The day-rates of the vessels that are used in the PS scenarios are given in Table 5-3. The PS scenarios are discussed briefly below. For a step-by-step description as in Table 5-2 for all PS-scenarios, including duration and costs, one is directed to Appendix H.

Vessel	**Day rates [$/day]**
PS	1.000.000
Barge	10.000
Tug	15.000

Table 5-3: Day-rates of the vessels of PS procedures

1. *Transfer in safe haven*

Both the topsides and the substructure will be transferred from the quay to two separate barges. These barges will be transported by assistance of a tug to the safe haven. The PS will sail to the safe haven as well. In the save haven the substructure will be transferred to the PS. The PS with the substructure will sail to the site-location. The PS then installs the substructure. The PS will also install the foundation (suction anchors). Thereafter, the PS will sail back to the safe haven to pick up the topsides. The topsides will be transferred onto the PS in the safe haven. The PS will sail the topsides to the site-location and install the topsides. The cost and duration are shown in Table 5-4.

	Duration [days]	**Costs [$]**
No mobilization cost	16,5	12,820,000
With mobilization cost	16,5	22,820,000

Table 5-4: Duration and costs; safe haven

2. *Topsides safe haven, substructure yard*

The substructure will be transferred from the quay to a barge and from the barge to the PS close by the construction yard. This is done because the PS has a higher cruise velocity than a barge. The PS sails with the substructure to the site-location and installs the substructure. The foundation (suction anchors) is installed by the PS. A barge with the topsides is transferred from the construction yard to the safe haven, where the transfer of the topsides to the PS takes place. The PS will sail to the site-location and installs the topsides. The cost and duration are shown in Table 5-5.

	Duration [days]	**Costs [$]**
No mobilization cost	12,2	16,110,000
With mobilization cost	12,2	26,110,000

Table 5-5: Duration and costs; topsides safe haven, substructure yard

Note: This could be a suited procedure when the PS sails along the production yard.

3. *Both structures on PS from yard*

The topsides and the substructure will be transferred from the quay to individual barges. The PS sails to the substructure yard, where the substructure transfer from barge to PS takes place. The PS sails to the topsides yard, where the topsides transfer from barge to PS is done. Thereafter, the PS will sail to the site-location and installs the substructure. After the foundation (suction anchors) is installed, the topsides is moved on top of the substructure. The cost and duration are shown in Table 5-6.

	Duration [days]	**Costs [$]**
No mobilization cost	11,2	14,680,000
With mobilization cost	11,2	24,680,000

Table 5-6: Duration and costs; substructure and topsides on PS from yards

4. *Substructure from yard, topside safe haven and conventional skirt piles installed by PS*

The transport and installation procedure in this scenario is similar to scenario 2. The only difference is the type of foundation. The soil properties influence the type of foundation that can be used. When the soil conditions do not allow for suction anchors, skirt piles may be an option for the foundation. The PS will install the skirt pile foundation in this scenario. Compared to scenario 2, an additional barge is needed for the transport of the skirt piles to the site-location.

After the substructure is installed as described in scenario 2, the skirt pile barge and the PS are used for the installation of the skirt pile foundation. When the skirt piles are in-place the topsides are placed on top of the substructure. The cost and duration are shown in Table 5-7.

	Duration [days]	**Costs [$]**
No mobilization cost	29,2	33,440,000
With mobilization cost	29,2	43,440,000

Table 5-7: Duration and costs; Substructure from yard, topsides safe haven and skirt pile installation by PS

5. *Launch tower installed by PS, skirt piles, topside picked up at safe haven*

Scenario 5 uses skirt piles as foundation, enabling the possibility for the substructure to be launched. A launch barge is used to transport the substructure from the yard and launch the substructure at the site-location. The topsides are transported on a barge to the safe haven. At the safe haven the topsides are transferred from the barge to the PS. The PS sails to the site-location and positions the substructure. A skirt pile barge is transported to the site-location and the PS installs the skirt pile foundation. The final step for the PS is to position the topsides on top of the substructure. The cost and duration are shown in Table 5-8.

	Duration [days]	**Costs [$]**
No mobilization cost	29,6	28,080,000
With mobilization cost	29,6	38,080,000

Table 5-8: Duration and costs; Launch tower installed by PS, skirt piles, topside picked up at safe haven

6. *Launch tower installed by PS, skirt piles, topside picked up from yard*

This scenario is similar to scenario 5, but the transfer of the topsides to the PS is different. The topsides are transferred near the yard, instead of in the safe haven. The PS sails to the site-location. The substructure is transported on a launch barge and launched at the site-location. The PS installs the substructure and thereafter the foundation (again a skirt pile barge is used for the foundation transport). The topsides are moved in position on the substructure. The cost and duration are shown in Table 5-9.

	Duration [days]	**Costs [$]**
No mobilization cost	29,6	30,060,000
With mobilization cost	29,6	40,060,000

Table 5-9: Duration and costs; Launch tower installed by PS, skirt piles, topside picked up from yard

7. *Substructure and skirt piles installed by crane vessel*

The installation process of skirt piles is the most time-consuming part in the scenarios. Using a crane-vessel instead of the PS to install the skirt piles will reduce the costs of the installation of the foundation. The substructure is transported and launched by a launch barge. Skirt piles are transported to the site-location on a separate barge. A crane vessel is used to install the substructure and to drive the skirt piles. The topsides are transported on a barge to the safe haven and transferred on to the PS at the safe haven. The PS sails to the site-location and installs the topsides. The costs and duration are shown in Table 5-10.

	Duration [days]	**Costs [$]**
No mobilization cost	30,2	22,520,000
With mobilization cost	30,2	32,520,000

Table 5-10: Duration and costs; Substructure & skirt piles installed by crane vessel

Overview PS scenarios

All seven PS scenarios, and the conventional scenario, are listed in Table 5-11. The duration and cost differ significantly between the different scenarios. Only three scenarios are found to be less expensive than the conventional scenario (green in Table 5-11). These were all scenarios where the mobilization costs could be distributed over multiple projects. Actually, when using a PS scenario mobilizing for one project only, none of the scenarios is economically feasible.

Conventional	**Days**		**Total costs**
KBB	31.4	$	21,990,000
PS Scenarios	**Days**		**Total costs**
Mobilization for multiple projects			
Safe haven	16.5	$	12,820,000
Safe haven for topside, jacket from yard	12.2	$	16,110,000
No safe haven, both on PS	11.2	$	14,680,000
PS with conventional piles	29.2	$	33,440,000
PS with conventional launch barge, foundation install by PS, topside safe haven	29.6	$	28,080,000
PS with conventional launch barge, topside at yard	29.6	$	30,060,000
PS with conventional launch barge, foundation install by crane vessel topside safe haven	30.2	$	22,519,000
Mobilization only for Kebabangan			
Safe haven	16.5	$	22,820,000
Safe haven for topside, jacket from yard	12.2	$	26,110,000
No safe haven, both on PS	11.2	$	24,680,000
PS with conventional piles	29.2	$	43,440,000
PS with conventional launch barge, foundation install by PS, topside safe haven	29.6	$	38,080,000
PS with conventional launch barge, topside at yard	29.6	$	40,060,000
PS with conventional launch barge, foundation install by crane vessel topside safe haven	30.2	$	32,519,000

Table 5-11: Overview total project costs and duration, for conventional and PS scenarios

An interesting scenario is the “Safe Haven”. Even with the mobilization only for Kebabangan the scenario cost is nearly the same (orange box in Table 5-11). The duration of the whole scenario is nearly halved. Shorting the operation time has a couple of advantages:

Installation window

Workability is important at these kinds of operations. A smaller installation window (shorter duration of the scenario) results in less influence from the workability, resulting in less delays. In addition, the PS is a very large vessel and the workability will be better than the conventional way of installing (i.e. less waiting on workable weather).

First oil

Shortening the total project duration means production of hydrocarbons can start earlier. The so-called “deferment” is a principle that is used to discount for the value given to get first-oil (i.e. earlier production of hydrocarbons results in a profit and vice versa.). The deferment is used for calculating the revenues for Kebabangan. Table 5-12 shows the amount of hydrocarbons the platform will produce. The revenues are calculated with the current (source (Nasdaq, 2015)) oil and natural gas price (Table 5-12).

Amount	**Unit**	**Price [$/unit]**	**Revenue [$/day]**
825	Million standard cubic feet per day [MMscf/d]	2.806	$ 2.314.950
80.000	Barrels per day [Bbl/d]	56,66	$ 4.532.800
22.000	Barrels of condensate per day [Bbl/d]	56,66	$ 1.246.520
		Total	**$ 8.094.270**

Table 5-12: Production and revenue Kebabangan

Using a rule of thumb, the deferment varies between 7% and 10%, being conservative, 8% is chosen to calculate the difference in revenue between the scenarios (Table 5-13). For every day the hydrocarbons are produced later, 8% of the revenue per day can be added to the total cost of the scenario.

Deferment	8%
Total revenue/day	$ 8.094.270
Deferment/day	$ 647.542

Table 5-13: Deferment discount calculation

The comparison of the scenarios including the deferment will be done as describe below:

- When theoretically reducing the duration of the scenario to zero days, the deferment has no influence. The scenario will now cost the operator the scenario cost.
- Adding a day to the installation process, the production is postponed by a day.
- Multiplying the amount of days for each scenario with the deferment/day and adding this to the scenario cost will result in a theoretically "total cost" of the scenario.

The scenarios that are less expensive than the conventional installed Kebabangan scenario are shown in green in Table 5-14. It is found that there are now more scenarios economically feasible. The difference in total duration in days has a large impact on the three scenarios mentioned in Table 5-11. The savings are larger when including the deferment with the PS scenarios. "Mobilization only for Kebabangan" even shows three economically feasible scenarios.

Conventional	**Days**	**Total costs**
KBB	31.4	$ 42,316,000
PS Scenarios	**Days**	**Total costs**
Mobilization for multiple projects		
Safe haven	16.5	$ 23,486,000
Safe haven for topside, jacket from yard	12.2	$ 24,021,000
No safe haven, both on PS	11.2	$ 21,944,000
PS with conventional piles	29.2	$ 52,360,000
PS with conventional launch barge, foundation install by PS, topside safe haven	29.6	$ 47,262,000
PS with conventional launch barge, topside at yard	29.6	$ 49,242,000
PS with conventional launch barge, foundation install by crane vessel topside safe haven	30.2	$ 42,064,000
Mobilization only for Kebabangan		
Safe haven	16.5	$ 33,486,000
Safe haven for topside, jacket from yard	12.2	$ 34,021,000
No safe haven, both on PS	11.2	$ 31,944,000
PS with conventional piles	29.2	$ 62,360,000
PS with conventional launch barge, foundation install by PS, topside safe haven	29.6	$ 57,262,000
PS with conventional launch barge, topside at yard	29.6	$ 59,242,000
PS with conventional launch barge, foundation install by crane vessel topside safe haven	30.2	$ 52,064,000

Table 5-14: Total cost including deferment

As shown in Table 5-14 the most favourable scenario (including deferment) is: "No safe haven, both on PS". In Table 5-15 a similar step by step plan is given for this scenario. In Figure 5-4 the installation scenario of the PS is shown.

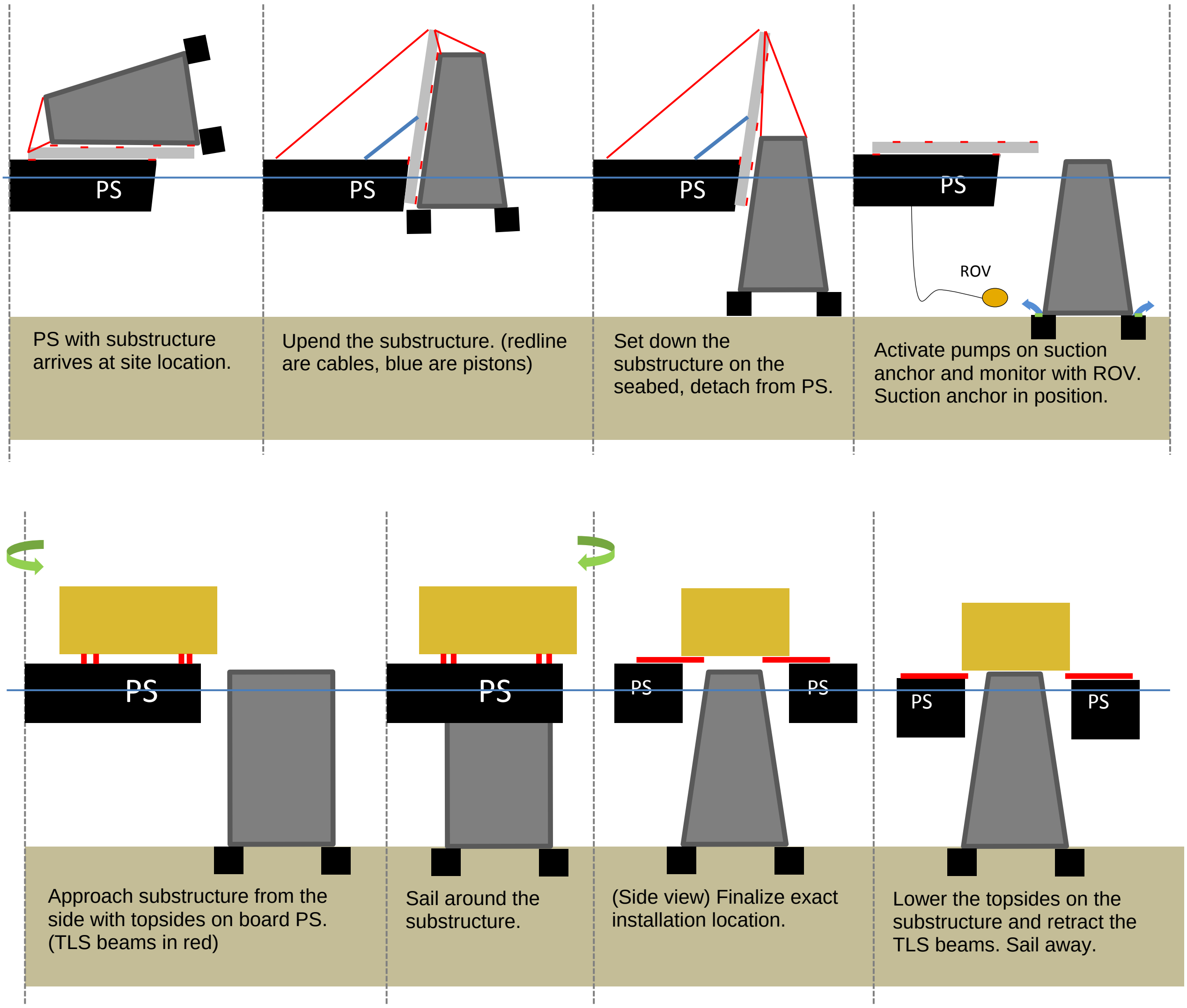


Figure 5-4: "No safe haven, both on PS" installation procedure

Step number	No safe haven, both on PS		duration [days]
1	Jacket barge	Mobilisation of jacket barge	7,0
2	Jacket barge	Load out jacket on barge	1,0
3	PS	Mobilisation of PS	2,0
4	Jacket barge and PS	Load jacket from barge on PS	1,5
5	Jacket barge	Demobilise barge	7,0
6	PS	PS sail to topside yard	1,1
7	Topside barge	Mobilisation of topside barge	7,0
8	Topside barge	Load out topside on barge	1,0
9	Topside barge and PS	Load topside on PS	1,0
10	Topside barge	Demobilise barge	7,0
11	PS	PS sail to install location	2,8
12	PS	Install jacket	1,0
13	PS	Install foundation	1,0
14	PS	Horizontally level the legs	1,0
15	PS	Install Topsides	0,8
16	PS	Demobilise PS	2,0
	Total installation time		**11,2**

Table 5-15: "No safe haven, both on PS" installation procedure

5.2.4 Conclusion

Without the deferment three out of seven scenarios with mobilization for multiple projects were found economically feasible. Including the deferment, four out of seven scenarios are economically feasible with mobilization for multiple projects. The savings increase to $20.000.000.-.
Mobilizing the PS for only the Kebabangan project including the deferment leads to three scenarios being economically feasible. The savings then increase to $10.000.000,-.

Note 1: The scenarios with large savings include suction anchors. Use of suction anchors will be addressed in Section 5.4.

Note 2: Other scenarios are not economically feasible on this potential area. This does not mean the conventional scenario is more preferred. Possible savings on construction at the topsides and substructure when using the PS to install the platform could make the other scenarios still feasible (using skirt piles).

5.3 Substructure design

5.3.1 Introduction

The substructure design was considered as a second potential area for optimization.

As mentioned in Chapter 2 and 3, the design of the substructure depends on:

- The configuration of the topsides;
- Support frame in the topsides (permanent support and temporary lift points);
- The environmental forces on the substructure (waves, current);
- The environmental forces on the topsides (wind); and
- The forces due to the weight of the topsides.

5.3.2 The conventional substructure design

The main function of a substructure is the support of the topsides. It is therefore important to look at the configuration of the topsides.

There is little public information on topside configuration. Allseas is not specialized in designing topsides, but for some projects drawings and weight reports are available. Using this information, a rough composition of weight distribution can be made. Two projects were used for reference.

At the first project the topside is divided in several smaller topsides (all with their own substructure). Each has their own functionality (living quarters, Processing, Flare boom, etc.). The proportions between the different modules can be determined.
The second platform consists of an integrated topsides. Information is available on the weight composition, which enables to come up with a rough estimation of the weight distribution of the platform.

Using both the information, a percentage estimation of the total weight of a platform is made. (Column 2, Table 5-16) The total weight of the conventional Kebabangan topsides is known, so an estimation is made on the distribution on the Kebabangan topsides. (Column 3, Table 5-16.)

Topside module	**[%] total weight**	**Weight Kebabangan [ton]**
Flare	1,9	316
Helicopter-deck	0,9	130
Living quarters	11,6	1.970
Utility	29,4	1.998
Process	29,3	5.032
Support frame	26,9	4.573

Table 5-16: Weight distribution approximation

With the weight estimations a new topsides can be constructed. Knowing the distribution the placement of the supports (top of the substructure) can be optimized. (See Appendix D for the weight distribution used by “The Handbook for Offshore Engineering” (Subrata, 2005)).

Design philosophy for substructures

The design philosophy is driven by an iterative process, based on the conventional design circle (Figure 5-5). The preliminary design of a substructure is done based on the forces it has to withstand. Certain dimensions, diameters and wall thicknesses are found. Looking into the installation method in more detail, will result in extra steel required. The launch runners on a launch substructure will result in a larger attack area, meaning the forces will be larger. The dimensions of the substructure need to be adjusted. The diameters of the members might increase enlarging the attack area gain. Also the substructure will be getting heavier which might result in bigger launch runners. This is an iterative process that will make the substructure heavier step by step.

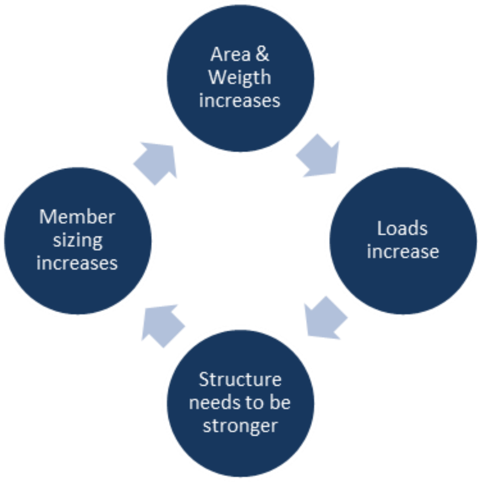


Figure 5-5: Design circle (conventional)

5.3.3 The PS substructure design

Dividing the topsides in two equal halves and placing the above-mentioned parts in such an order that the Centre Of Gravity (COG) is located directly above the legs, is the starting point of the topside design. Taking the weights into account and placing the COG above the legs, the distribution in Figure 5-6 is obtained. A 3D impression is shown in Figure 5-7.

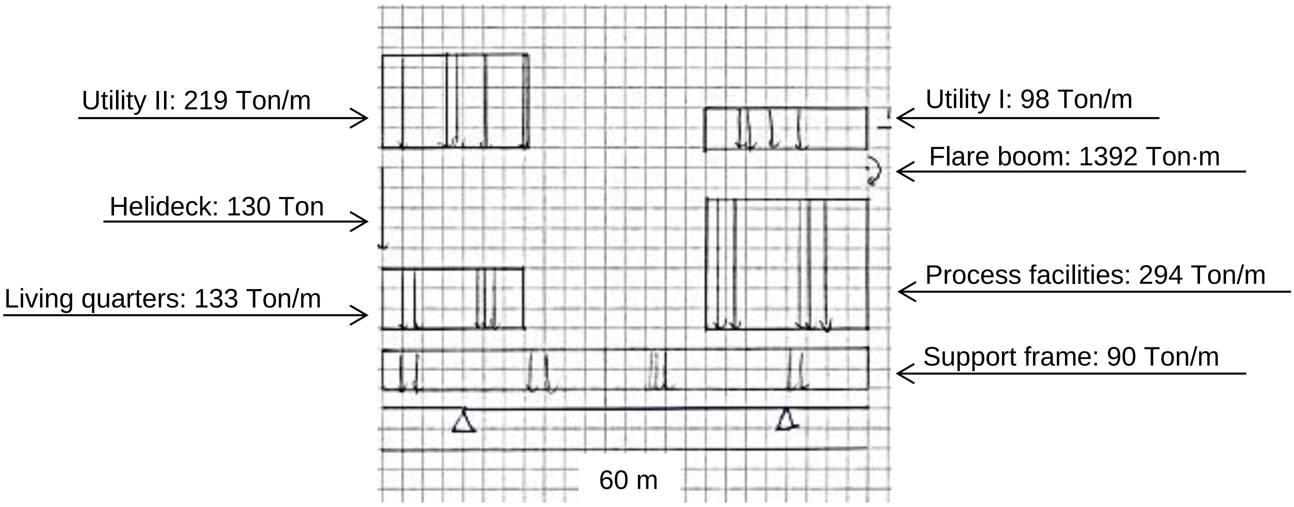


Figure 5-6: Weight lay-out of topsides PS

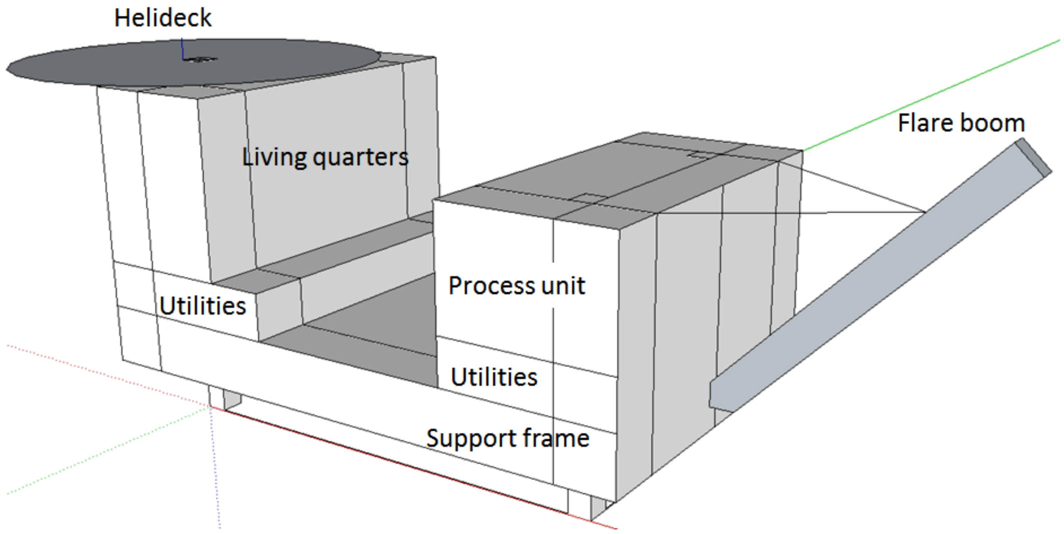


Figure 5-7: Topsides PS for Kebabangan

The weight distribution philosophy on the topsides design is not the only consideration in the topsides configuration. As mentioned in Section 3.3.3, a tender assist (temporary drill tower) must be able to be positioned on the topsides as well. A gap in the middle of the topsides is used for the tender assist. The tender assist must be positioned in line with the riser/conductor support frame. The riser support frame will therefore be positioned directly below, in the middle of the substructure (Figure 5-8). This is a design requirement for the substructure design.

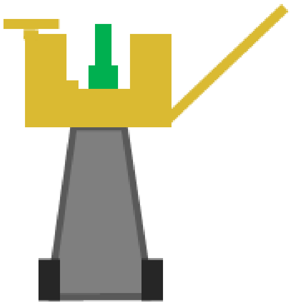


Figure 5-8: Topsides PS
with tender assist

While designing a steel substructure an estimation of certain dimensions is the first step. With rules of thumb, the initial height, diameter, wall thickness etc. can be determined for all the individual steel elements (legs, horizontal and diagonal members, Figure 5-9) on a substructure. The complete calculation of the substructure can be found in Appendix D. The rules of thumb that are used originate from “Handbook of offshore engineering” (Chakrabarti, 2006). Based on these rules of thumb and the configuration of the topside, a tower construction for the substructure can be designed.

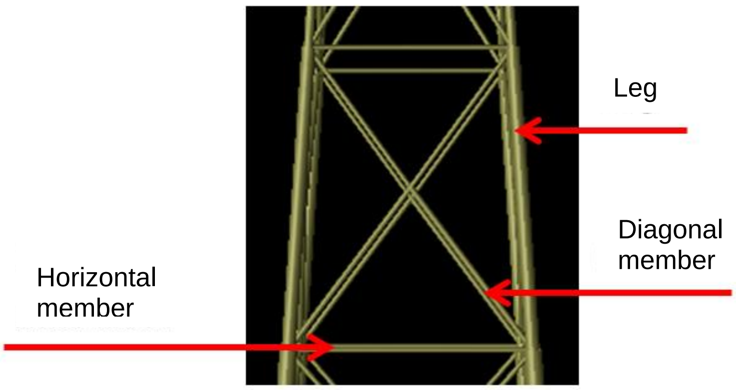


Figure 5-9: Legs, members

Design philosophy for PS

Using the PS to install the substructure, launch runners or temporary steel will be reduced to a minimum. Making the substructure lighter and the attack area will not increase drastically. Figure 5-10 shows this reversed circle philosophy. Reducing the amount of legs from eight to four will result in a lighter substructure. The JLS on the PS even prefers a four legged substructure.

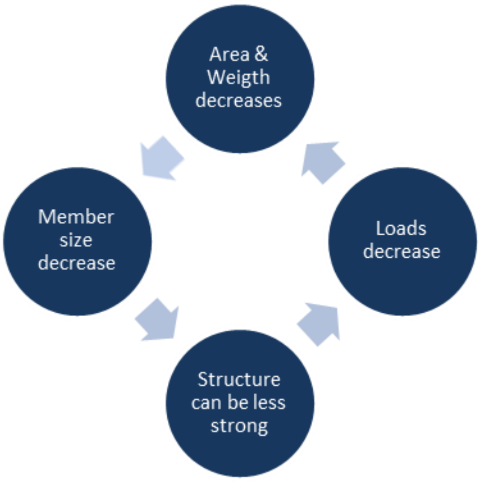


Figure 5-10: Design circle (reversed)

A minimalistic substructure in terms of steel will then be the result of this design philosophy. Examples are the use of four legs instead of eight and a less dense substructure by the use of less but longer diagonals. One of the important boundary conditions of the PS is the minimum distance between the MSL and the lifting points of the topsides. The maximum draft, the remaining freeboard, height of the TLS beams and the jokes range result in a minimum distance of 15m. The connection between the topsides and the substructure is depended on this distance. The current distance between the MSL and the deck at Kebabangan is estimated at 11m. This distance can be result of the installation technique or the environmental influences at the location.

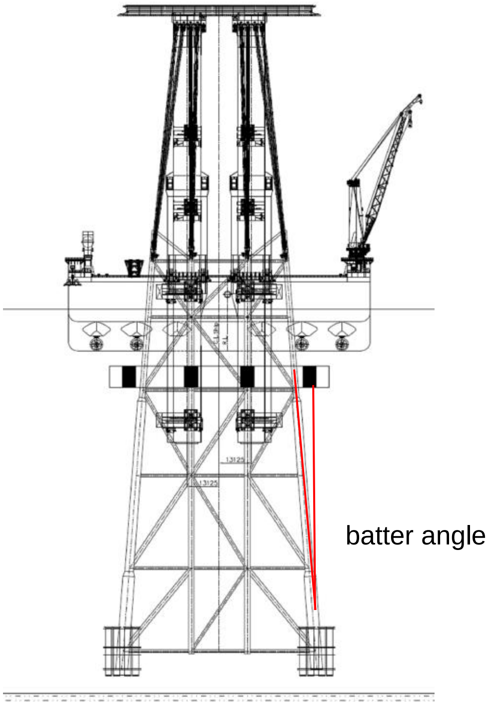


Figure 5-11: Aft PS, JLS (Allseas method statement (2015))

The key design criteria and limitations when installing the new platform with the PS (Figure 5-11) are listed below:

- The batter angle is the angle between the vertical and the legs. With the JLS boundaries in mind and the perpendicular TLBs it will be very convenient to use batter angles in two of the four vertical panels (between two legs) of the substructure, as shown in Figure 5-11. This way the skidding and the sledges can be used very easy and without any additional adjustments.
- The elevation of the deck of the topsides is either determined by the wave height, storm surge etc. or limits of the installation method. Using the PS to install the topsides the lifting points of the topsides need to be at 15m above MSL.
  Members (bracings) can be arranged in a numerous ways. A couple of things are important, like: the maximum length (40m), diameter (1,5m) of the members and the welding angle. Welding cannot be done if the angle between two members is too small (less than 30 degrees, see Figure 5-12).

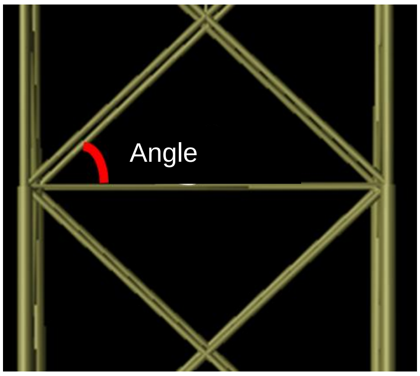


Figure 5-12: Welding angle

The way the rule of thumb is applied is as follows:

- The Height of the platform: This is determined by the water depth, tidal range, subsidence (the distance the platform will sink into the ground over the life time) and the storm surge.
- The other boundary needed to be taken into account is de installation type. The PS needs a 15m gap between the water surface and the lifting points.

Calculating the deck elevation for the environmental influences and comparing it to the deck elevation needed for installation with the PS results in the following:

$$D_{max} = MSL + half\ the\ tidal\ range + subsidence + storm\ surge$$
$$Deck\ elevation\ environment = D_{max} + 0{,}55 \cdot H_{max} + airgap = 149\ [m]$$

Or

$$Deck\ elevation\ PS = MSL + 15 = 155[m]$$

With:

• D_{max}	Water depth	140	[m]
• H_{max}	Wave height	12	[m]
• $airgap$		1,5	[m]
• $subsidence$		0,4	[m]
• $storm\ surg$		0,4	[m]
• $half\ the\ tidal\ range$		1,06	[m]

The extra deck height compared to the conventional height is a minor disadvantage in the design of the optimized substructure.

It is noted that the deck elevation could be lower than the lifting points. This automatically means the temporary lift points (used for installation) are needed besides the permanent support points, which is undesirable.

Note. The difference between the deck-elevation of 11m on page 59 and the calculated 9m. This difference is probably the result of the use of different environmental data.

The height is known and the dimensions of the topsides are known. The configuration of a substructure can be determined. There are some points of interest. The distance between the lowest horizontal brace and the seafloor must be at least 0,5m after the foundation is in place. No horizontal bracing plane must be in the splash zone. Welding the substructure allows the angle between members to between 30-60 degrees. An angle outside this range will simply not be weldable due to lacking space.

With the PS having perpendicular Tilting Lift Beams (TLBs) the batter angle is limited to a batter angle in only two planes. Making use of a batter angle will allow the structure to cope with the horizontal forces more easily. Knowing there will be five sledges on the TLBs the first sketches can be made. The reaction forces of the sledges will be vertical. Logically the sledges are therefore positioned underneath the joints where the diagonal-, horizontal-bracings and the legs are joint together. Five horizontal bracings will therefore be convenient. The spacing between the horizontals (in vertical direction) will be more or less the same.

The preliminary member sizing will be determined with the correlations shown below. The footprint at the seabed is chosen to be 40x40m as a starting point. The batter angle used is 1:15 in only 2 planes, which results in an area of 20x40m at the top of the substructure. This is a preliminary estimation of the dimensions and is based on, but not the same as the case study's foot print and batter angle.
With this starting point, height and the welding angle boundaries, a design is made. In Appendix D a coordinate system is used to give a position where the joints (connection member to member and leg to member) are located. All the members and legs are listed as a line between two joints, all with their own length (L).
The length (L) of a member (or leg) has a correlation with the radius (r). The distance between two ends of a member is known from the graphical design. With factor-K, the radius of the member can be calculated (Chakrabarti, 2006).

$$K_{factor} \cdot \frac{L}{r} = 80; with\ K = 0,8$$
$$r = \sqrt{\frac{I}{A}}$$
$$I \approx \pi \cdot D^3 \cdot \frac{t}{8}$$
$$A \approx \pi \cdot D \cdot t$$

$$D \approx 0,023L$$

$$\frac{\mathrm{D}}{\mathrm{t}}\ ratio\ depends\ on\ the\ height \begin{cases} At\ top\ of\ substructure: 30 \\ At\ bottom\ of\ substructure: over\ 40 \end{cases}$$

With:

• D	Diameter	[m]
• I	Inertia	[m^4]
• t	wall thickness	[m]
• r	radius	[m]
• K_{factor}	K- factor	[-]
• A	Area	[m^2]
• L	Length	[m]

With these correlations the estimation of the members will be done. A complete overview of the member sizing can be found in Appendix D.
For commercial purposes there are some standard values that will be used. The diameters of commercially available tubulars go up in steps of 2 inches. The wall thicknesses go up in steps of 0,125 inch.

A visualisation of the substructure as result of the rule of thumb is shown in Figure 5-13.

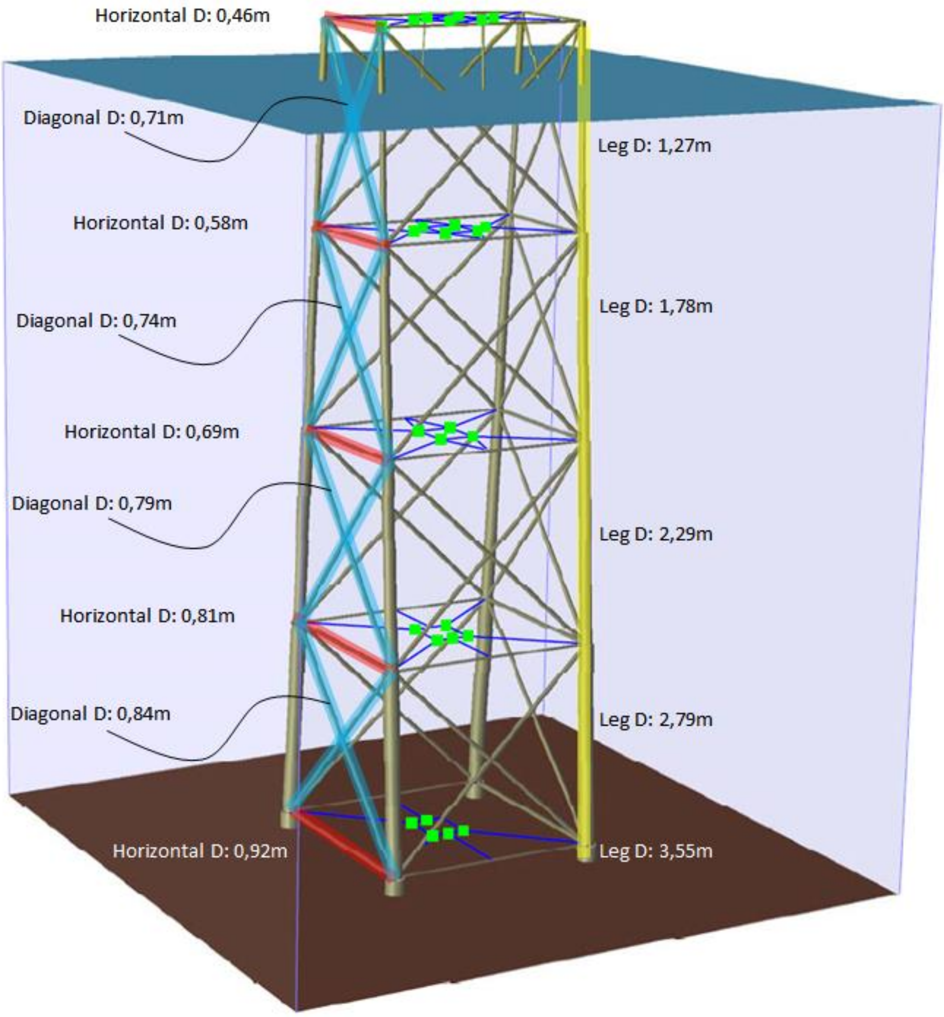


Figure 5-13: Diameter overview of legs and members

These calculated dimensions are a starting point for an optimization and the start of a loop process to come up with the final dimensions of the substructure. This loop process is part of the circle mentioned in Figure 5-14. With these first dimensions the forces on the structure can be calculated. Together with the weight of topsides, the legs and members can be checked. (A preliminary check on buckling of the legs is done, see Appendix D.) When they are too strong or too weak, adjustments can be made. Then again with the changed dimensions the forces need to be calculated again, etc. This iterative process is out of the scope of this research. Nowadays finite element models are used to optimize substructures.

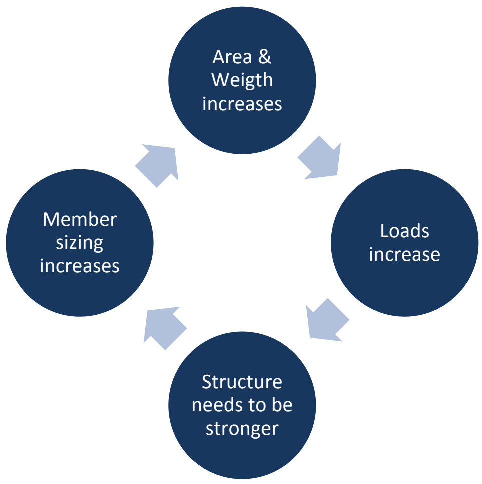


Figure 5-14: Iterative design process

The optimizing and going through this detailed iterative process is beyond the scope of this research (Figure 5-14). The designed structure will be used in this research. Though, a visual representation of the structure is shown in Figure 5-15.
The total calculations on the rule of thumb for every member of this substructure can be found in Appendix D of the PS substructure design.

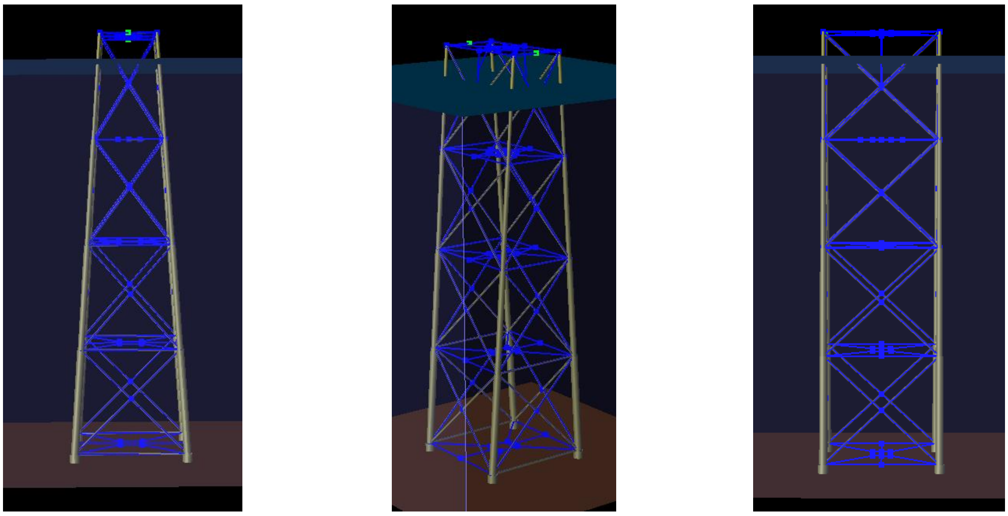


Figure 5-15: PS substructure for Kebabangan, modelled in Sesam GeniE

Savings

After the checks the amount of steel can be calculated. With the lengths, diameters and wall thicknesses, the volume of steel used for the substructure will be calculated. With the steel density of 7.850 [kg/m^3] the substructures weight is calculated. This results in a preliminary reduction of 60% compared to the conventional tower (Table 5-17).

	Weight [kg]	**Weight [ton]**
Dry weight PS tower	4.827.546	4.828
Original weight KBB	12.300.000	12.300
Reduction		60,8%

Table 5-17: Steel reduction

The rule of thumb/guidelines results in dimensions for the preliminary design. To be able to compare the weight of the conventional substructure with the optimized substructure for PS installation, additional weight must be added due to inaccuracies, anodes, secondary steel e.g. Offshore industry standards use approximately 20-30% (based on expert opinion) to add to the weight calculated by the rule of thumb (Table 5-18) to make a comparison.

Total dry weight PS	4.827.546	[kg]	4.828	[ton]
30% addition	1.448.264	[kg]	1.448	[ton]
Total weight PS tower	6.275.810	[kg]	6.276	[ton]

Table 5-18: Steel reduction re-evaluated

In the offshore industry, construction steel for substructures costs approximately 5000$/ton.
This will then result in a cost saving of (Table 5-19):

Total dry weight PS		**6.276**	**[ton]**
Original weight Kebabangan		12.300	[ton]
Reduction		6.024	[ton]
Construction steel saving	5.000$/ton	30.120.000	[$]

Table 5-19: Economical savings

The difference in dimensions is visualised in Figure 5-16. The dimensions show the PS substructure is somewhat higher, but less wide.

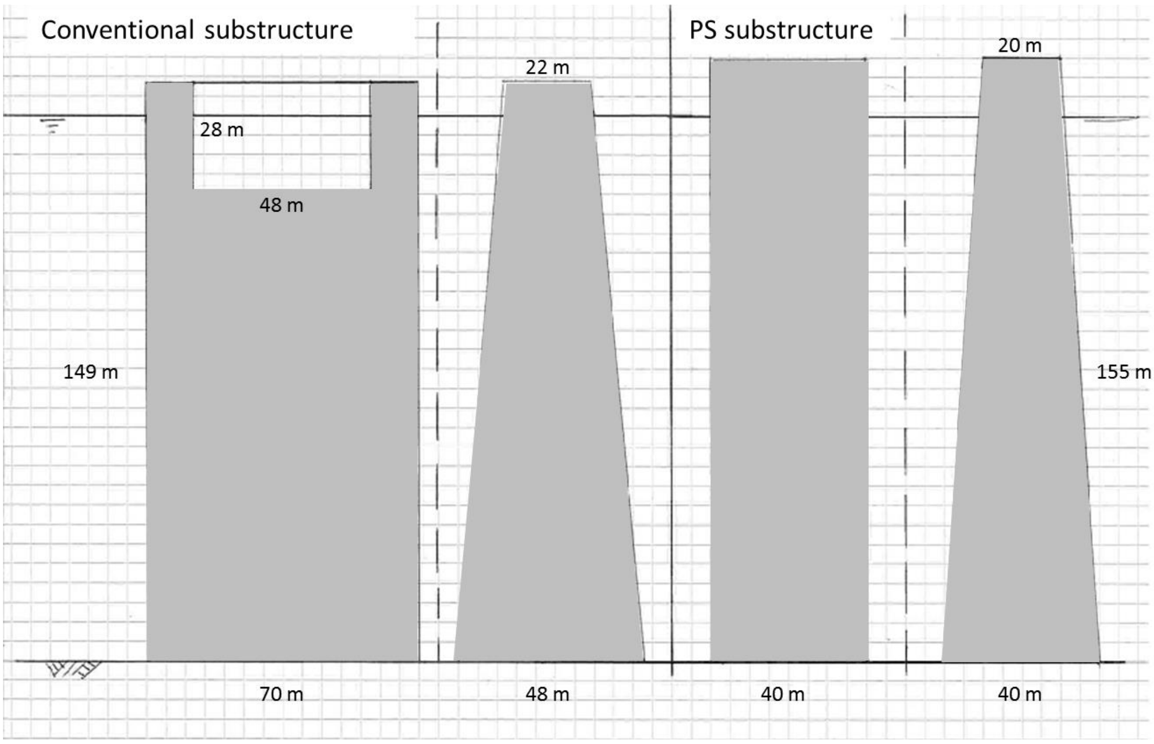


Figure 5-16: Substructure Conventional and PS

5.3.4 Conclusion

The savings adopted in this section are mainly caused to the following:

- The conventional platform has 8 legs, compared to the 4 legs in the optimized design.
- The skid-beams and the supports for these skid beams are not needed any more.
- Float-over operations require a large gap in the middle of the substructure. Due to the gap the substructure needs additional bracings to ensure the structural integrity. This gap automatically results in a relative wide (stretched) substructure which requires additional steel to make it wider. The optimized substructure does not need the gap in de middle and can therefore be kept slimmer.
- The reduction of steel is based on rule of thumb and is based on a preliminary design phase. The factor of 1,3 will cover the extra steel needed for further design phases. After this preliminary design phase more detailed design phases must be executed to gain more insight and less uncertainty in the final design. The installation of the PS may need even more steel. When transporting the substructure on its side on the PS, the support points may need reinforcement to cope with the stresses induced by the horizontal position and the forces induced by the motions of the vessel due to waves. This could exceed the factor of 1,3. The profit could therefore optimistic.

The “Construction steel saving” relates to the focus area in Section 5.2. With this substructure design specially designed for installation with the PS, there is a large steel reduction. This reduction translates into a cost saving that make transport and installation methods mentioned in Section 5.2 possible.

The total project (construction, transport and installation of the substructure) will be less expensive even when the foundation of skirt piles is done by PS. For projects where the soil composition might not be suitable for suction anchor, it might be still economically feasible to use the PS for the entire project when the substructure is designed to be installed by the PS.

5.4 Integrate foundation by using suction anchor

5.4.1 Introduction

Conventionally the foundation was installed by skirt piles. Using the PS for installation, the foundation design is an important area for optimization. Foundation by suction anchors will be investigated in this section of the report.

In Figure 5-17 a step-by-step approach is shown on how the suction anchors will be designed such that the PS will be able to install it and that the strength and bearing capacity of the suction anchor will suffice.

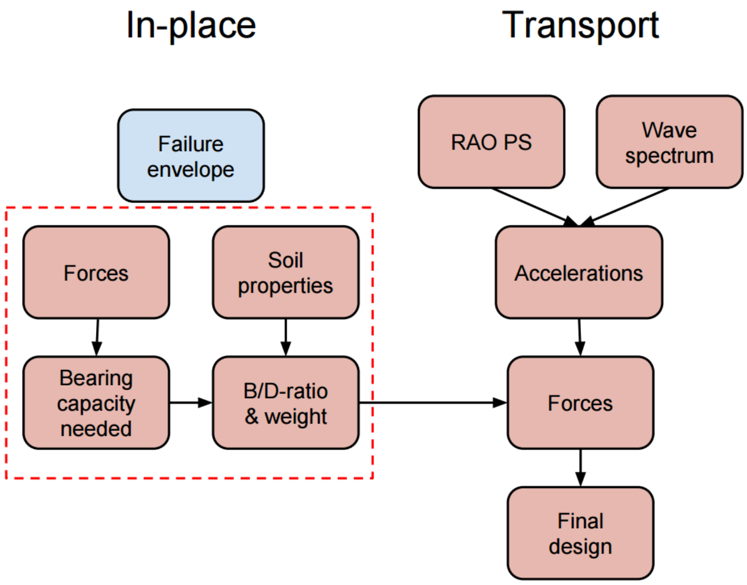


Figure 5-17: Suction anchor design

A suction anchor will primarily be designed to be able to deliver the required bearing capacity the platform needs. This is dependent on the forces (including gravity) acting on the platform. The platform is designed on a wave with a 100-year return period (refer to Section 3.2.2). The soil bearing capacity needs to cope with the forces acting on the foundation. The soil conditions are therefore an important part of the design on the size of the suction anchor. The soil might consist out of different layers/types of soil, all with their own properties. The steps taken for the in-place condition are also shown schematic in Figure 5-17 (red box).

The in-place conditions are used for the sizing of the suction anchor (addressed in Section 5.4.2, 5.4.3). With the size of the suction anchor the initial dimensions and weights are calculated (B/D-ratio & weight, Figure 5-17) (addressed in Section 5.4.4).

The suction anchors are positioned at the bottom of the substructure. In the transport phase the suction anchor is hanging at the end of the substructure and will be exposed to movements and accelerations of the PS (Figure 5-18). These movements are caused by the sea state during transport (addressed in Section 5.4.5)

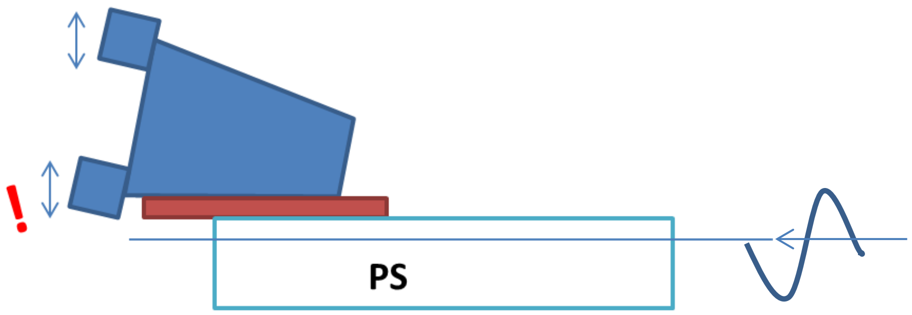


Figure 5-18: Accelerations during transport

These movements of the PS can be predicted by the Response Amplitude Operators (RAO) of the PS. Knowing the movements of the PS, the accelerations and corresponding forces on the suction anchors are calculated (addressed in Section 5.4.6). These forces must be within limits so the suction anchor and the connection (suction anchor to jacket) will not fail (Figure 5-18).

Reinforcements can be added to handle the forces and stresses, resulting in a final design of the suction anchor.

5.4.2 Forces – In place

The environmental influences mentioned in Section 3.2.2 will cause forces on the substructure and topsides. The current is the water pushing against the substructure. The force caused by the current is dependent on the velocity of the current and the attack area of the substructure. A higher velocity results in a larger force. The waves and the wind also have their own contribution to the forces acting on the platform. The Morison equation (Faltinsen, 1990) is used to calculate these forces on the topsides and substructure. The forces introduced by the weight of the topsides and the substructure must be included as well. The Morison equation can be divided in a drag force $F_D$and an inertia force F_I. The total force is the sum of the two.

$$F_{total} = F_D + F_I = 0{,}5 \cdot \rho \cdot v \cdot |v| \cdot D_{DE} \cdot C_D + a \cdot 0{,}25 \cdot \pi \cdot {D_{IE}}^2 \cdot \rho \cdot C_M$$

The drag force is dependent on

- ρ — The density of the fluid, in this case sea water (1.025) and air (1,293) — [kg/m^3]
- v — The velocity of the sea water/air flowing around the object — [m/s]
- D_{DE} — The diameter of the component that experiences the drag force — [m]
- C_D — The drag coefficient. For a tube 0,75 — [-]

The inertia force depends on:

- a — The acceleration of the water/air attacking the structure — [m/s^2]
- D_{IE} — The diameter of the component that experiences the inertia force — [m]
- C_M — The inertia coefficient — [-]

The wind velocity given earlier in the report is measured at 10m above MSL. The wind velocities will increase with height. The following relation is used to determine the wind velocity at the elevation of the platform (Figure 5-19). Using an elevation of 30m, will result in a factor of 1,17 times the wind velocity at 10m elevation. ($U_w(30)$=26,7 m/s)

With:

- $U_w(z)$ — Wind velocity at height (z) — [m/s]
- U_w10) — Wind velocity at height 10m — [m/s]
- z — Height of desired wind velocity — [-]
- α — Alpha-factor — [-]

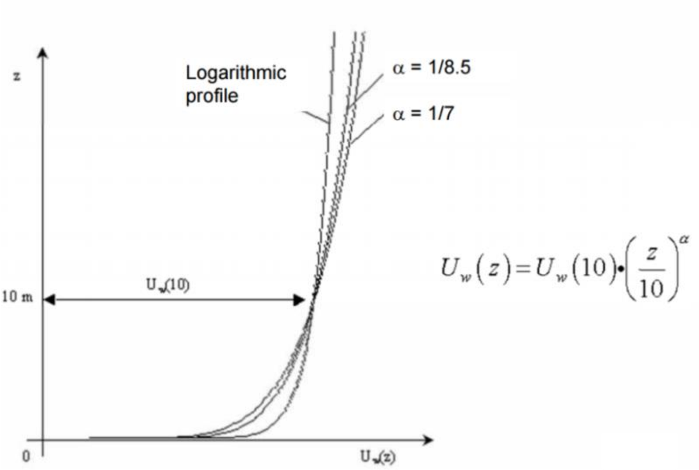


Figure 5-19: Wind profile over height (source (Touma, 1977))

The structure consists of large amount of tubular members. These members individually contribute to the attack area in the Morison equation. The stick model is used to get one equivalent diameter of substructure per unit height (Appendix D). The structure will be divided in segments with the same diameter, resulting in a stick with differing width. In Figure 5-20 the newly designed substructure from Section 5.3 is shown with the representative stick model. The width of the grey shape represents the equivalent diameter of the substructure.

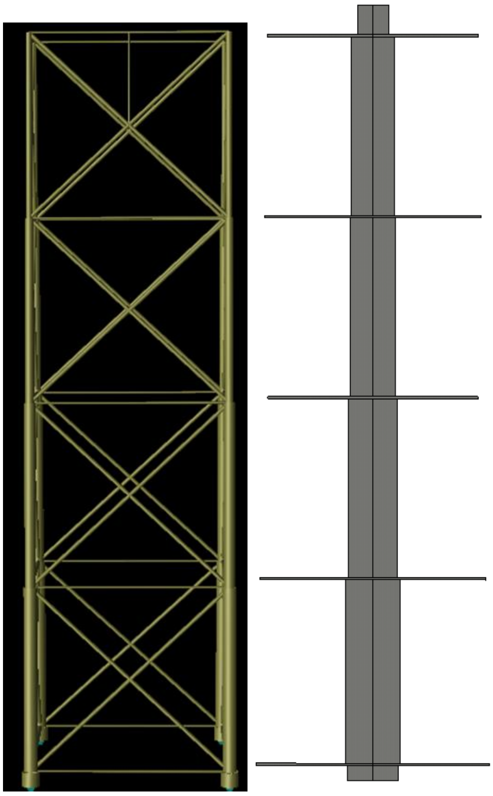


Figure 5-20: Tower visualisation excluding risers & equivalent Stick model

By making use of the stick model the total attack area on the structure and topsides due wind, waves and current can be calculated. The velocity of the water particles in waves needed for the Morison equation will derived by the Airy water wave theory (Massie, 2001).

Velocity potential $\Phi(s,z;t) = \frac{\zeta \cdot g}{\omega} \cdot \frac{\cosh k(z+d)}{\cosh(k \cdot d)} \cdot \sin(k \cdot s - \omega \cdot t)$

Deriving this equation shows and using the dispersion relation:

$$\omega^2 = k \cdot g \cdot \tanh(k \cdot d)$$

Velocity $v(s,z;t) = \zeta * \omega \cdot \frac{\cosh k(z+d)}{\sinh(k \cdot d)} \cdot \cos(k \cdot s - \omega \cdot t)$

Acceleration $a(s,z;t) = \zeta * \omega^2 \cdot \frac{\cosh k(z+d)}{\sinh(k \cdot d)} \cdot \sin(k \cdot s - \omega \cdot t)$

With the environmental data from chapter 3.2.2, the following parameters are used (Table 5-20):

Parameter	Amount	Unit
ζ	6	[m]
wave period	16,1	[s]
k, wave number	0,0155	[-]
v, Current velocity	0,74-1,27	[m/s]
v, Wind velocity	26,7	[m/s]
d, depth	Varying	[m]

Table 5-20: Parameters Airy wave theory

The force for every layer of the stick model can be calculated. All these forces will be used to generate a total force on the structure. Figure 5-21 shows the total forces acting on the structure and moment present at the bottom of the substructure.

The moments are calculated using the stick model. The forces on the equivalent diameters all have their own distance from the seafloor. The total moment is the sum of the individual moments.

Force		**Amount**	**Units**
Horizontal	Wind	1,4	[MN]
	Current	0,7	[MN]
	Waves	19,1	[MN]
Vertical		229,3	[MN]

Table 5-21: Forces on the tower

Moments		**Amount**	**Units**
	Wind	239,2	[MNm]
	Current	98,6	[MNm]
	Waves	711,0	[MNm]
	Weight	-4.586,3	[MNm]

Table 5-22: Moments on the tower

The environmental forces push against structure horizontally and will create an overturning moment that may flip the structure on its side. From this point in the report till Section 5.4.3, the platform is considered to rotate on the bottom of the right leg in Figure 5-21 when looking at the static equivalent forces on the structure. The weight of the substructure and the topsides will create a counteracting moment (around the same right bottom corner). When the moment delivered by the weight is larger than the moment caused by the horizontal forces, the structure will not tip over.

A Unity Check (UC) is a capacity ratio. When in a certain system the capacity is exceeded by a force, the UC will return a number larger than 1. When the capacity is not exceeded, the returned number of the UC will be smaller than 1.

A UC is used to check whether the structure (without foundation) will tip over. In this case the moment caused by the weight of the substructure and topsides is the moment that must not be exceeded by the moment induced by the environment. The UC for this platform will show if the platform will tip over.

$$Unity\ Check\ (UC) = \frac{Moment_{environmnetal}}{Moment_{weight}}$$

$$UC \leq 1 \qquad (within\ limits, no\ tipping)$$
$$UC \geq 1 \qquad (out\ of\ limits)$$

Unit check		**0,2287**	[-]

Table 5-23: Unity Check

With the moments form Table 5-22 the UC can be calculated. A UC of 0,23 (Table 5-23) shows that the suction anchor will not have to deal with tensile (pulling) forces and will at all-time be in compression. See Figure 5-21 for a visualisation of the forces and moments on the substructure.

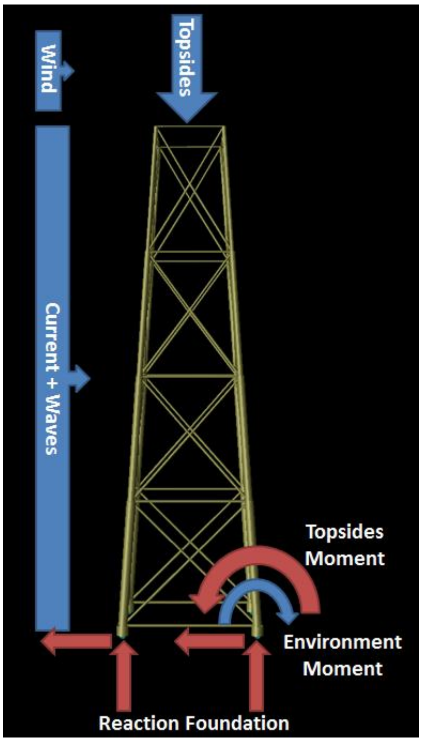


Figure 5-21: Forces and moments on the tower

5.4.3 Bearing capacity

With the forces and moments determined, the bearing capacity needed for the suction anchors is known as well. Within this research some assumptions are made in the distribution and transfer of the loads:

- The vertical and horizontal forces due to the weight will be distributed equally over the four legs and thus over the suction anchor at the bottom of the designated leg.
- The moment that a suction anchor will attract to itself is dependent on the soil properties and the dimensions of the suction anchor. It is difficult to estimate how much of the moment will handled by the suction anchor. A simplification for the purpose of this research results in an estimation. The moment caused by the forces can also be translated in vertical forces needed to counteract the occurring moment. The two extremes (all moment in the suction anchor, no moment in the suction anchor) will be evaluated and the average will be used (50/50). This assumption is based on two scenarios. If the soil is infinitely stiff (concrete), 100% of the moment can be transferred to the soil (clamed support). When the soil is infinitely weak (water), 0% of the moment will be transferred to the soil (pinned support). Meaning the suction anchor will deal with half the moment and the rest of the moment will be compensated by vertical forces in the suction anchor. The actual value will be between these scenarios and a the average will be used.
- When looking at the environmental forces acting on the foundation these are mainly acting for a short period of time on the structure. This means that the water does not have the time to escape the pores. When the force acts for a short period of time the actual soil stress increases as well as the water pressure. This means the effective soil stress does not increase. This describes undrained behaviour of the soil.
  The relation between the effective stress and the water pressure is given as:

$$\sigma'_{effective} = \sigma_{actual} - P_{water\ presuure}$$

  This relation is used to describe the occurring stresses when the soil is undrained.

Appendix E explains the complete theoretical method (Wielen, 2015).

The forces and moments a suction anchor must handle in the two extreme situations (100% and 0% moment) is shown in Table 5-24.

Case	**Vertical Force [kN]**	**Horizontal Force [kN]**	**Moment [kNm]**
0 moment in anchor	75.868,8	5.431,4	0
All moment in anchor	57.328,3	5.431,4	262.200

Table 5-24: Forces on a suction anchor

The strength of the soil is needed to be able to calculate the dimensions of the suction anchor to provide the needed bearing capacity. The soil properties at the location are given in Table 5-25.

Type of soil	**Top [m]**	**Bottom [m]**	**Internal angle of friction [deg]**
Silty sand	-140	-144	30
Sandy silt	-144	-153	32
Silt to clayey silt	-153	-183	29
Silty clay	-183	--	--

Table 5-25: Soil properties

The different layers all have their own soil strength. The dimensions of the suction anchors consist of the diameter (D_0) and the length the suction anchor will penetrate the seabed (L_{emb}). Due to soil layering the dimensions must be determined iteratively. Each layer has its own capacity and will influence the behaviour of the suction anchor.

The iterative process has the following input and output parameters:

D_0	[m]	Diameter of the suction anchor.
L_{emb}	[m]	Height of the suction anchor.
UC1	[-]	Unity check when the suction anchor will not take up any moment.
UC2	[-]	Unity check when the suction anchor will take up all of the moment.
50/50	[-]	The combined unity check. The real value will lie between UC1 and UC2. For the purpose of this research the average of UC1 and UC2 will be used. (This relates to the assumption at the beginning of this section of the report.)
Area	[m^2]	The area is directly related to the weight of the suction anchor. With a D/t-ratio of 275 used by SPT a wall thickness (t) can be obtained. Using the density of steel of 7.850 [kg/m^3] the weight can be calculated accordingly.
B/D	[-]	The B/D-ratio is a ratio used in suction anchor industry. This ratio gives the relation between the diameter and the height of the suction anchor.

5.4.4 Suction anchor sizing

The anchor will experience a vertical force, horizontal force and a moment. First the vertical and horizontal capacities of the suction anchor are calculated. If the soil strength capacity exceeds the needed bearing capacity, the unity check for the suction anchor will be smaller than 1.

Vertical capacity

The vertical capacity is the force of the wall friction ($F_{0,eff}$) of the suction anchor and the tip force (F_{tip}) on the underside of the suction anchor. The model used for this research assumes the suction anchor will be installed to an installation depth, hereafter the topsides is positioned on top. The weight of the topsides will cause the suction anchor to penetrate the soil a little more. At this point the underside of top-plate of the suction anchor is assumed to be touching the seabed (right hand side Figure 5-22). Due to the unity check from Table 5-22 is smaller than 1, there will not be a pulling force on the suction anchor. The vertical capacity will therefore be increases to the entire base of the suction anchor ($F_{fullbase}$). This allows to use $F_{fullbase}$ and $F_{0,eff}$ in the operational phase of the platform.

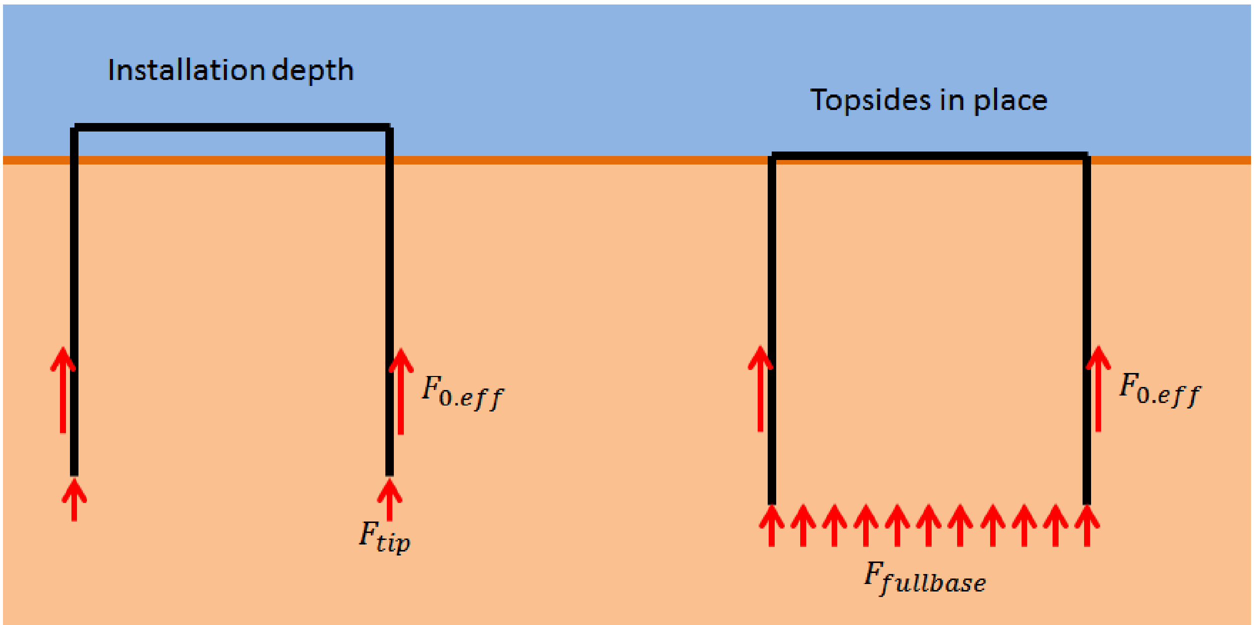


Figure 5-22: Vertical bearing capacity schematic

The total vertical capacity

$$V_{max} = \frac{F_{0.eff} + F_{fullbase}}{\Omega_{Fos.V}}$$

With (Ref. (Carter, 2010)):

$$F_{fullbase} = \xi_s \cdot \xi_d \cdot N_c \cdot \frac{1}{4} \cdot \pi \cdot {D_0}^2 * s_{u.AV} (Lemb): \text{coefficients (Vesic, 1975)} \begin{cases} \xi_s = 1{,}2 \\ \xi_d = 1 + 0{,}4 \cdot tan^{-1}(\frac{L}{D}) \\ N_c = (2 + \pi) \end{cases}$$

$$s_{u.AV}: \{undrained\ strength\ parameters\ of\ soil, active\ and\ pasive\ soil\ failure\}$$

$$S_{u.AV}(z) = \frac{S_{u.DSS}(z) + S_{u.C}(z) + S_{u.E}(z)}{3}$$

Active strength parameters (DNV, 1992)

$$S_{u.DSS}(z) = \tan(\phi(z)) \cdot \sigma_{eff.v}(z)$$

Passive strength parameters

$$S_{u.C}(z) = \frac{\sin(\phi(z))}{1 - \sin(\phi(z))} \cdot \sigma_{eff.v}(z)$$

Strength parameters at equilibrium

$$S_{u.E}(z) = \frac{\sin(\phi(z))}{1+\sin(\phi(z))} \cdot \sigma_{eff.v}(z)$$

The wall friction of the shaft

$$F_{0.eff} = \int_0^{L_{emb}} f_{s.eff}(z) \cdot (\pi \cdot D_0) dz$$

Shaft friction stress (DNV, 1992)

$$f_{s.eff}(z) = K_0(z) \cdot \tan(\delta(z)) \cdot \sigma_{eff.v}(z)$$

Lateral pressure coefficient

$$K_0(z) = 1 - \sin(\Phi(z))$$

Angle of external friction

$$\delta(z) = \Phi(z) - 5° \quad \{angle\ of\ external\ friction\}$$

Vertical effective stress

$$\sigma_{eff.v}(z) = \int_0^z \gamma_{eff.v}(z)\, dz$$

$$\Omega_{Fos.V} : \{safety\ factor\}$$

Horizontal capacity

The force the underside of the suction anchor delivers is a sliding force, (H_{tip}) (friction). The force acting on the shell is much larger than the sliding force and is called the lateral force ($H_{lateral}$). The total horizontal force (H_{max}) is calculated.

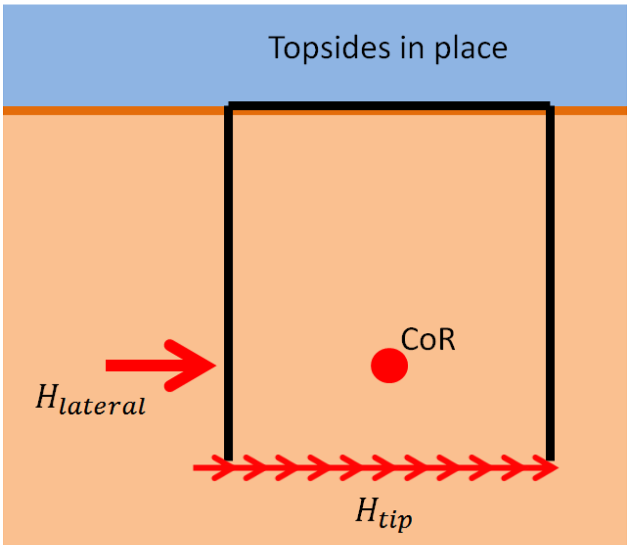


Figure 5-23: Horizontal bearing capacity schematic

The total horizontal capacity

$$H_{max} = \frac{H_{tip} + H_{lateral}}{\Omega_{Fos.H}} \cdot H_{correction\ factor}$$

With:

$$H_{tip=} s_{u.AV}(Lemb) \cdot (0{,}25 \cdot \pi \cdot D_0{}^2)$$

$$H_{lateral} = \int_0^{Lemb} P_u(z) \cdot D_0 dz$$

Ultimate unit resistance

$$P_u(z) = N_p(z) \cdot s_{u.AV}(z) + \sigma_{eff.v}(z)$$

Lateral bearing factor (DNV, 1992)

$$N_p(z) = N_1 - N_2 \cdot \exp(\frac{-\xi \cdot z}{D_0})$$

$$N_1 = 10{,}5$$
$$N_2 = 5{,}5$$

$$\xi = \begin{cases} \left(0{,}25 + \frac{0{,}05}{D_0}\right) & if\ D_0 < 0{,}167m \\ 0{,}55 & if\ D_0 > 0{,}167m \end{cases}$$

Correction factor ($H_{correction\,factor}$) corrects for the location of the $H_{lateral}$. The force $H_{lateral}$ is calculated as a point load. The location of this load must be such that the suction anchor will not rotate. "Taiebat and Carter (2010)" found that the location on a suction anchor where a pure horizontal point force does not make the suction anchor rotate is located at 0,60 of the height, measured from the top of the suction anchor.

With the soil strength at the site location and the size of this specific suction anchor, the moment at this location where $H_{lateral}$ is assumed will probably not be equal to zero. The $H_{lateral}$ must therefore be corrected. The horizontal capacity will be less when the point of centre of rotation (cor) is at a different location on the suction anchor. Figure 5-24 shows the relation.

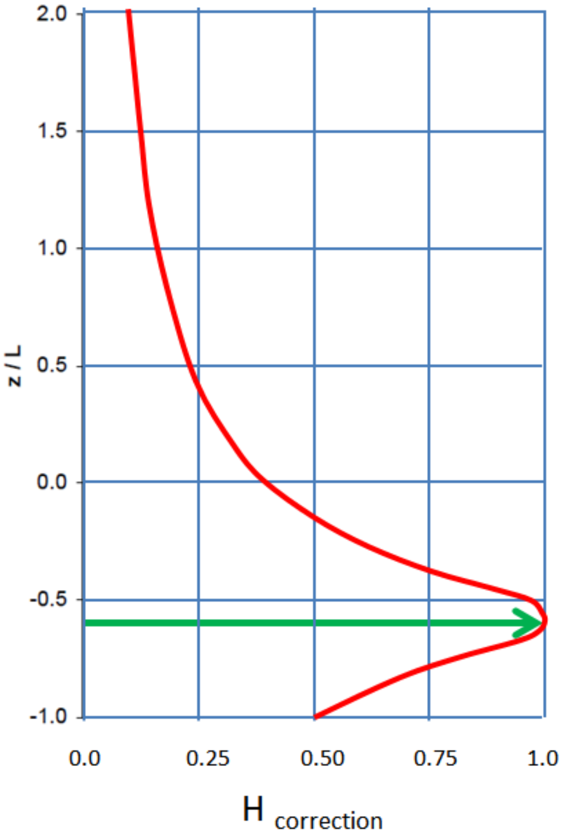


Figure 5-24: Lateral resistance versus the load application point (Carter, 2010)

The reduction of the horizontal capacity is corrected by $H_{correction\,factor}$. The two load cases (no moment and all the moment transferred to the suction anchor) both will have their own correction factor.

- The case where no moment will be present in the suction anchor, the lateral force will be at the mudline. This results in a correction factor of approximately 0,4.
- When all the moment will be attracted by the suction anchor, the location where the moment is zero will be at:

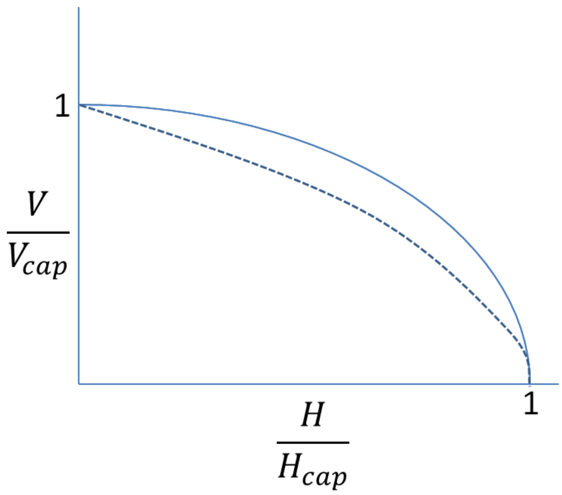
$$z_{moment=0} = \frac{M_{mudline}}{F_{H\,mudline}} = \frac{262.000}{5431} = 52{,}4$$

  This results in a z/L-ratio ($\frac{52{,}4}{14{,}5}$) of 3,6. This ratio is out of the range of graph in Figure 5-24. The graph is nearing a near vertical line. For this research the lowest value of the graph is therefore used (0,1).

For the given parameters for this research at the averaged load case (50/50), $H_{correction\,factor}$ is found to be 0,25.

An assumption of this method is that it uses the soil strength from each soil layer separately. In real-life the stronger layers will attract more force and moments than the weaker soils. Meaning that the capacity of the weaker soils will not be used completely. For a layered soil deposit with inhomogeneous properties, this will result in inaccuracies for the soil strength. The soil layers at the installation location have internal friction coefficients fairly close to each other (Table 5-25). The capacity of the soil will be quite similar and the inaccuracies are considered to be minimal. This is an assumption that allows the method to use homogeneous soil characteristics for each individual layer in the calculations.

The vertical and horizontal capacities influence each other. When the horizontal force increases, the vertical capacity gets influenced and vice versa. The correlation is related to the diameter and the length of the suction anchor. A typical correlation is shown in Figure 5-25. The correlation-line can have different shapes (example dotted and solid in Figure 5-25). The line is called the failure envelope of the suction anchor and represents the strength capacity of the soil and thus the suction anchor.



$$\left(\frac{H}{H_{max}}\right)^{\frac{7}{8}+\frac{3\cdot L_{emb}}{D_0}} + \left(\frac{V}{V_{max}}\right)^{5{,}5+\frac{L_{emb}}{D_0}} = 1$$

Figure 5-25: Bearing capacity, typical failure envelope (source (Chairat Supachawarote, 2004))

Using the above-mentioned method to determine the dimensions of the suction anchor, the following diameters and heights were given as input to determine an optimum suction anchor. As mentioned earlier this is an iterative process and the D_0 and L_{emb} are varied as input factor.

D_0 [m]	L_{emb} [m]	UC1 [-]	UC2 [-]	50/50 [-]	Area [m^2]	B/D [-]
12	12	1,535	1,218	1,38	565	1,00
12	13	1,4	1,097	1,25	603	0,92
12	14	1,273	1,006	1,14	641	0,86
12	15	1,178	0,924	1,05	679	0,80
12	16	1,076	0,861	0,97	716	0,75
12	17	1,033	0,799	0,92	754	0,71
12	18	0,935	0,733	0,83	792	0,67
13	12	1,359	1,069	1,21	623	1,08
13	13	1,235	0,972	1,10	664	1,00
13	14	1,12	0,889	1,00	705	0,93
13	15	1,03	0,813	0,92	745	0,87
13	16	0,964	0,755	0,86	786	0,81
13	17	0,889	0,697	0,79	827	0,76
13	18	0,831	0,651	0,74	868	0,72
14	12	1,19	0,955	1,07	682	1,17
14	13	1,097	0,857	0,98	726	1,08
14	14	0,992	0,781	0,89	770	1,00
14	15	0,91	0,722	0,82	814	0,93
15	12	1,067	0,85	0,96	742	1,25
15	13	0,964	0,769	0,87	789	1,15
15	14	0,885	0,7	0,79	836	1,07

Table 5-26: Iterative dimensioning suction anchor.

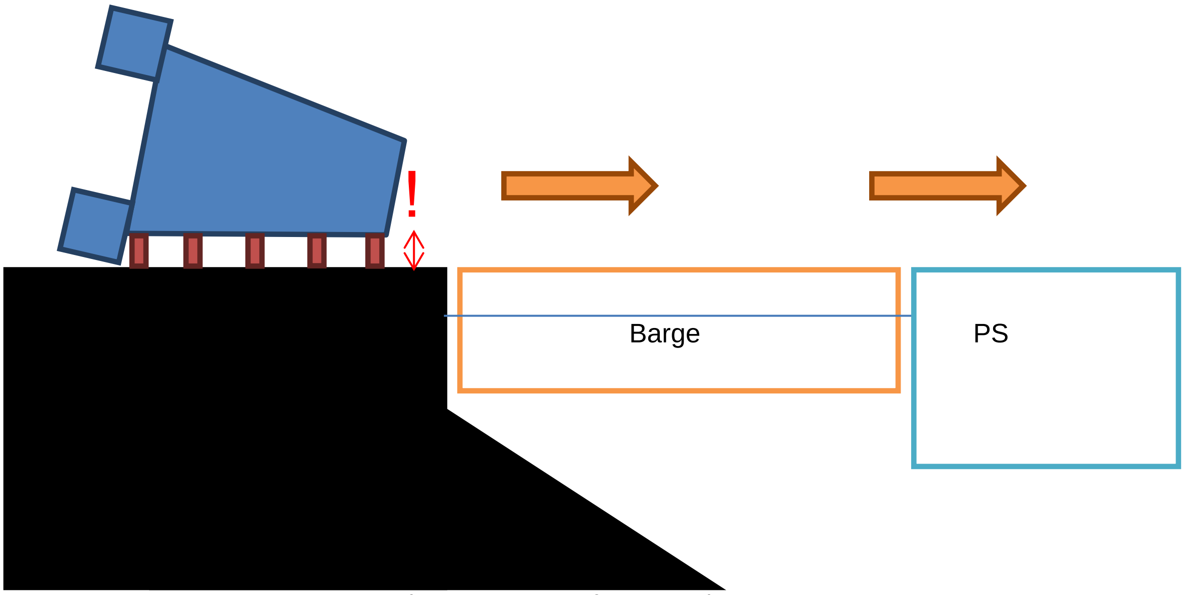


Figure 5-26: Transfer, quay - barge - PS

Before choosing a diameter and height for the suction anchor, there is a PS boundary to keep in mind. Transferring the substructure from the quay to the barge and from the barge to the PS will be done by the support-sledges underneath the substructure. The height of these sledges specially designed for the PS is 5,8m. If a higher elevation is needed the sledges needs adjustments. The adjustments are possible, but it is desirable that the suction anchor will be dimensioned such the adjustments are not needed. With the bottom of the leg being 3,556m in diameter the elevation from the centre of the suction anchor to the deck will be 7,578m. With an elevation gap between the barge deck and the lowest point of the suction anchor of 1,00 meter, a maximum diameter of 13,1m can be transferred.

With a safety factor ($\Omega_{Fos.V}$) of 1,5 on the bearing capacity of the suction anchor, a unity check less than 0,95 is chosen to be acceptable. This will lead to a suction anchor with a diameter of 13,1m and a height of 14,5m, orange box in Table 5-27.

D_0 [m]	L_{emb} [m]	UC1 [-]	UC2 [-]	50/50 [-]	Area [m^2]	B/D [-]
13,1	13	1,203	0,954	1,08	670	1,01
13,1	13,5	1,155	0,916	1,04	690	0,97
13,1	14	1,113	0,871	0,99	711	0,94
13,1	14,5	1,054	0,831	0,94	732	0,90
13,1	15	1,025	0,796	0,91	752	0,87
13,2	13	1,196	0,948	1,07	676	1,02
13,2	13,5	1,148	0,898	1,02	697	0,98
13,2	14	1,107	0,866	0,99	717	0,94
13,2	14,5	1,048	0,826	0,94	738	0,91

Table 5-27: UC on size suction anchor

The corresponding failure envelope is shown in Figure 5-27. The black dot in the top of the figure is the load-case with UC1. The UC2 is below the red line. This graph differs from the schematic failure envelope in Figure 5-25. The forces are not normalized and a pulling force is shown in the graph. With the average "50/50" a UC of 0,94 is obtained. This point lies within the red line, so the needed bearing capacity is achieved.

Note that this method does not make use of the capacity reduction when the soil is layered with highly differing strength parameters. The capacity will be less when this phenomenon is taken into account. As mentioned earlier, the soil strength parameters of the soil at location are fairly close to each other. This will result in relative small inaccuracies.

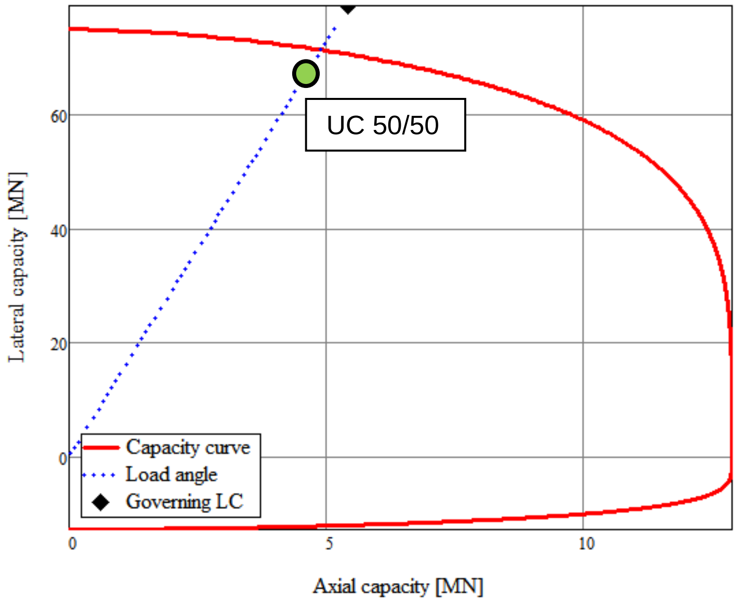


Figure 5-27: Failure envelope D:13,1m, L:14,5m

With a diameter of 13,1m and a D/t-ratio of 275, the wall thickness will be 47,6mm. The weight is calculated with the density of construction steel [7.850 kg/m^3]. Suction Pile Technology (SPT) uses a factor 2,0 for the amount of reinforcement and structural steel needed for the suction anchor. This leads to a total weight per suction anchor of 547 ton.

5.4.5 Transport – motions

Now the dimensions are known, the next step in the scheme is taking the motions in to account. By combining the RAO of the PS and the wave spectrum the accelerations can be derived. The accelerations occurring at the connection between the leg and suction anchor are crucial. For this research there are assumptions made:

- The PS will be considered ridged;
- The substructure and its support will be considered ridged.

The transport phase and the installation phase are two scenarios to consider.
The transport phase uses the 10-years return maximum conditions. The met-ocean data shows a significant wave height (H_s) of 4,9m and a wave period of 7,4 sec (T_z). According the Noble Denton (Denton0030, 2013) the periods that need to be investigated can be found using the following correlation:

$$\sqrt{13 \cdot H_s} \leq T_p \geq \sqrt{30 \cdot H_s}$$
$$7{,}98s \leq T_p \geq 12{,}12s$$

The RAOs of the PS are known and can be used to calculate the accelerations of the vessel for the given sea state. (The used wave spectrum for the South China Sea is Pierson Moskowitz.) This is done by making use of the transfer function. (Appendix G shows a more elaboration on the method.)

$$S_{PS}(\omega) = \left|\frac{z_a}{\zeta_a}(\omega)\right|^2 \cdot S_\zeta(\omega)$$
$$\frac{z_a}{\zeta_a}(\omega) = \text{RAO PS}$$

With the suction anchors positioned underneath each leg of the substructure the location of the connection between the leg and suction anchor is known. The movements of the ship can be translated to the movements at the bottom of each leg. Doing this for all four legs in the given sea-state the dominant accelerations at the connection can be found. The coordinates of the suction anchors are shown Table 5-28 and
Figure 5-28.

	Coordinates [m]		
	$X_{position}$	$Y_{position}$	$Z_{position}$
Bottom leg 1.1	-75,00	20,00	51,73
Bottom leg 1.2	-75,00	20,00	91,73
Bottom leg 2.1	-75,00	-20,00	51,73
Bottom leg 2.2	-75,00	-20,00	91,73

Table 5-28: Coordinates suction anchors

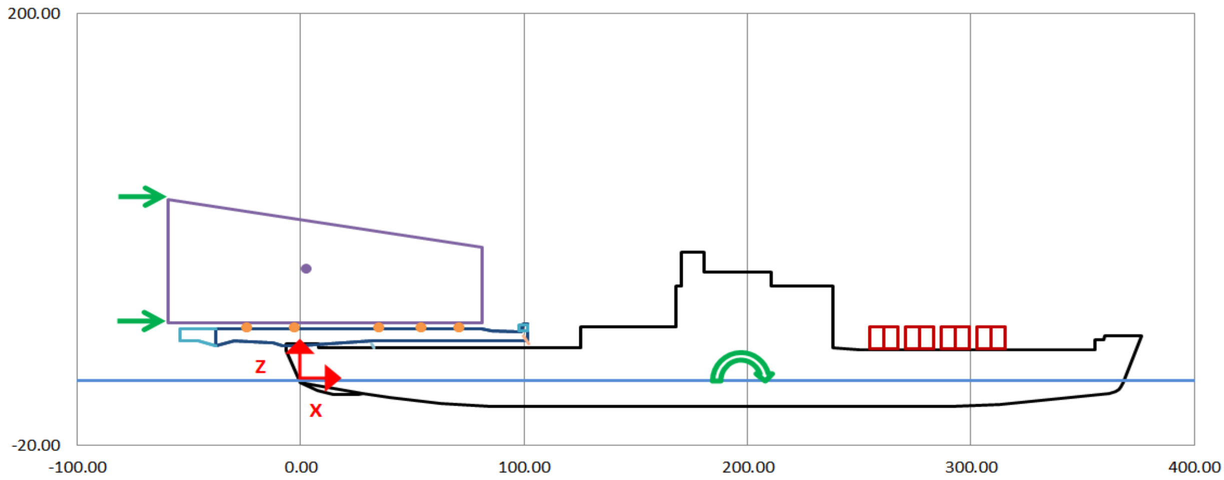


Figure 5-28: Location of origin on PS with substructure (green arrows: location of suction anchors and rotation point)

The maximum accelerations and the rotation acceleration are in the X-, Y- and Z-plane and are a combination of all the motions of the ship. For example the Z acceleration is a combination of the heave, pitch and roll movements of the ship. The accelerations are given in Table 5-29.

	X	Y	Z	rx	ry	rz	wave dir.	H_s	T_p
	[m/s^2]	[m/s^2]	[m/s^2]	[deg/s^2]	[deg/s^2]	[deg/s^2]	[deg]	[m]	[s]
Surge	0,44	1,32	1,29	0,98	0,29	0,16	105	4,9	10,5
Sway	0,37	2,81	1,11	1,79	0,26	0,11	90	4,9	12
Heave	0,43	1,45	1,38	1,10	0,28	0,16	105	4,9	12
Roll	0,37	2,81	1,11	1,79	0,26	0,11	90	4,9	12
Pitch	0,43	1,79	1,01	0,93	0,30	0,12	75	4,9	10,5
Yaw	0,44	1,38	1,34	1,04	0,29	0,16	105	4,9	11

Table 5-29: Accelerations at the bottom of the jacket on the PS

The installation phase uses the 1-year return period conditions. These conditions are less severe. In Appendix G the met-ocean data for installation can be found.

5.4.6 Transport – forces

These accelerations will have to be translated to the suction anchor. With the relation $F = m \cdot a$ the forces and $M = I_{mass} \cdot r(x, y, z)$ the moments, the reaction forces and moments can be calculated needed to accelerate the suction anchor with the same rate as the bottom of the legs.

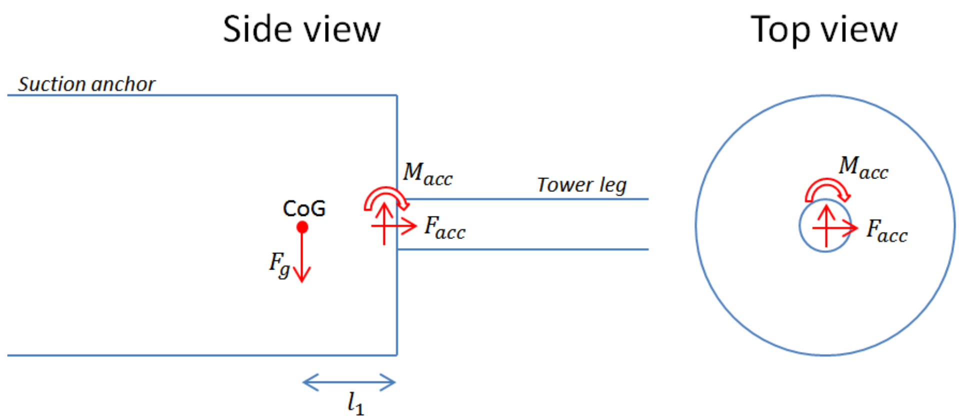


Figure 5-29: Forces on suction anchor, transport phase

$$F_g = m_{suction\ anchor} \cdot g$$
$$F_{x,y,z} = m_{suction\ anchor} \cdot a_{x,y,z}$$
$$M_g = F_g \cdot l_{CoG}$$
$$M_{rx,ry,rz} = I_{mass\ (x,y,z)} \cdot r(x, y, z)$$

With:

- F_g [N] Gravitational force
- $m_{suction\ anchor}$ [kg] Mass suction anchor
- g [m/s^2] Gravitational acceleration
- $F_{x,y,z}$ [N] Force due to accelerations PS
- $a_{x,y,z}$ [m/s^2] Accelerations PS
- M_g [Nm] Moment cause by F_g
- l_{CoG} [m] Length from CoG to connection
- $M_{rx,ry,rz}$ [Nm] Moment due to rotational accelerations PS
- $I_{mass\ (x,y,z)}$ [kgm^2] Mass moment of inertia
- $r(x, y, z)$ [deg/s^2] Rotational accelerations
- $r_{x,y,z}$ [m] Distance from rotational centre axis

The mass moments of inertia are needed. There are two different moments of inertia. This is due to the symmetry of the anchor.

$$I_{mass(x,y,z)} = \sum_{i=1}^{n} m_i r_{x,y,z}{}^2 = \int dm \cdot r_{x,y,z}{}^2$$

I_{Roll} [kgm^2]	I_{Pitch} [kgm^2]	I_{Yaw} [kgm^2]
16.510.280	23.892.026	23.892.026

The forces can be calculated accordingly.

	X [N]	Y [N]	Z [N]	Rx [Nm]	Ry [Nm]	Rz [Nm]	wave dir. [deg]	H_s [m]	T_p [s]
Surge	240.874	723.492	707.839	16.248.586	7.039.342	3.911.889	105	4,9	10,5
Sway	203.395	1.539.302	604.671	29.475.950	140.646	60.550	90	4,9	12
Heave	232.870	793.805	757.003	18.241.310	155.331	88.518	105	4,9	12
Roll	107.148	810.902	318.539	29.475.950	74.092	31.897	90	4,9	12
Pitch	178.007	747.934	422.001	15.405.795	125.096	47.992	75	4,9	10,5
Yaw	182.926	577.391	556.961	17.204.419	122.266	68.533	105	4,9	11

Table 5-30: Forces and moments during transport

From the numbers in Table 5-29 and Table 5-30 it can be seen that the wave period and the wave direction with respect to the PS have an influence on the forces. The wave directions in column 8 of Table 5-30 result in the largest force on the structure. In practice the PS will not sail directly into these wave directions. The PS can choose to avoid a certain wave direction by “zig-zagging” to the installation location.

The foundation will be subjected to the transport forces and the in-place forces. Bracings are needed to reinforce the connection between the leg and the suction anchor. These bracings need to be dimensioned on the maximum loads. Comparing the in-place and installation loads give the governing load case.

5.4.7 Transport versus in-place

The connection between the leg and the suction anchor has a different orientation (Figure 5-30). Meaning the horizontal force in the inplace corresponds to the vertical force in the transport phase.

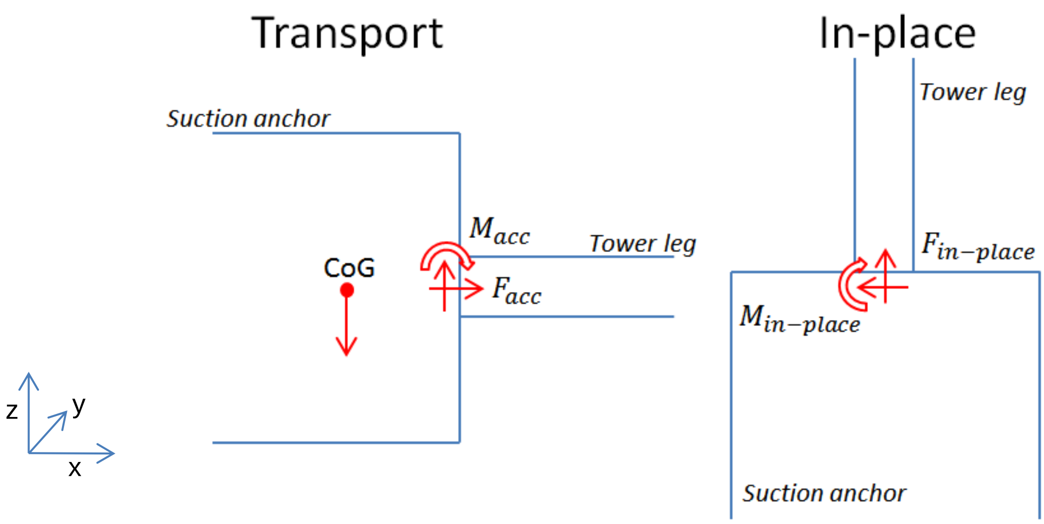


Figure 5-30: Orientation suction anchor

The forces that will act on the connection in the same manner will be compared. From Table 5-31 it can be seen the majority of the forces on the connection are larger in the in-place condition. However the parallel force on the connection (horizontal in-place and vertical in transport) is larger at the transport condition. The force perpendicular to the connection even differs from direction, meaning a pulling and a pushing force. Pushing does not influence the weld connection but pulling does. (M_z is the twisting of the leg. This moment is not calculated in the in-place condition.) The connection will be dimensioned on the in-place condition, but must be checked with the transport phase to make sure the parallel connection will not fail during transport.

Transport	**[MN]**	**[MN]**	**In-place**
Fz	-6,12	5,309	**Fx**
Fy	0,24	4,01	**Fy**
Fx	0,24	-57,33	**Fz**
	[MNm]	**[MNm]**	
Mz	0,07	198,1	**Mx**
My	15,96	262,2	**My**
Mx	0,51	--	**Mz**

Table 5-31: Forces comparison

The connection between the leg and suction anchor will be welded to each other. The most simplistic way of welding is shown in red in Figure 5-31. Welding failure is assumed to be the first failing mechanism. The top plate of the suction anchor and the leg are therefore assumed to be sufficiently strong. With this assumption the suction anchor and the leg of the substructure will be strong enough. The failing of the weld is the failure mechanism that is investigated.

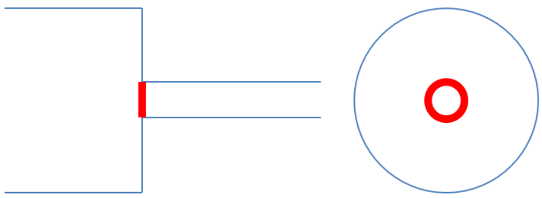


Figure 5-31: Weld, no bracing

Calculating the weld capacity and comparing this to the capacity needed to cope with the forces will provide a UC for only the weld connection. The following welding parameters are defined:

- a [m] Weld throat thickness
- A_w [m^2] Weld throat area
- D [m] Tube diameter
- d [°] Weld angle
- F [N] Acting force
- F_n [N] Normal force
- F_s [N] Shear force
- L [m] Effective weld length
- M [Nm] Bending moment
- $s_{\wedge}$ [MPa] Normal stress vertical to the weld direction
- $s_{||}$ [MPa] Normal stress parallel to the weld direction
- T [Nm] Torque
- $t_{\wedge}$ [MPa] Shear stress vertical to the weld direction
- $t_{||}$ [MPa] Shear stress parallel to the weld direction
- Z_w [m^3] Module of weld section

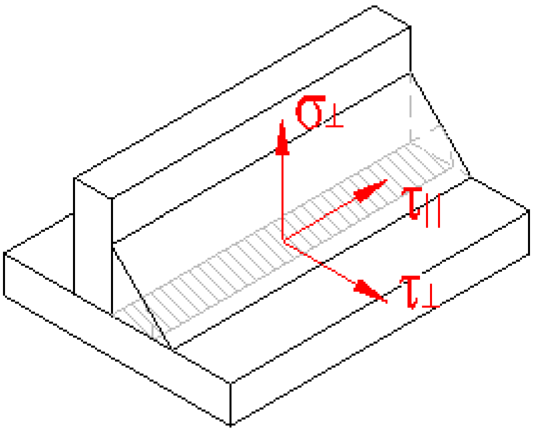


Figure 5-32: Weld parameters

The following relations are used to calculate the needed welding capacity.

Load with normal force F_z:

$$\sigma_{\perp} = \frac{F_z}{A_w}$$

Load with bending moment M:

$$\sigma_{\perp} = \frac{M \cdot r_y}{I_{wx}}$$

Load with shear force Fx:

$$\tau_{\perp} = \tau_x = \frac{F_x}{A_w}$$

Load with shear force Fy:

$$\tau_{\parallel} = \tau_y = \frac{F_y}{A_w}$$

Load with torque T:

$$\tau_{\parallel} = \tau_y = \frac{T \cdot r_x}{J_w}$$

$$\tau_{\perp} = \tau_x = \frac{T \cdot r_y}{J_w}$$

With:

- A_w [m^2] Weld throat area
- I_w [m^4] Moment of inertia of the weld

$$I_{m1,2} = \frac{m_{1,2} \cdot {l_{1,2}}^2}{12}$$

$$A = \int dA$$

$$I_{x,y,z} = \int y^2 \cdot dA + A \cdot d^2$$

$$I_{circle,no\ bracing} = \frac{\pi((D + 2a)^4 - D^4)}{64}$$

J_w [m^4] Polar moment of inertia of the weld
$\sigma_{\perp}$ [MPa] Normal stress vertical to the weld dir.
$\sigma_{||}$ [MPa] Normal stress parallel to the weld dir.
$\tau_{\perp}$ [MPa] Shear stress vertical to the weld dir.
$\tau_{||}$ [MPa] Shear stress parallel to the weld dir.

For connections stressed by combined loads, the resulting equivalent “Von Mises” stress in the weld is specified from the relation (Von Mises, R (1913)):

$$S_w = \sqrt{{\sigma_\perp}^2 + {\sigma_\parallel}^2 - \sigma_\perp \cdot \sigma_\parallel + {\tau_\perp}^2 + {\tau_\parallel}^2}$$

Using the forces and moments of the in-place conditions the following UC_{Stress} is found (Table 5-32).

	S_w, stress [MPa]	Capacity [MPa]	Safety factor	Unity Check
In-place	5043	510	0,66	14,98
Transfer	175	510	0,66	0,52

Table 5-32: UC in-place and transfer phase

The in-place conditions UC_{Stress} is 14,98 for the weld connection. As expected the single weld is not enough to withstand the forces in-place. There are two measures to increase the capacity:
1. The weld length can be increased. This will increase the shear capacity of the weld.
2. The moment of inertia can be increased. Increasing the moment of inertia will increase the capacity for moments in the connection.

Placing bracings will increase the moment of inertia and will automatically increase the weld area. Looking at the forces and moments acting on the connection it shows that the moments have a significantly larger influence on the capacity of the connection than the shear forces.

Theoretically increasing the moment of inertia by a factor 10 will almost show a factor 9 reduction of the UC_{Stress}. Increasing the area (weld length) shows a very small change in the UC_{Stress}.

5.4.8 Governing load-case

The moment of inertia will be increased by the use of bracings. (See the green tube in Figure 5-33.)

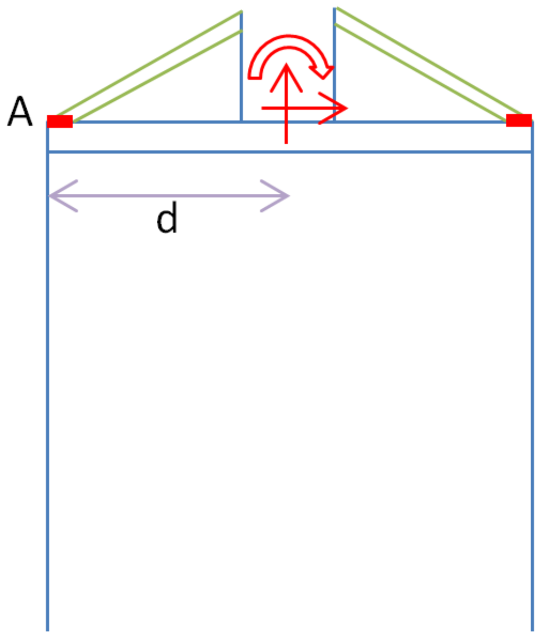


Figure 5-33: Suction anchor with bracings, side view

By making reverse use of Steiner's theorem the radius of the bracings can be determined.

$$I_{z'} = I_z + d^2 \cdot A$$

With:
- $I_{z'}$ [m^4] Total area moment of inertia
- I_z [m^4] Moment of inertia bracing + leg connection
- d [m] Distance from centre suction anchor
- A [m^2] Area of bracing

The UC for the connection is mostly influenced by the second moment of inertia. The influence is nearly one on one. This means that when increasing the second moment of inertia by 15 the UC will be almost 15 times smaller. Per bracing this must be equal to 7,5 times the initial second moment of inertia. This leads to the following equation.

$$7{,}5 \cdot I = 3 \cdot \pi \cdot {r_{bracing}}^3 \cdot t_{wall\ bracing} + 2 \cdot \pi \cdot r_{bracing} \cdot t_{wall\ bracing} \cdot (r_{suction\ anchor} - r_{bracing})^2$$

Solving this equation gives $r_{bracing}$ equal to 0,437m. The diameter of the bracings will then be 0,875m.

The force acting vertically on this brace is equal to the moment decoupled over the diameter of the suction anchor. Using the moment from Table 5-30 a vertical force equal to 20.000kN must be dealt with.

The bracing is under an angle, resulting in a larger axial force. The buckling force of this bracing is calculated to check whether the bracing will hold.

$$F_{buckling} = \frac{4\pi^2 \cdot EI}{l^2}$$

With the second moment of inertia calculated earlier and the length of the bracing, the buckling load result is 90.000kN. This means the brace will not fail due to buckling.

The transport forces with bracings are within the limits as well. The extra weld area provides enough capacity to withstand the shear stress.

5.4.9 Resonance

The forces and moments on the suction anchor are larger at the in place condition as shown in Table 5-32. However there is one issue that might cause the transport phase to be governing. Resonance may occur when the period in which the ship moves, matches (or is near) the natural frequency of the suction anchor.

The natural frequency of the suction anchor will be determined by calculating the stiffness of the suction anchor and its bracings. This will be done by first calculating the deflection under its own weight. From here the stiffness of the suction anchor can be determined.

The suction anchor can be divided in three parts. The leg and the bracings, the top plate which contains the stiffeners and the shell of the suction anchor (Figure 5-34).

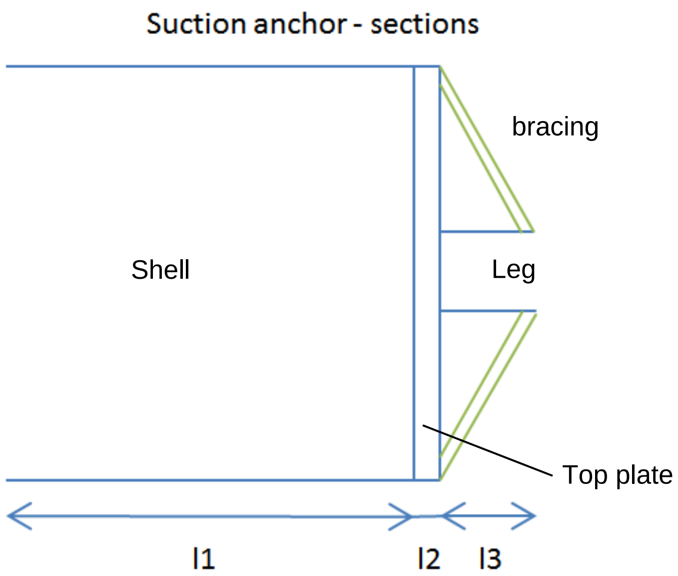


Figure 5-34: Suction anchor - parts

Natural frequencies have different modes. The first couple of modes will probably be seen in deformations of the shell of the suction anchor (l1, Figure 5-34). The deformation interesting for this research is the deformation of the top-plate and the bracings. This is the connection that must be sufficiently strong.

The weights of the parts (l1, l2, l3) are different and will differ over the length. This leads to the distributed loads shown in Figure 5-35.

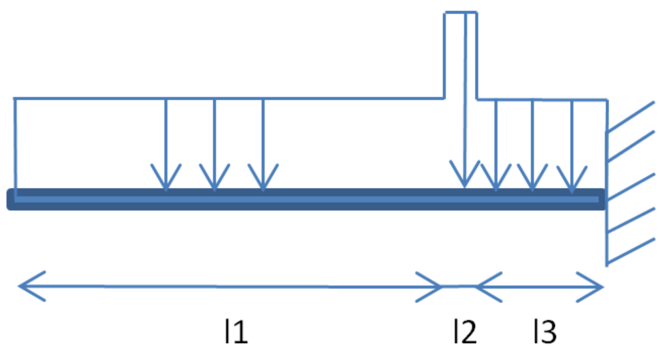


Figure 5-35: Suction anchor - distributed load (not to scale)

The suction anchor will be modelled as a clamped cantilever beam over length l3. Over l3 a distributed load (q) will be used to model the weight over this length. The top-plate over l2 will be modelled as a point load (it is a relatively slim distance and weight is concentrated). The suction anchor shell (l1) will be modelled as a moment (M) that acts at the end of l2. (See Figure 5-36 for an overview). The magnitude of the acting forces and moments are given in Table 5-33.

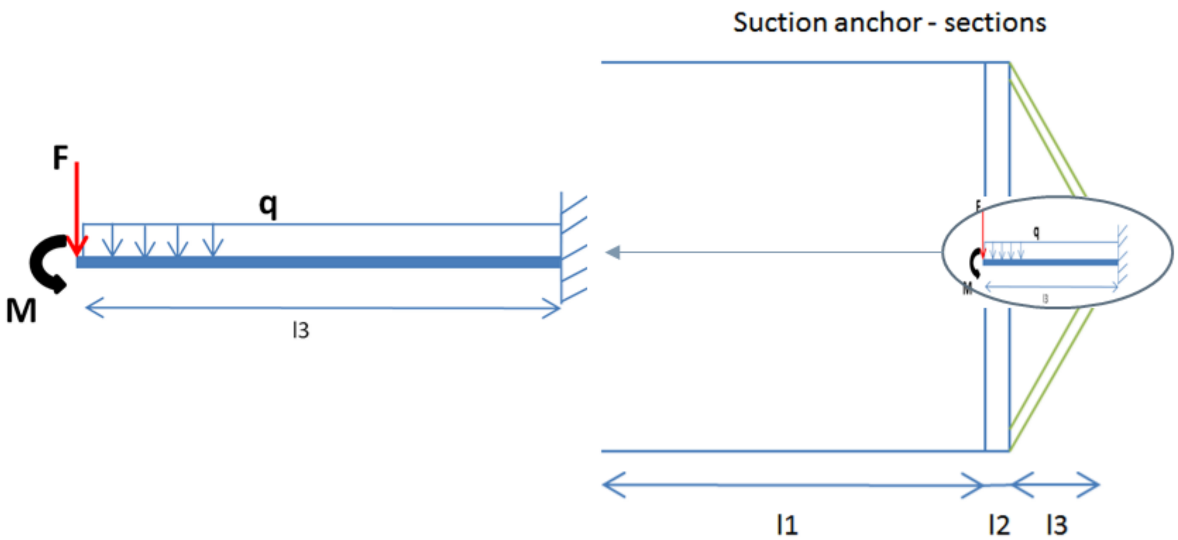


Figure 5-36: Suction anchor model

	L3	l2	L1	Unit
Length	3	0,3	14,2	[m]
q (Distributed load)	67.101	10.379.373	150.857	[N/m]
M (Moment)	n/a	n/a	15.209.443	Nm
F (Force)	n/a	3.113.812	n/a	N

Table 5-33: q, M, F translated

The formulas used to calculate the deflection (δ) for the three loadings are (source (Hartsuijker, 2004)):

$$\delta_{Distributed\ load\ (q)} = \frac{q \cdot l^4}{8 \cdot EI}$$

$$\delta_{Point\ load\ (F)} = \frac{F \cdot l^3}{3 \cdot EI}$$

$$\delta_{Moment\ (M)} = \frac{M \cdot l^2}{2 \cdot EI}$$

With:

- q distributed load [N/m]
- l length [m]
- E e-modules [N/m^2]
- I Inertia [m^4]
- F Force [N]
- M Moment [Nm]
- δ displacement [m]

In Figure 5-37 the moment of inertia of the suction anchor is given over the length. The moment of inertia over l3 is depending on the length. (It increases over length.)

Steiner's theorem is used to calculate the moment of inertia of l3 due to the bracings (green tubes in Figure 5-34). The distance from the centre of the clamped cantilever beam to the bracings varies over the length. The distance has an exponential factor in Steiner's theorem making the moment of inertia grow exponential (Figure 5-37).

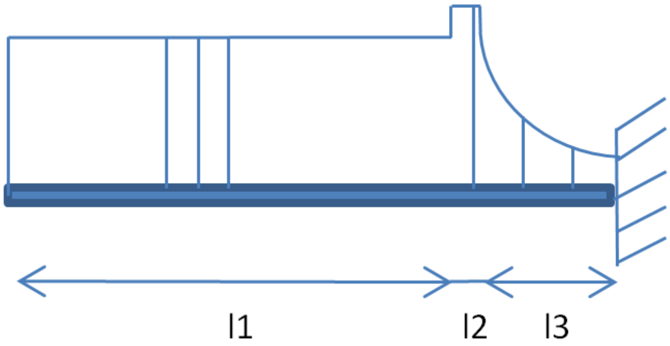


Figure 5-37: Suction anchor - moment of inertia over the length (not to scale)

Moment of inertia over the length, Steiner theorem (source (Hartsuijker, 2004)):

$$I_{tot} = 2(I_{bracing} + d_{bracing}{}^2 \cdot A_{bracing}) + I_{leg} + 2(I_{bracing})$$

With:

- I	moment of Inertia	[m^4]
- d	distance from centre axis	[m]	(Figure 5-33)
- A	Area	[m^2]	(Figure 5-33)

By integrating the deflection over the length to incorporate the growing inertia, the following integrals were used to calculate the total deflection (δ):

$$\delta_{l_3\,q} = \int_0^3 \frac{q \cdot l_3{}^4}{8 \cdot E \cdot (\pi \cdot r_{leg}{}^3 \cdot t_{leg} + 2 \cdot (\pi \cdot r_{bracing}{}^3 \cdot t_{bracing}) + \frac{4{,}3}{3} \cdot l^2 \cdot 2(\pi \cdot r_{bracing}{}^3 \cdot t_{bracing})} dl$$

$$\delta_{l_3 M} = \int_0^3 \frac{M \cdot (l_3 + l_2)^2}{2 \cdot E \cdot (\pi \cdot r_{leg}{}^3 \cdot t_{leg} + 4 \cdot (\pi \cdot r_{bracing}{}^3 \cdot t_{bracing}) + \frac{4{,}3}{3} \cdot l^2 \cdot 2(\pi \cdot r_{bracing}{}^3 \cdot t_{bracing})} dl$$

$$\delta_{l_3 F} = \int_0^3 \frac{F \cdot (l_3 + 0{,}5 \cdot l_2)^3}{3 \cdot E \cdot (\pi \cdot r_{leg}{}^3 \cdot t_{leg} + 4 \cdot (\pi \cdot r_{bracing}{}^3 \cdot t_{bracing}) + \frac{4{,}3}{3} \cdot l^2 \cdot 2(\pi \cdot r_{bracing}{}^3 \cdot t_{bracing})} dl$$

With all the formulas derived the deflection can be calculated. This will result in a total deflection of:

$$\delta\ [m] = \delta_{l_3\,q} + \delta_{l_3 M} + \delta_{l_3 F}$$

The total deflection at the end of L3 will then be: $\delta = 0{,}104\ cm$

With the total force known the stiffness can be calculated.
Stiffness (k):

$$k_{stiffness}\ [\mathrm{N/m}] = \frac{F_{suction\ anchor}}{\delta_{total}}$$

$F_{suction\ anchor}$	[N]	Force caused by the gravity of the suction anchor combined at the end of l3.

The natural frequency (f_0) for this mode can be calculated as follows:

$$f_0 = \frac{1}{2\pi} \cdot \sqrt{\frac{k_{stiffness}}{m_{suction\ anchor}}} = 28{,}1\ Hz$$

This natural frequency is compared with the movements of the PS.

The pitch, roll and heave motion (Figure 5-38) will be checked. These motions are contributing to the vertical displacements. From Figure 5-39, Figure 5-40 and Figure 5-41 it can be seen that the period the PS moves is around 10 seconds (0,1 Hz). Therefore resonance is unlikely to occur.

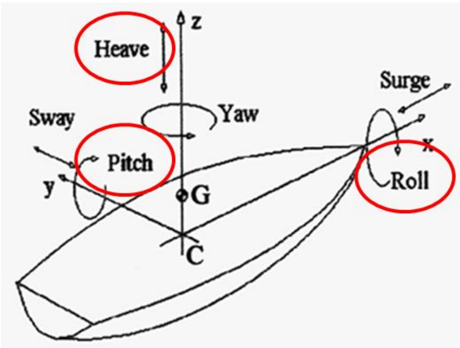


Figure 5-38**:** Pitch, heave and roll motion

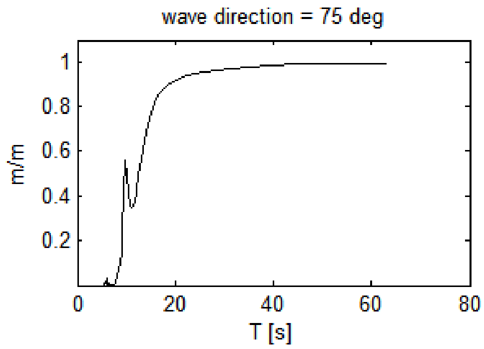


Figure 5-39**:** Heave

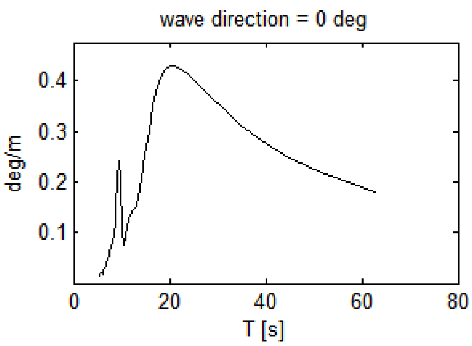


Figure 5-40: Pitch

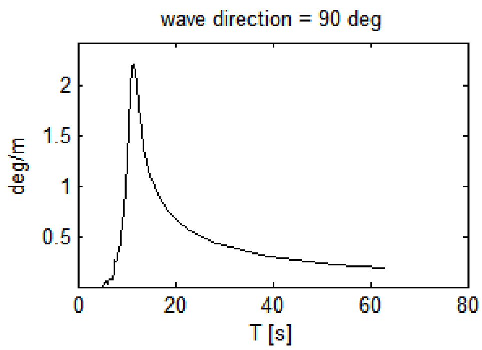


Figure 5-41: Roll

5.4.10 Finite Element Method

This section contains simulations done in Femap to verify the results obtained analytically. Femap is finite element method software for structural purposes.

Stresses in-place (bracings)
The stresses caused by the environmental 100-year return event will be checked with the analytical found dimensions of the braces. Femap represents the stresses with color codes. Starting from low stresses (purple), to the larger stresses (red) (Figure 5-42).

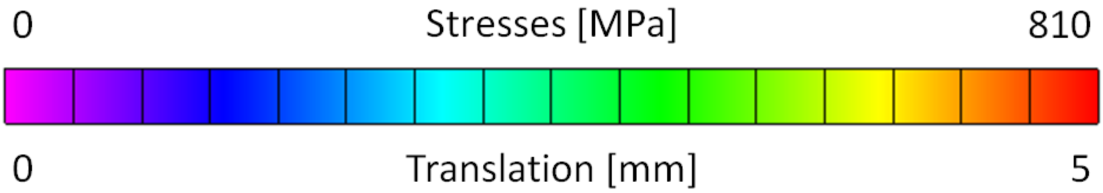


Figure 5-42: Femap stress/deformation colour scale

The total stress measured at the location where the bracing is connected to the top plate is around 810 MPa (red in Figure 5-42). The bracings are modeled as ridged lines. The dimensions and the position of the bracings calculated in section 5.4.8 shows a force vertically at the bracing of 19,7MN. Figure 5-43 shows that nearly all the stress induced by the moment is attracted to the bracings (see color concentration in Figure 5-42). Analytically the same calculation shows 20MN. This means the used method to calculate the distribution of the loads and the dimensioning of the bracings has a 1,5% deviation from the model.

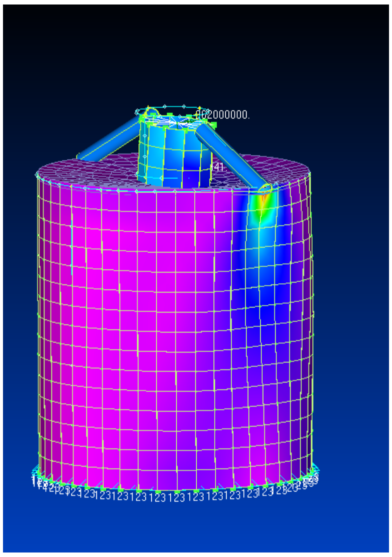


Figure 5-43: Inplace stress and defromation

Resonance
To check if the analytically calculated natural frequency of the suction anchor is correct, Femap was used. The suction anchor has a lot of modes. The one interesting for this research is the mode responsible for the movements of the leg on the top plate. Analytical a natural frequency of 28,1 Hz was calculated. Modelling the top plate with Femap and analysing the modes of the natural frequency is done in this section.

Femap represents the deformations with color codes. Starting from no deformation (purple), to the larger deformations (red) (Figure 5-42).

The first mode is shown in Figure 5-44. It shows the shell to deform in a way that the bottom of the shell will be ellipse shaped. These ellipses can be formed in numerous directions and several modes describe ellipses like this one.

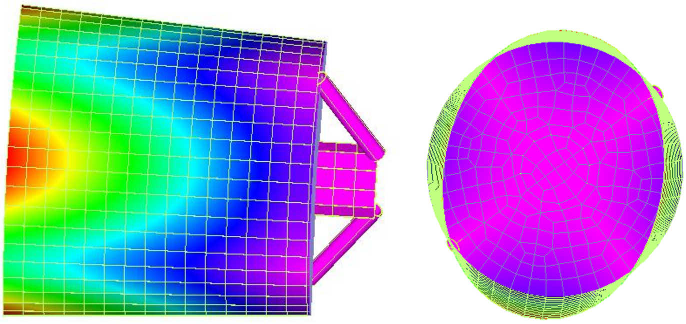


Figure 5-44: First mode, natural frequency [1,6 Hz]

Observing mode 10 of the Femap model, shows the shell of the suction anchor to take the shape shown in Figure 5-45.

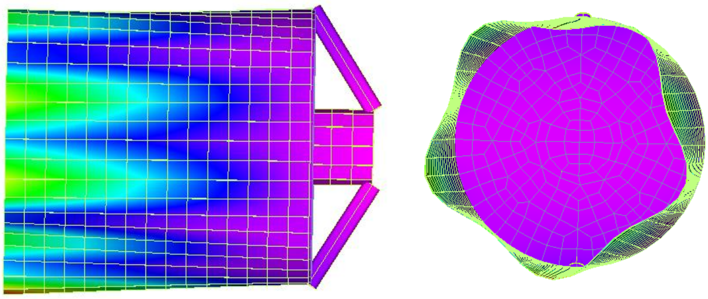


Figure 5-45: Mode 10, natural frequency [6,8 Hz]

Mode 19 deforms as shown in Figure 5-46.

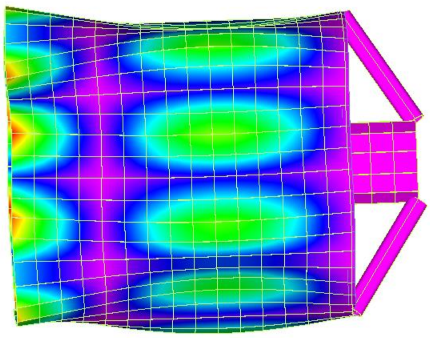


Figure 5-46: Mode 19, natural frequency [16,2 Hz]

The first shape that deforms the top-plate and the bracings is shown in Figure 5-47. The deformation in the top-plate and the bracings is the deformation where the connection is designed upon (the deflection is around 0,001m, which is close to the analytically calculated deformation).

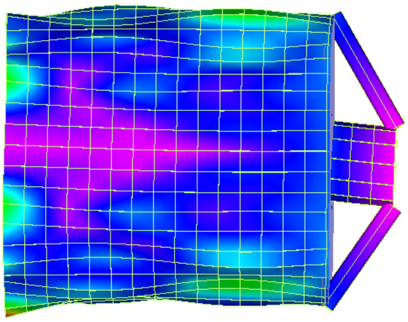


Figure 5-47: Mode 44, natural frequency [29,8 Hz]

The frequency of mode 44 is very close to the analytically calculated natural frequency in the same mode. Because the frequencies are so close (Femap 29,8Hz; analytically 28,1Hz) to each other, it means the analytical approach describes the natural frequency quite accurate. Both frequencies are significantly larger than the frequencies in which the PS moves. Resonance is therefore very unlikely to occur.

5.4.11 Leg deflection

The Femap and the analytical method used to model the deflection shows that the approach is accurate. One phenomenon is not incorporated yet.
The connection to the substructure was assumed to be ridged. However the leg could deflect as well due to the forces induced by the suction anchor. Figure 5-48 shows the deflection of the leg. The red arrow represents the moment induced by the suction anchor weight.

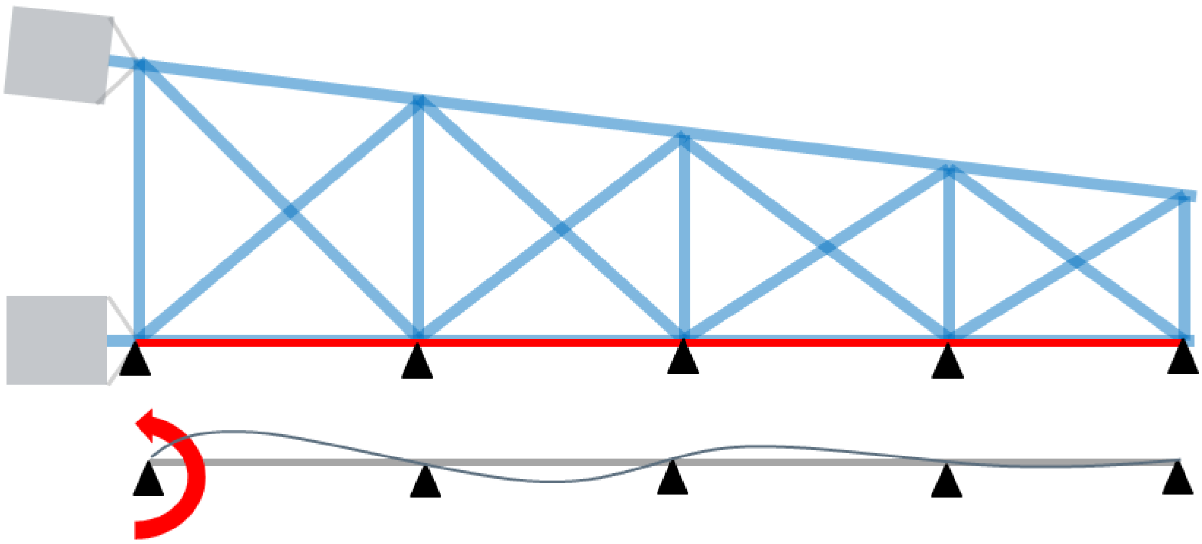


Figure 5-48: Deflection leg

The deflection of the leg will decrease over the distance. The largest deflections are expected in the first section of the leg. This part of the leg is shown in Figure 5-49. Adding the other sections of the leg will only increase the stiffness of the system. Therefore the deflection induced by the first section is calculated. When this deflection is not causing resonance (natural frequency is higher), adding the other sections will not causing resonance, due to the increasing stiffness.

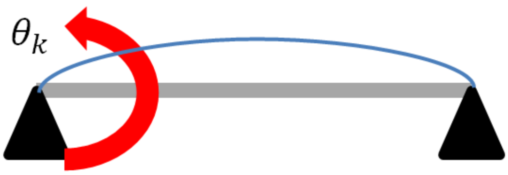


Figure 5-49: First leg part deflection

The angle (θ_k) is given by:

$$\theta_k = \frac{M \cdot l}{3E \cdot I}$$

The angle will result in a deflection at the suction anchor of:

$$\delta_k = 0{,}018\ m$$

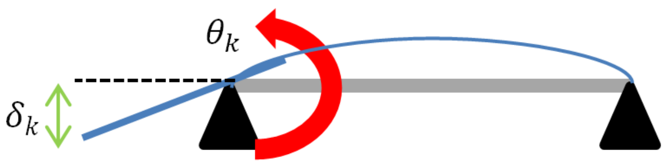


Figure 5-50: Deflection location suction anchor

When computing the natural frequency accordingly will result in:

$$f_{0,\mathrm{k}} = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} = 5{,}2\ Hz$$

This natural frequency is lower than the previously calculated natural frequency (f_0). However this frequency is significantly lower than the movements of the PS. Resonance is unlikely to occur here as well.

6 CONCLUSIONS & RECOMMENDATIONS

The conclusions and recommendations are found in this Chapter.

6.1 Conclusions

The purpose of this research was to investigate and quantify the optimizations that can be achieved within the area of platform design, when using the Pioneering Spirit for transport and installation.

The Kebabangan platform (located in the South China Sea) was used as a case study to quantify and compare the potential optimizations.

A Multi-Criteria Analysis was carried out to identify the areas where the greatest potential lies for optimization. This analysis resulted in three main areas of interest:

- Transport and installation procedure for the entire platform.
- Substructure design.
- Integrated foundation design – suction anchors.

Based on this research, for each of the aforementioned areas of interest, the following conclusions are drawn.

Transport and installation procedure for the entire platform.
The research compares the conventional transport and installation procedure with seven newly developed procedures using the Pioneering Spirit. The Pioneering Spirit may or may not be mobilized for multiple projects when heading to the South China Sea, both scenarios were considered.

Under the assumption that the PS is mobilized for multiple projects, in three of the seven procedures, the involvement the Pioneering Spirit would lead to a large cost saving. A 30% reduction in costs (including day rates and mobilization costs) is found for the case study, comparing these three procedures to the conventional transport and installation procedure at Kebabangan.

For comparison, the calculations were made for the case where the PS is only mobilized for one project only. This did not result in significant cost-saving (in fact, only one procedure was evenly costly as the conventional method).

With the Pioneering Spirit, the duration of the procedures is massively reduced. Including the deferment (the value-representation of producing first oil per day) leads to an additional procedure to be economically feasible on the mobilization for multiple projects: bringing the total to 4 out of 7 procedures leading to a large cost saving. The largest savings are gained in the scenario where the PS sails to the site-location with both the topsides and substructure on top and installs the entire platform using suction anchors for the foundation.

Even more, when taking the deferment into account, this leads to three out of seven procedures being economically feasible (costs -20%) when mobilizing the Pioneering Spirit only for this project.

Substructure design.
The substructure design for the installation with the Pioneering Spirit leads to a total steel reduction of 40% in the preliminary design. This is due to the following reasons:

- Compared to a float-over platform the temporary support points can be placed closer to each other, resulting in a less wide substructure.
- Without a launch operation there are no launch runners and (temporary) buoyancy tanks required.
- Installation with the PS will avoid impact loads during launching. Thus the boat-landing and less robust foundation components can be pre-installed onshore, resulting in a shorter installation duration offshore.
- An additional advantage caused by the relocation of the permanent support points on the substructure and consequently the permanent support points on the topsides, is a more compact topsides layout.

Integrated foundation design – suction anchors.
Lowering the substructure into place at the installation location with the Jacket Lift System has advantages. The advantage compared to launching is the controlled way of lowering the tower into place, reducing impact loads during the launch. Therefore suction anchors are used instead of the conventional used skirt piles. This is the largest time saving in installation phase (at least -30% of the total duration).

The soil strength at the installation location of the case study is found to be sufficient to provide the needed bearing capacity to withstand the forces on the platform (environmental influences and weight) with a suction anchor diameter of 13,1m and a length of 14,5m. A diameter of 13,1m lies within the transfer restrictions of the Pioneering Spirit.

The connection between the suction anchor and the leg of the tower will be exposed to forces in-place and forces caused by accelerations during transport. Bracings to reinforce the connection are needed to withstand the forces in-place.

The accelerations during transport will not lead to resonance of the suction anchor. Resonance will not be a governing load-case.

In order to carry out an additional check on the analytical results, a Femap-model is set-up. Femap is a finite element modelling program, which shows insight in the results and the show resemblance. The resonance has a deviation of 3% and is significantly larger than the frequency the Pioneering Spirit moves. The bracing-seizing and the corresponding stresses have an accuracy of 1,5%.

Summary
Concluding, a platform design has a lot of interaction with the different sections (topsides, substructure, and foundation) and the installation method of the platform. The three analytical approaches show that an optimized platform can result in significant savings. Even when the soil would not allow for suction anchors, the savings on the other optimization areas will still make the installation with PS economically favourable.

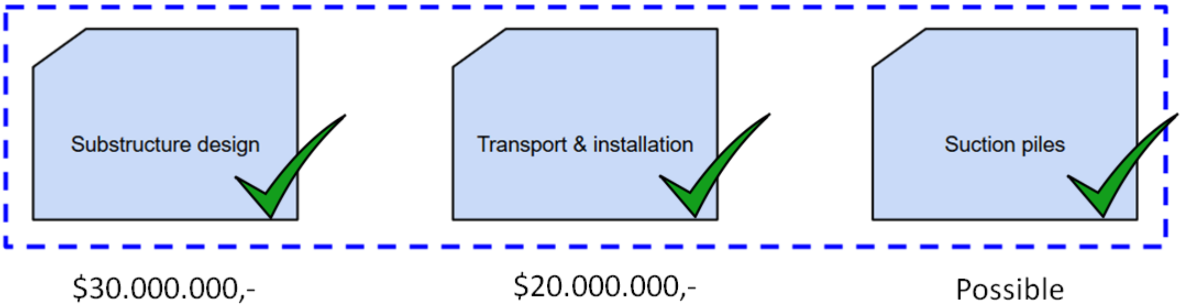


Figure 6-1 Areas for optimization

6.2 Recommendations

This research is a first study on this subject. This resulted in the making of some assumptions during this research, all mentioned throughout the report. In this section possible future steps for a more accurate end result are discussed.

General recommendation

For the purpose of this research the broad perspective was a good eye opener: showing what is possible. A general recommendation for further research therefore is to focus on one area of optimization only, and investigate this in great detail. This research can serve as a starting point for future research regarding the optimization of the installation of offshore platforms by using Pioneering Spirit.

The comparison between the case study (Kebabangan) and Pioneering Spirit was done. Applying the same method used in this research on a different case study will provide a wider perspective on how and where the PS can lead to optimization.

Transport and installation procedure for entire platform.

Within the economic feasibility-study of the procedures, the workability was not investigated extensively. The workability of the Pioneering Spirit can be calculated, but no information on workability of the conventional transport and installation procedure was available for comparison. The Pioneering Spirit is expected to have a larger workability due to its size and the ballasting opportunities. Thus, there will be advantages when looking at workability using de Pioneering Spirit. For future projects, it is recommended to take the workability into account of both the conventional method and PS method.

Substructure design.

For the preliminary substructure design, rules of thumb were used. These rules of thumb give a rough first estimate on the dimensions. Using this rule of thumb a factor of 1,3 (expert opinion) was applied to account for extra steel needed for the final design. For future research, it is recommended to further detail the design of the substructure by calculating the strength of each individual member (iterative process, including dynamic behaviour). This will result in a more detailed and more accurate overview of the cost savings of the substructure.

Integrated foundation design – suction anchors.

The soil data used for this research was very limited. When more detailed design of the foundation is to be made, a more accurate soil profile should be obtained.

The method used in this research does not include any finite element modelling for the soil behaviour. For an accurate estimation on the dimensions and the capacity of a suction anchor this is recommended. When the soil is strongly layered this is even required.

7 BIBLIOGRAPHY

Allseas, 2014. *Internal wheater data Allseas,* Delft: s.n.

Allseas, 2015. *Method statement,* Delft: Allseas BV.

Anon., n.d. *Heerema.com.* [Online]
Available at: www.heerema.com

Brasfond, 2015. *Brasfond.* [Online]
Available at: www.brasfond.com.br
[Accessed 2015].

Carter, H. T. &. J., 2010. *A failure surface for caisson foundations in undrained soils,* Sydney: University of Technology Sydney, NSW, Australia.

Chairat Supachawarote, M. R. a. S. G., 2004. *Inclined Pull-out Capacity of Suction Caissons,* Perth: Centre for Offshore Foundation Systems, University of Western Australia..

Chakrabarti, S. K., 2006. Handbook of offshore engineering. In: 1 ed. Illionois, USA: Offshore Structure Analysis Inc., p. 279 onward.

CHU, P. C., 2004. South China Sea Wind-Wave Characteristics. *J O U R N A L O F A T M O S P H E R I C A N D O C E A N I C T E C H N O L O G Y,* p. 1718.

Denton0030, N., 2013. *GUIDELINES FOR MARINE TRANSPORTATIONS,* s.l.: Noble Denton.

DNV, 1992. *Foundations,* Hovik: Det Norske Veritas.

DNV-RP-C202, JANUARY 2013. *Buckling Strength of Shells,* s.l.: DNV.

engineer, T., 2015. *The engineer.* [Online]
Available at: http://www.theengineer.co.uk/
[Accessed 2015].

Faltinsen, 1990. *www.orcina.com.* [Online]
[Accessed 2015].

Hamilton, J. D. M. &. J. M., 1993. *P-Ultimate for Undrained Analysis of Laterally Loaded Piles,* s.l.: s.n.

Hartsuijker, C., 2004. *Toegepaste mechanica.* s.l.:s.n.

KPOC, 2014. *ToR for Share holder's Transport and Installation Review.* s.l., s.n.

Massie, J. J. a. W., 2001. Offshore hydromechanics. In: Delft: s.n., p. 5.9.

Nasdaq, 2015. *www.nasdaq.com.* [Online]
Available at: http://www.nasdaq.com/markets/crude-oil.aspx

OE4651, 2013. *Excersise accompanying Bottom founded structures,* Delft: TU Delft.

Offshore, 2014. *Offshore Energy Today.* [Online]
Available at: http://www.offshoreenergytoday.com/wp-content/uploads/2014/11/Kebabangan.jpg
[Accessed 12 November 2014].

Senders & Kay, 2002.

Subrata, C. B. T., 2005. *Handbook of Offshore Engineering.* Great Britain: Elsevier.

today, o. e., 2014. *Offshore energy today.* [Online].

Touma, J., 1977. Air Pollution Control Association. In: *Dependence of the wind profile power law on stability for various locations.* s.l.:s.n., pp. 863-866.

Vesic, 1975. s.l.:Vesic.

Wielen, V. v., 2015. *Suction anchor design,* Delft: Allseas.

8 LIST OF FIGURES

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10 LIST OF SYMBOLS

Symbol	Units	Definition
50/50	[-]	unity check average
A	[m^2]	area
a	[m/s^2]	acceleration
B	[m]	breadth suction anchor (in 2D)
Bbl/d	[barrels/day]	barrels oil per day
C_d	[-]	drag coefficient
C_m	[-]	inertia coefficient
D	[m]	diameter
D_0	[m]	diameter suction anchor
D_{DE}	[m]	equivalent diameter for drag force
D_{IE}	[m]	equivalent diameter for inertia force
D_{max}	[m]	maximum water depth
E	[N/m2]	e-modulus
f_0	[Hz]	natural frequency
$F_{0,eff}$	[N]	Wall friction
$F_{fullbase}$	[N]	Base force suction anchor
F_{tip}	[N]	vertical force on tip of shell suction anchor
$F_{x,y,z}$	[N]	force in x,y,z direction\
g	[m/s^2]	gravitational acceleration
h	[m]	water depth
$H_{correnction}$	[-]	correction factor horizontal force
$H_{lateral}$	[N]	force horizontal suction anchor
H_{max}	[m]	maximum wave height
H_{tip}	[N]	force at tip of suction anchor shell
I	[m^4]	second moment of inertia
J	[m^4]	polar moment of inertia
K	[-]	stiffness
k	[-]	wave number
K_0	[-]	lateral pressure coefficient
K_{factor}	[-]	K-factor
$k_{stiffness}$	[N/m]	stiffness
kts	[nm/hour]	knots
L	[m]	length
L_{emb}	[m]	length embedment suction anchor
m	[m]	meters
M	[Nm]	moment
M	[Nm]	moment
MMscf/d	[$feet^3$/day]	million standard cubic feet per day
MSL	[m]	Mean Sea Level
nm	[nm]	nautical miles
N_p	[-]	lateral bearing factor
P	[N/m^2]	water pressure
P_u	[Mpa]	ultimate unit resistance

q	[N/m]	distributed load
r	[m]	radius
rx,ry,rz	[deg/s^2]	rotational acceleration
s	[-]	horizontal position
S_{uAV}	[Mpa]	stress parameters
S_w	[Mpa]	equivalent Von Mises stress
t	[m]	thickness
T	[m]	draft
T	[Mpa]	shear stress
T_p	[s]	wave period
UC	[-]	Unity Check
U_w	[m/s]	wind velocity
v	[m/s]	velocity
V_{max}	[N]	total vertical capacity
V_{max}	[N]	total vertical capacity suction anchor
$W_{1min,\ 10m}$	[m/s]	wind velocity during 1 minute at an elevation of 10m
δ	[m]	displacement
$\delta(z)$	[deg]	external friction angle
ζ	[m]	half wave height
θ	[deg]	internal friction angle
λ	[m]	wave length
ρ	[kg/m^3]	density
σ	[N/m^2]	stress
σ	[N/m^2]	stress
σ'	[N/m^2]	effective stress
Φ	[-]	velocity potential
ω	[rad/s]	angular frequency
Ω	[-]	safety factor

11 LIST OF ABBREVIATIONS

Abbreviation	Meaning
COG	Centre Of gravity
ctc	centre-to-centre
JLS	Jacket Lift system
KBB	Kebabangan
MCA	Multi Criteria Analysis
MSL	Mean Sea Level
PS	Pioneering Spirit
ROV	Remotely Operated Vehicles
SPT	Suction Pile Technology
TLB	Tilting Lift Beam

12 APPENDICES

Appendix A Field data

Shell discovered the Kebabangan gas field in 1994, and an appraisal well drilled in 2002. The well penetrated gas columns in a number of reservoir intervals. Kebabangan is estimated to contain about 2 Tcf of natural gas[10].

The Kebabangan (KBB) Petroleum Operating Company (KPOC) is currently embarking on the KBB Northern Hub Project to develop oil and gas reserves offshore Sabah, Malaysia, approximately 135 km North-East of Kimanis. The KBB Platform will be located in a water depth of 140 meters and have a design capacity of 825 MMscfd for gas and 22 kbpd for condensate. The KBB Platform will be a single integrated PdUQ (Production, drilling, Utilities and Quarters) platform where drilling is undertaken by a TAD rig. Receiving, process and exporting capacity for 90 kbpd of oil and associate water is included for 3rd. party oil field tiebacks, and the Shell Malikai oil field will be tied in soon after KBB start-up.

The platform, measuring approximately 18,000 metric tonnes in weight and 39 metres in height, is one of the largest offshore structures ever built in Malaysia. It is designed with the capacity to process up to 825 million standard cubic feet of natural gas, 80,000 barrels of crude oil and 22,000 barrels of condensate daily.[11]

The coordinates of the platform are: 06°26'39.974''N 115°23'38.314''E. A plan of pipelines is shown in Figure 12-1.

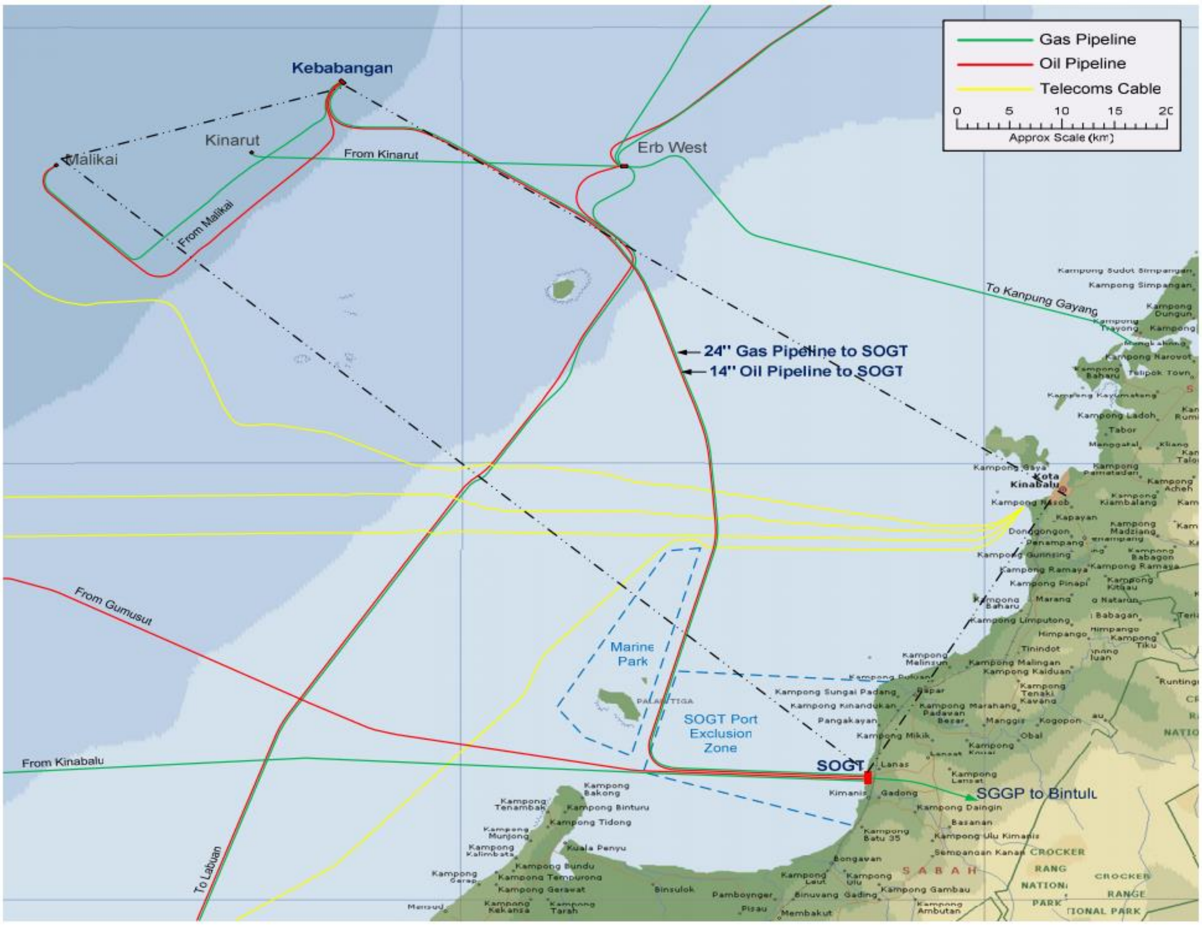

Figure 12-1: Pipeline map

[10] http://www.oilonline.com/news/upstream/kpoc-hits-first-gas-kebabangan#sthash.XN0WTFHH.dpuf
[11] http://www.offshoreenergytoday.com/gas-flows-from-kebabangan-malaysia/

Appendix B Capabilities/ Limits of the PS

This appendix shows the key figures of the PS and durations of procedures.

Length hull	382	[m]
Length between perpendiculars	370	[m]
Breadth moulded	123.75	[m]
Depth moulded	29	[m]
Draught, scantling	27	[m]
Draught, operational (typically)	17	[m]
Draught, transport	13-17	[m]
Draught, transit	11.5	[m]
Slot length	122	[m]
Slot breadth	58.75	[m]
Vessel cruise speed	13.7	[kts]
Vessel loaded speed	11.8	[kts]
Length	382	m
power installed, diesel generators (8)	95	[MW] (total)
azimuth thrusters (DP3)	12	[pcs.]
accommodation for	571	[persons]

Figure 12-2: Pioneering Spirit main dimensions

Description	Value	Dimension
Maximum transport capacity forklift unit	103	MN
Maximum lift capacity forklift unit	74.5	MN
Maximum (total) vertical stroke	4	m
Maximum CTC distance force to aft clamps	80.6	m
Maximum leg diameter (friction clamp)	2.25	m
Minimum longitudinal CTC distance jacket legs	12.2	m
Speed X-direction during positioning	0.1	m/s
Speed Y0direction during positioning	0.5	m/s
Maximum speed Z-direction during fast lift	0.36	m/s
Maximum speed Z-direction during quick lowering	0.34	m/s
Length lifting beam	65	m
Width lifting beam	6	m
CTC of lifting beams	6.1	m

Figure 12-3: Topsides Lift System summary

Phase	position	Duration	Dimension
Positioning the Pioneering Spirit around platform	1	1	h
Attaching the lift equipment to topside	2	4:8	h
Pre-tension	3	2:8	h
Fast lift	4	20	s
Vessel moves away from the jacket	5	1	h
Sea fastening	6	1	h

Figure 12-4: Critical cycle time for 8 forklift unites combined, Topside removal

Phase	position	Duration	Dimension
Positioning the Pioneering Spirit around jacket	1	1	h
Positioning above jacket	2	1	h
Quick lowering	3	5	s
De-pressurising pretension	4	2:8	h
Disconnecting clamps	5	4:8	h
Vessel moves away from the platform	6	1	h
Sea fastening	7	1	h

Figure 12-5: Critical cycle time for 8 forklift units combined, Topsides installation

Phase	position	Duration	Dimension
Positioning the Pioneering Spirit around a barge	1	2	h
Mooring of a barge to the Pioneering Spirit	2	2	h
Attaching the lift equipment to topside	3	4:8	h
Pretension	4	2:8	h
Fast lift	5	10	s
Disconnection barge and vessel	6	2	h
Barge moves away from vessel	7	2	h
Sea fastening	8	1	h

Figure 12-6: Critical cycle time for 8 forklift units combined, Topsides load-in from a cargo barge

Phase	position	Duration	Dimension
Positioning a barge into a vessel slot	1	1	h
Mooring of a barge to the Pioneering Spirit	2	2	h
Positioning above skiddable stools	3	2	h
Lowering by ballasting vessel	3	4:8	h
De-pressurising pretention	4	2:8	h
Disconnecting clamps	5	4:8	h
Disconnection barge and vessel	6	2	h
Vessel moves away from a barge	7	2	h
Sea fastening	6	1	h

Figure 12-7:n Critical cycle time for 8 forklift units combined, Topside load-out onto a cargo barge

Dimension	Column1	Unit
JLS SWL	25,000	[t]
TLB SWL @ 106 deg. TLB angle	14,900	[t]
Main hoist blocks factored load	4,552	[t]
Main hoist full load hoisting speed	3.38	[m/min]
Jacket support structure upper sledge SWL (z-drive)	4,100	[t]
Jacket support structure lower sledge SWL (z-drive)	6,100	[t]
Length main body TLB	139.65	[m]
Length main body TLB above hinge HOF	109.65	[m]
Length main body TLB below hinge HOF	30	[m]
Short tail extension	16	[m]
Tail length below hinge HOF including short tail	46	[m]
Minimum centre to centre distance of TLBs	21	[m]
Maximum centre to centre distance of TLBs without jib	86.25	[m]
Minimum TLB operating angle (auxiliary hoist / MH5B)	65	[deg.]
Maximum TLB operating angle	115	[deg.]

Figure 12-8: Jacket Lift System summary

Appendix C Multi-Criteria Analysis

The motives on the given scores are mentioned in this section.

Section	Phase	Criteria	Description	Advantage
Topsides	Construction	Time	Construction time of the topside in the yard	Smaller topside, less time
		Steel	Structural amount of steel used in the topside	Smaller topside, smaller span, less steel
		Workability	Effort needed to get the construction build (complexity)	Less overhang so more better reachable places
		Safety	Safety during construction	Smaller, less height or depth, safer
		Development cost	Development costs for the construction phase	No additional steel needs lower special developments
	Transportation	Time	Transport time	Moving it on the PS is quicker, higher workability
		Steel	Steel needed for transport, (sea fastening, etc.)	Sea-fastening is needed any way, less movement on PS perhaps
		Workability	Till what sea state can transport of the topside be done	PS will be more stable
		Safety	Safety during transport	Transport on the PS will be safer due to a more stable vessel
		Development cost	Development costs for the transportation phase	Only one or two vessels are needed. So less logistic problems, no need to search for multiple vessels with the right capacity
	Installation	Time	Time needed for installation	18 hours as well, but waiting on weather will be smaller
		Steel	Temporary steel that is needed for installation (temporary lift points, etc.)	Little gain here
		Workability	Sea state till which the installation can be done	PS will be more stable
		Safety	Safety during installation	Due to the compensating system little personnel needed
		Development cost	Development costs for the installation phase	The ship is built for this kind of operations

	Commissioning	Time	Time it takes to commission the platform	Integrated saves a lot of time
		Steel	Steel needed for the commissioning	
		Workability	How easily can the commissioning be done	
		Safety	Safety during commissioning	
		Development cost	Development cost of the commissioning phase	
Substructure	Construction	Time	Construction time of substructure the in the yard	Smaller means less steel = less time
		Steel	Structural amount of steel used in the substructure	Smaller means less steel
		Workability	Effort needed to get the construction build (complexity)	Less dense means less complex so higher workability
		Safety	Safety during construction	Smaller, less height, safer
		Development cost	Development costs for the construction phase	No runners, tanks means a save on the iterative process
	Transportation	Time	Transport time	Moving it on the PS is quicker, higher workability
		Steel	Steel needed for transport, (sea fastening, etc.)	Sea-fastening is needed any way, less movement on PS perhaps
		Workability	Till what sea state can transport of the topside be done	PS will be more stable
		Safety	Safety during transport	Transport on the PS will be safer due to a more stable vessel
		Development cost	Development costs for the transportation phase	Only one or two vessels are needed. So less logistic problems, no need to search for multiple vessels with the right capacity
	Installation	Time	Time needed for installation	12 hours, not much gain but the upend of the launch takes a lot of time, and direct install of the boat landing etc.
		Steel	Temporary steel that is needed for installation (temporary lift points, buoyancy tanks, launch runners, etc.)	No need for rails and tanks
		Workability	Sea state till which the installation can be done	PS will be more stable
		Safety	Safety during installation	No high speed launch, people on the barge
		Development cost	Development costs for the installation phase	Less dynamic impacts
	Commissioning	Time	Time it takes to commission the platform	
		Steel	Steel needed for the commissioning (straighten top of legs)	
		Workability	How easily can the commissioning be done	
		Safety	Safety during commissioning	
		Development cost	Development cost of the commissioning phase	
Foundation	Construction	Time	Construction time of the foundation parts in the yard	Suction anchors will take more time onshore
		Steel	Structural amount of steel used in the topside	More steel but no skirt pile sleeves
		Workability	Effort needed to get the construction build	Further research will show the suction pile
		Safety	Safety during construction	Further research will show the suction pile
		Development cost	Development costs for the construction phase	It shows a lot of potential so Development cost will be very useful, Anchors are already built so it is a combination
	Transportation	Time	Transport time	The time to get them there will be influenced by the weight on the jacket, so will be slower instead of on a barge
		Steel	Steel needed for transport, (sea fastening, etc.)	Further research will show the suction pile
		Workability	Till what sea state can transport of the topside be done	Scientific depth

		Safety	Safety during transport	Scientific depth
		Development cost	Development costs for the transportation phase	Scientific depth
	Installation	Time	Time needed for installation	Step change
		Steel	Temporary steel that is needed for installation	Only pumps
		Workability	Sea state till which the installation can be done	Scientific depth, with the self-penetration
		Safety	Safety during installation	Hammering is less safe
		Development cost	Development costs for the installation phase	Scientific depth
	Commissioning	Time	Time it takes to commission the foundation	Close valve , grout and bring up pump
		Steel	Steel needed for the commissioning	Pump with ROV to surface
		Workability	How easily can the commissioning be done	Easier than the outnumbered skirt piles
		Safety	safety during commissioning	
		Development cost	Development cost of the commissioning phase	

Appendix D Substructure calculation and use rules of thumb

The substructure is build up from coordinates. Between a coordinate legs or members can be placed. The coordinates all have an individual node number. The substructure is shown in below:

Tower	Coordinates				Riser frame			
node nr	**X**	**Y**	**Z**		at every horizontal	**X**	**Y**	**Z**
110	0	0	0		9111	16.75	16	3
111	0	0	3		9211	16.75	24	3
112	0	2.5	40		9121	23.25	16	3
113	0	5	77		9221	23.25	24	3
114	0	7.5	114					
115	0	10	151		9112	16.75	16	40
					9212	16.75	24	40
120	40	0	0		9122	23.25	16	40
121	40	0	3		9222	23.25	24	40
122	40	2.5	40					
123	40	5	77		9113	16.75	16	77
124	40	7.5	114		9213	16.75	24	77
125	40	10	151		9123	23.25	16	77
					9223	23.25	24	77
131	20	1.25	21.5					
132	20	3.75	58.5		9114	16.75	16	114
133	20	6.25	95.5		9214	16.75	24	114
134	20	8.75	132.5		9124	23.25	16	114
135	20	10	151		9224	23.25	24	114
210	0	40	0		9115	16.75	16	151
211	0	40	3		9215	16.75	24	151
212	0	37.5	40		9125	23.25	16	151
213	0	35	77		9225	23.25	24	151
214	0	32.5	114					
215	0	30	151		811	20	0	3
					821	20	40	3
220	40	40	0		8111	20	16	3
221	40	40	3		8211	20	24	3
222	40	37.5	40					
223	40	35	77		812	20	2.5	40
224	40	32.5	114		822	20	37.5	40
225	40	30	151		8221	20	24	40
					8121	20	16	40
231	20	38.75	21.50					
232	20	36.25	58.50		813	20	5	77
233	20	33.75	95.50		823	20	35	77
234	20	31.25	132.50					
235	20	30	151.00		814	20	7.5	114.00
					824	20	32.5	114.00
331	0	20	22.73					
332	0	20	59.82		815	20	10	151.00
333	0	20	96.92		825	20	30	151.00
334	0	20	134.04					
335	0	20	151.00		835	11.96	20	151.00
					845	28.04	20	151.00
431	40	20	22.73					
432	40	20	59.82		834	12.69	20	114.00
433	40	20	96.92		844	27.31	20	114.00
434	40	20	134.04					
435	40	20	151.00					

The length between the connected nodes can be calculated. The corresponding diameter, wall thickness can be determined by using the rule of thumb.
From here the equivalent diameter for the Morison equation can be calculated. Below the entire calculation is shown.

Beams (vertical)	Node 1	point 2	length [m]	D (prediction) [m]	Dde	Die	D/t	t (prediction) [m]	[inch]	Volume steel	dry weight [kg]	I [m⁴]	Bucking Load [MN]	Load carried (static)		Attack area [m²]
(legs)															UC	
110111	110	111	3.00	3.556	3.556	3.556	60	0.05927	0.0603	1.987465079	15899.72063	1.0122	932429.9184	57.63375	**6E-05**	10.92
111112	111	112	37.08	2.794	2.800370568	2.79718347	60	0.04657	0.0476	15.23826512	121906.121	0.3875	2336.1587	57.63375	**0.0247**	106.7287975
112113	112	113	37.08	2.286	2.291212283	2.288604658	60	0.03810	0.0381	9.977980767	79823.84614	0.1700	1024.7972	53.64844	**0.0524**	87.88994098
113114	113	114	37.08	1.778	1.782053998	1.780025845	60	0.02963	0.0318	6.459380205	51675.04164	0.0664	400.3721	49.66313	**0.124**	69.05108443
114115	114	115	37.08	1.27	1.272895713	1.271447032	60	0.02117	0.0222	3.230864535	25846.91628	0.0170	102.2458	45.67781	**0.4467**	50.21222788
120121	120	121	3.00	3.556	3.556	3.556	60	0.05927	0.0603	1.987465079	15899.72063	1.0122	932429.9184	57.63375	**6E-05**	10.92
121122	121	122	37.08	2.794	2.800370568	2.79718347	60	0.04657	0.0476	15.23826512	121906.121	0.3875	2336.1587	57.63375	**0.0247**	106.7287975
122123	122	123	37.08	2.286	2.291212283	2.288604658	60	0.03810	0.0381	9.977980767	79823.84614	0.1700	1024.7972	53.64844	**0.0524**	87.88994098
123124	123	124	37.08	1.778	1.782053998	1.780025845	60	0.02963	0.0318	6.459380205	51675.04164	0.0664	400.3721	49.66313	**0.124**	69.05108443
124125	124	125	37.08	1.27	1.272895713	1.271447032	60	0.02117	0.0222	3.230864535	25846.91628	0.0170	102.2458	45.67781	**0.4467**	50.21222788
210211	210	211	3.00	3.556	3.556	3.556	60	0.05927	0.0603	1.987465079	15899.72063	1.0122	932429.9184	57.63375	**6E-05**	10.92
211212	211	212	37.08	2.794	2.800370568	2.79718347	60	0.04657	0.0476	15.23826512	121906.121	0.3875	2336.1587	57.63375	**0.0247**	106.7287975
212213	212	213	37.08	2.286	2.291212283	2.288604658	60	0.03810	0.0381	9.977980767	79823.84614	0.1700	1024.7972	53.64844	**0.0524**	87.88994098
213214	213	214	37.08	1.778	1.782053998	1.780025845	60	0.02963	0.0318	6.459380205	51675.04164	0.0664	400.3721	49.66313	**0.124**	69.05108443
214215	214	215	37.08	1.27	1.272895713	1.271447032	60	0.02117	0.0222	3.230864535	25846.91628	0.0170	102.2458	45.67781	**0.4467**	50.21222788
220221	220	221	3.00	3.556	3.556	3.556	60	0.05927	0.0603	1.987465079	15899.72063	1.0122	932429.9184	57.63375	**6E-05**	10.92
221222	221	222	37.08	2.794	2.800370568	2.79718347	60	0.04657	0.0476	15.23826512	121906.121	0.3875	2336.1587	57.63375	**0.0247**	106.7287975
222223	222	223	37.08	2.286	2.291212283	2.288604658	60	0.03810	0.0381	9.977980767	79823.84614	0.1700	1024.7972	53.64844	**0.0524**	87.88994098
223224	223	224	37.08	1.778	1.782053998	1.780025845	60	0.02963	0.0318	6.459380205	51675.04164	0.0664	400.3721	49.66313	**0.124**	69.05108443
224225	224	225	37.08	1.27	1.272895713	1.271447032	60	0.02117	0.0222	3.230864535	25846.91628	0.0170	102.2458	45.67781	**0.4467**	50.21222788
134135	134	135	18.54	0.426470178	0.427442568	0.426956096	27	0.01580	0.0159	0.379697976	3037.583809	0.0004	10.4213			9.465230758
234235	234	235	18.54	0.426470178	0.427442568	0.426956096	27	0.01580	0.0159	0.379697976	3037.583809	0.0004	10.4213			9.465230758
																0

																0
Beams (horizontal)	**point 1**	**point 2**	**length [m]**	**D (prediction) [m]**	**Dde**	**Die**	**D/t**	**t (prediction) [m]**	**0.003175**	**Volume steel**	**dry weight [kg]**	**I [m^4]**	**Bucking Load [MN]**	**Load carried**		
																0
121221	121	221	40.00	0.92	40	6.066300355	43	0.021395349	0.0222	2.507374133	20058.99307	0.006319319	32.7438			40.16
122222	122	222	35.00	0.805	35	5.308012811	39	0.020641026	0.0222	1.912919232	15303.35386	0.004189503	28.3534			31.115
123223	123	223	30.00	0.69	30	4.549725266	35	0.019714286	0.0222	1.398759513	11190.0761	0.002601794	23.9668			23.22
124224	124	224	25.00	0.575	25	3.791437722	31	0.018548387	0.0191	0.831803218	6654.42574	0.00128698	17.0715			16.475
125225	125	225	20.00	0.46	20	3.033150178	27	0.017037037	0.0191	0.527793692	4222.349535	0.000642588	13.3184			10.88
111211	111	211	40.00	0.92	40	6.066300355	43	0.021395349	0.0222	2.507374133	20058.99307	0.006319319	32.7438			40.16
112212	112	212	35.00	0.805	35	5.308012811	39	0.020641026	0.0222	1.912919232	15303.35386	0.004189503	28.3534			31.115
113213	113	213	30.00	0.69	30	4.549725266	35	0.019714286	0.0222	1.398759513	11190.0761	0.002601794	23.9668			23.22
114214	114	214	25.00	0.575	25	3.791437722	31	0.018548387	0.0191	0.831803218	6654.42574	0.00128698	17.0715			16.475
115215	115	215	20.00	0.46	20	3.033150178	27	0.017037037	0.0191	0.527793692	4222.349535	0.000642588	13.3184			10.88
111811	111	811	20.00	0.46	0	0	43	0.010697674	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
811121	811	121	20.00	0.46	0	0	43	0.010697674	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
112812	112	812	20.00	0.46	0	0	39	0.011794872	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
812122	812	122	20.00	0.46	0	0	39	0.011794872	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
113813	113	813	20.00	0.46	0	0	35	0.013142857	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
813123	813	123	20.00	0.46	0	0	35	0.013142857	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
114814	114	814	20.00	0.46	0	0	31	0.01483871	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
814124	814	124	20.00	0.46	0	0	31	0.01483871	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
115135	115	135	20.00	0.46	0	0	27	0.017037037	0.0191	0.527793692	4222.349535	0.000642588	13.3184			10.88
125135	125	135	20.00	0.46	0	0	27	0.017037037	0.0191	0.527793692	4222.349535	0.000642588	13.3184			10.88
211821	211	821	20.00	0.46	0	0	43	0.010697674	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
821221	821	221	20.00	0.46	0	0	43	0.010697674	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
212822	212	822	20.00	0.46	0	0	39	0.011794872	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88
822222	822	222	20.00	0.46	0	0	39	0.011794872	0.0128	0.35965958	2877.276641	0.000449915	9.3250			10.88

213823	213	823	20.00	0.46	0	0	35	0.013142857	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
823223	823	223	20.00	0.46	0	0	35	0.013142857	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
214824	214	824	20.00	0.46	0	0	31	0.01483871	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
824224	824	224	20.00	0.46	0	0	31	0.01483871	0.0159	0.442994998	3543.959987	0.000546819	11.3335			10.88
215235	215	235	20.00	0.46	0	0	27	0.017037037	0.0191	0.527793692	4222.349535	0.000642588	13.3184			10.88
235225	235	225	20.00	0.46	0	0	27	0.017037037	0.0191	0.527793692	4222.349535	0.000642588	13.3184			10.88
																0
																0
Beams (diagonal)	**point 1**	**point 2**	**length [m]**	**D (prediction) [m]**	**Dde**	**Die**	**D/t**	**t (prediction) [m]**	**0.003175**	**Volume steel**	**dry weight [kg]**	**I [m^4]**	**Bucking Load [MN]**	**Load carried**		
ZX-plane							*t min 0.5inch*	*0.0127*	*0.003175*							0
131111	131	111	27.27	0.8182	0.379053301	0.675401607	42	0.0195	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
131112	131	112	27.27	0.8182	0.379053301	0.675401607	40	0.0205	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
131122	131	122	27.27	0.8182	0.379053301	0.675401607	40	0.0205	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
131121	131	121	27.27	0.8182	0.379053301	0.675401607	42	0.0195	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
																0
132112	132	112	27.27	0.8182	0.379053301	0.675401607	38	0.0215	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
132113	132	113	27.27	0.8182	0.379053301	0.675401607	36	0.0227	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
132123	132	123	27.27	0.8182	0.379053301	0.675401607	36	0.0227	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
132122	132	122	27.27	0.8182	0.379053301	0.675401607	38	0.0215	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
																0
133113	133	113	27.27	0.8182	0.379053301	0.675401607	34	0.0241	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
133114	133	114	27.27	0.8182	0.379053301	0.675401607	32	0.0256	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
133124	133	124	27.27	0.8182	0.379053301	0.675401607	32	0.0256	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
133123	133	123	27.27	0.8182	0.379053301	0.675401607	34	0.0241	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
																0
134114	134	114	27.27	0.8182	0.379053301	0.675401607	30	0.0273	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
134115	134	115	27.27	0.8182	0.379053301	0.675401607	28	0.0292	0.0318	2.139388758	17115.11007	0.006074409	67.7048			24.6053008
134125	134	125	27.27	0.8182	0.379053301	0.675401607	28	0.0292	0.0318	2.139388758	17115.11007	0.006074409	67.7048			24.6053008
134124	134	124	27.27	0.8182	0.379053301	0.675401607	30	0.0273	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
																0

231211	231	211	27.27	0.8182	0.379053301	0.675401607	42	0.0195	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
231212	231	212	27.27	0.8182	0.379053301	0.675401607	40	0.0205	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
231222	231	222	27.27	0.8182	0.379053301	0.675401607	40	0.0205	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
231221	231	221	27.27	0.8182	0.379053301	0.675401607	42	0.0195	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
																0
232212	232	212	27.27	0.8182	0.379053301	0.675401607	38	0.0215	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
232213	232	213	27.27	0.8182	0.379053301	0.675401607	36	0.0227	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
232223	232	223	27.27	0.8182	0.379053301	0.675401607	36	0.0227	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
232222	232	222	27.27	0.8182	0.379053301	0.675401607	38	0.0215	0.0222	1.515710088	12125.6807	0.004404721	49.0946			24.6053008
																0
233213	233	213	27.27	0.8182	0.379053301	0.675401607	34	0.0241	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
233214	233	214	27.27	0.8182	0.379053301	0.675401607	32	0.0256	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
233224	233	224	27.27	0.8182	0.379053301	0.675401607	32	0.0256	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
233223	233	223	27.27	0.8182	0.379053301	0.675401607	34	0.0241	0.0254	1.725330402	13802.64322	0.004975194	55.4531			24.6053008
																0
234214	234	214	27.27	0.8182	0.379053301	0.675401607	30	0.0273	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
234215	234	215	27.27	0.8182	0.379053301	0.675401607	28	0.0292	0.0318	2.139388758	17115.11007	0.006074409	67.7048			24.6053008
234225	234	225	27.27	0.8182	0.379053301	0.675401607	28	0.0292	0.0318	2.139388758	17115.11007	0.006074409	67.7048			24.6053008
234224	234	224	27.27	0.8182	0.379053301	0.675401607	30	0.0273	0.0286	1.933223292	15465.78634	0.00553168	61.6556			24.6053008
																0
																0
Beams (diagonal)	point 1	point 2	length [m]	D (prediction) [m]	Dde	Die	D/t	t (prediction) [m]	0.003175	Volume steel	dry weight [kg]	I [m^4]	Bucking Load [MN]	Load carried		#VALUE!
ZY-plane																0
331111	331	111	28.10	0.8429	1.200108108	1.005763114	42	0.0201	0.0222	1.609931799	12879.45439	0.004827455	50.6988			26.04222608
331112	331	112	24.58	0.7375	1.050094595	0.880042725	40	0.0184	0.0191	1.057101667	8456.813335	0.002776529	38.0860			20.19671448
331212	331	212	24.58	0.7375	1.050094595	0.880042725	40	0.0184	0.0191	1.057101667	8456.813335	0.002776529	38.0860			20.19671448
331211	331	211	28.10	0.8429	1.200108108	1.005763114	42	0.0201	0.0222	1.609931799	12879.45439	0.004827455	50.6988			26.04222608
332112	332	112	26.44	0.7932	1.058156371	0.916170787	38	0.0209	0.0222	1.423425104	11387.40083	0.004003557	47.4746			23.19523485
332113	332	113	22.81	0.6842	0.908288536	0.788306213	36	0.0190	0.0191	0.907803325	7262.426598	0.002203014	35.1161			17.51878448

332213	332	213	22.81	0.6842	0.908288536	0.788306213	36	0.0190	0.0191	0.907803325	7262.426598	0.002203014	35.1161			17.51878448
332212	332	212	26.44	0.7932	1.058156371	0.916170787	38	0.0209	0.0222	1.423425104	11387.40083	0.004003557	47.4746			23.19523485
333113	333	113	24.94	0.7482	0.936495396	0.837044702	34	0.0220	0.0222	1.264028497	10112.22798	0.003341897	44.5483			20.75270418
333114	333	114	21.16	0.6349	0.786800936	0.70677531	32	0.0198	0.0222	0.905296193	7242.369544	0.002009741	37.2020			15.21382854
333214	333	214	21.16	0.6349	0.786800936	0.70677531	32	0.0198	0.0222	0.905296193	7242.369544	0.002009741	37.2020			15.21382854
333213	333	213	24.94	0.7482	0.936495396	0.837044702	34	0.0220	0.0222	1.264028497	10112.22798	0.003341897	44.5483			20.75270418
334114	334	114	23.62	0.7086	0.835137734	0.769276299	30	0.0236	0.0254	1.287722971	10301.78377	0.003185327	47.3328			18.72165698
334115	334	115	19.69	0.5906	0.685654177	0.636363043	28	0.0211	0.0222	0.781307339	6250.458709	0.001605112	34.3334			13.28127523
334215	334	215	19.69	0.5906	0.685654177	0.636363043	28	0.0211	0.0222	0.781307339	6250.458709	0.001605112	34.3334			13.28127523
334214	334	214	23.62	0.7086	0.835137734	0.769276299	30	0.0236	0.0254	1.287722971	10301.78377	0.003185327	47.3328			18.72165698
431121	431	121	28.10	0.8429	1.200108108	1.005763114	42	0.0201	0.0222	1.609931799	12879.45439	0.004827455	50.6988			26.04222608
431122	431	122	24.58	0.7375	1.050094595	0.880042725	40	0.0184	0.0191	1.057101667	8456.813335	0.002776529	38.0860			20.19671448
431222	431	222	24.58	0.7375	1.050094595	0.880042725	40	0.0184	0.0191	1.057101667	8456.813335	0.002776529	38.0860			20.19671448
431221	431	221	28.10	0.8429	1.200108108	1.005763114	42	0.0201	0.0222	1.609931799	12879.45439	0.004827455	50.6988			26.04222608
432122	432	122	26.44	0.7932	1.058156371	0.916170787	38	0.0209	0.0222	1.423425104	11387.40083	0.004003557	47.4746			23.19523485
432123	432	123	22.81	0.6842	0.908288536	0.788306213	36	0.0190	0.0191	0.907803325	7262.426598	0.002203014	35.1161			17.51878448
432223	432	223	22.81	0.6842	0.908288536	0.788306213	36	0.0190	0.0191	0.907803325	7262.426598	0.002203014	35.1161			17.51878448
432222	432	222	26.44	0.7932	1.058156371	0.916170787	38	0.0209	0.0222	1.423425104	11387.40083	0.004003557	47.4746			23.19523485
433123	433	123	24.94	0.7482	0.936495396	0.837044702	34	0.0220	0.0222	1.264028497	10112.22798	0.003341897	44.5483			20.75270418
433124	433	124	21.16	0.6349	0.786800936	0.70677531	32	0.0198	0.0222	0.905296193	7242.369544	0.002009741	37.2020			15.21382854
433224	433	224	21.16	0.6349	0.786800936	0.70677531	32	0.0198	0.0222	0.905296193	7242.369544	0.002009741	37.2020			15.21382854
433223	433	223	24.94	0.7482	0.936495396	0.837044702	34	0.0220	0.0222	1.264028497	10112.22798	0.003341897	44.5483			20.75270418
434124	434	124	23.62	0.7086	0.835137734	0.769276299	30	0.0236	0.0254	1.287722971	10301.78377	0.003185327	47.3328			18.72165698
434125	434	125	19.69	0.5906	0.685654177	0.636363043	28	0.0211	0.0222	0.781307339	6250.458709	0.001605112	34.3334			13.28127523

434225	434	225	19.69	0.5906	0.685654177	0.636363043	28	0.0211	0.0222	0.781307339	6250.458709	0.001605112	34.3334			13.28127523
434224	434	224	23.62	0.7086	0.835137734	0.769276299	30	0.0236	0.0254	1.287722971	10301.78377	0.003185327	47.3328			18.72165698
																0
																0
Beams (Riser support frame)	point 1	point 2	length [m]	D (prediction) [m]	Dde	Die	D/t	t (prediction) [m]	0.003175	Volume steel	dry weight [kg]	I [m^4]	Bucking Load [MN]	Load carried		#VALUE!
																0
1119111	111	9111	23.16	0.5328	7.633779849	2.426520142	40	0.0133	0.0159	0.597137402	4777.099218	0.000861757	13.3151			14.28669828
2119211	211	9211	23.16	0.5328	7.633779849	2.426520142	40	0.0133	0.0159	0.597137402	4777.099218	0.000861757	13.3151			14.28669828
2219221	221	9221	23.16	0.5328	7.633779849	2.426520142	40	0.0133	0.0159	0.597137402	4777.099218	0.000861757	13.3151			14.28669828
1219121	121	9121	23.16	0.5328	7.633779849	2.426520142	40	0.0133	0.0159	0.597137402	4777.099218	0.000861757	13.3151			14.28669828
91119211	9111	9211	8.00	0.1840	8	1.213260071	40	0.0046	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
92118211	9211	8211	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008	1.24609E-06	0.9781			0.5159375
82119221	8211	9221	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008					0.5159375
92219121	9221	9121	8.00	0.1840	8	1.213260071	40	0.0046	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
91218111	9121	8111	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008	1.24609E-06	0.9781			0.5159375
81119111	8111	9111	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008					0.5159375
8218211	821	8211	16.00	0.3680	16	2.426520142	40	0.0092	0.0128	0.228535032	1828.280255	0.000225555	7.3045			7.232
8111811	8111	811	16.00	0.3680	16	2.426520142	40	0.0092	0.0128	0.228535032	1828.280255	0.000225555	7.3045			7.232
1129112	112	9112	21.51	0.4948	5.316137745	2.04737637	40	0.0124	0.0128	0.416975102	3335.800819	0.000563273	10.0900			12.451786
2129212	212	9212	21.51	0.4948	5.316137745	2.04737637	40	0.0124	0.0128	0.416975102	3335.800819	0.000563273	10.0900			12.451786
2229222	222	9222	21.51	0.4948	5.316137745	2.04737637	40	0.0124	0.0128	0.416975102	3335.800819	0.000563273	10.0900			12.451786
1229122	122	9122	21.51	0.4948	5.316137745	2.04737637	40	0.0124	0.0128	0.416975102	3335.800819	0.000563273	10.0900			12.451786
91128121	9112	8121	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008	1.24609E-06	0.9781			0.5159375
81219122	8121	9122	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008					0.5159375
91229222	9122	9222	8.00	0.1840	8	1.213260071	40	0.0046	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
92228221	9222	8221	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008	1.24609E-06	0.9781			0.5159375
82219212	8221	9212	3.25	0.0748	0	0	40	0.0019	0.0128	0.008096261	64.77009008					0.5159375
91129212	9112	9212	8.00	0.1840	8	1.213260071	40	0.0046	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
8228221	822	8221	13.50	0.3105	13.5	2.04737637	40	0.0078	0.0128	0.161611569	1292.892549	0.000132864	6.0439			5.32575

8121812	8121	812	13.50	0.3105	13.5	2.04737637	40	0.0078	0.0128	0.161611569	1292.892549	0.000132864	6.0439			5.32575
1139113	113	9113	20.04	0.4609	3.314552529	1.668232598	40	0.0115	0.0128	0.361084626	2888.677009	0.000452628	9.3448			10.91921555
2139213	213	9213	20.04	0.4609	3.314552529	1.668232598	40	0.0115	0.0128	0.361084626	2888.677009	0.000452628	9.3448			10.91921555
2239223	223	9223	20.04	0.4609	3.314552529	1.668232598	40	0.0115	0.0128	0.361084626	2888.677009	0.000452628	9.3448			10.91921555
1239123	123	9123	20.04	0.4609	3.314552529	1.668232598	40	0.0115	0.0128	0.361084626	2888.677009	0.000452628	9.3448			10.91921555
91139213	9113	9213	8.00	0.1840	8	1.213260071	40	0.0046	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
92139223	9213	9223	6.50	0.1495	0	0	40	0.0037	0.0128	0.035730716	285.8457244	1.29529E-05	2.5417			1.51775
92239123	9223	9123	8.00	0.1840	8	1.213260071	40	0.0046	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
91239113	9123	9113	6.50	0.1495	0	0	40	0.0037	0.0128	0.035730716	285.8457244	1.29529E-05	2.5417			1.51775
8239213	823	9213	11.47	0.2638	10.11686461	1.668232598	40	0.0066	0.0128	0.115776309	926.2104728	7.97038E-05	5.0226			3.989423359
8239223	823	9223	11.47	0.2638	10.11686461	1.668232598	40	0.0066	0.0128	0.115776309	926.2104728	7.97038E-05	5.0226			3.989423359
8139113	813	9113	11.47	0.2638	10.11686461	1.668232598	40	0.0066	0.0128	0.115776309	926.2104728	7.97038E-05	5.0226			3.989423359
8139123	813	9123	11.47	0.2638	10.11686461	1.668232598	40	0.0066	0.0128	0.115776309	926.2104728	7.97038E-05	5.0226			3.989423359
114834	114	834	17.81	0.4097	6.15602035	1.895718861	40	0.0102	0.0128	0.284270674	2274.165393	0.000314552	8.2194			8.793442484
8349214	834	9214	5.70	0.1311	1.969926512	0.606630036	41	0.0032	0.0128	0.027114313	216.9145069	8.41872E-06	2.1483			1.226025103
214834	214	834	17.81	0.4097	6.15602035	1.895718861	42	0.0098	0.0128	0.284270674	2274.165393	0.000314552	8.2194			8.793442484
8349114	834	9114	5.70	0.1311	1.969926512	0.606630036	43	0.0030	0.0128	0.027114313	216.9145069	8.41872E-06	2.1483			1.226025103
224844	224	844	17.81	0.4097	6.15602035	1.895718861	44	0.0093	0.0128	0.284270674	2274.165393	0.000314552	8.2194			8.793442484
8449124	844	9124	5.70	0.1311	1.969926512	0.606630036	45	0.0029	0.0128	0.027114313	216.9145069	8.41872E-06	2.1483			1.226025103
124844	124	844	17.81	0.4097	6.15602035	1.895718861	46	0.0089	0.0128	0.284270674	2274.165393	0.000314552	8.2194			8.793442484
8449224	844	9224	5.70	0.1311	1.969926512	0.606630036	47	0.0028	0.0128	0.027114313	216.9145069	8.41872E-06	2.1483			1.226025103
91149214	9114	9214	8.00	0.1840	8	1.213260071	48	0.0038	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
92149224	9214	9224	6.50	0.1495	0	0	49	0.0031	0.0128	0.035730716	285.8457244	1.29529E-05	2.5417			1.51775
92249124	9224	9124	8.00	0.1840	8	1.213260071	50	0.0037	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
91249114	9124	9114	6.50	0.1495	0	0	51	0.0029	0.0128	0.035730716	285.8457244	1.29529E-05	2.5417			1.51775
8249214	824	9214	9.10	0.2093	7.415849057	1.289088825	52	0.0040	0.0128	0.071908019	575.2641558	3.83016E-05	3.8344			2.669099038
8249224	824	9224	9.10	0.2093	7.415849057	1.289088825	53	0.0039	0.0128	0.071908019	575.2641558	3.83016E-05	3.8344			2.669099038
8149114	814	9114	9.10	0.2093	7.415849057	1.289088825	54	0.0039	0.0128	0.071908019	575.2641558	3.83016E-05	3.8344			2.669099038

8149124	814	9124	9.10	0.2093	7.415849057	1.289088825	55	0.0038	0.0128	0.071908019	575.2641558	3.83016E-05	3.8344			2.669099038
115835	115	835	15.59	0.3586	4.112786885	1.516575089	57	0.0063	0.0128	0.216854284	1734.834273	0.000208206	7.0992			6.902133741
8359215	835	9215	6.24	0.1435	1.645114754	0.606630036	58	0.0025	0.0128	0.032770434	262.163473	1.1319E-05	2.4122			1.418697884
215835	215	835	15.59	0.3586	4.112786885	1.516575089	59	0.0061	0.0128	0.216854284	1734.834273	0.000208206	7.0992			6.902133741
8359115	835	9115	6.24	0.1435	1.645114754	0.606630036	60	0.0024	0.0128	0.032770434	262.163473	1.1319E-05	2.4122			1.418697884
225845	225	845	15.59	0.3586	4.112786885	1.516575089	61	0.0059	0.0128	0.216854284	1734.834273	0.000208206	7.0992			6.902133741
8459125	845	9125	6.24	0.1435	1.645114754	0.606630036	62	0.0023	0.0128	0.032770434	262.163473	1.1319E-05	2.4122			1.418697884
125845	125	845	15.59	0.3586	4.112786885	1.516575089	63	0.0057	0.0128	0.216854284	1734.834273	0.000208206	7.0992			6.902133741
8459225	845	9225	6.24	0.1435	1.645114754	0.606630036	64	0.0022	0.0128	0.032770434	262.163473	1.1319E-05	2.4122			1.418697884
91159215	9115	9215	8.00	0.1840	8	1.213260071	65	0.0028	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
92159225	9215	9225	6.50	0.1495	0	0	66	0.0023	0.0128	0.035730716	285.8457244	1.29529E-05	2.5417			1.51775
92259125	9225	9125	8.00	0.1840	8	1.213260071	67	0.0027	0.0128	0.055074884	440.5990706	2.53631E-05	3.2855			2.144
91259115	9125	9115	6.50	0.1495	0	0	68	0.0022	0.0128	0.035730716	285.8457244	1.29529E-05	2.5417			1.51775
8259215	825	9215	6.82	0.1569	4.638926174	0.909945053	69	0.0023	0.0128	0.039552682	316.4214527	1.51731E-05	2.7016			1.644125951
8259225	825	9225	6.82	0.1569	4.638926174	0.909945053	70	0.0022	0.0128	0.039552682	316.4214527	1.51731E-05	2.7016			1.644125951
8159115	815	9115	6.82	0.1569	4.638926174	0.909945053	71	0.0022	0.0128	0.039552682	316.4214527	1.51731E-05	2.7016			1.644125951
8159125	815	9125	6.82	0.1569	4.638926174	0.909945053	72	0.0022	0.0128	0.039552682	316.4214527	1.51731E-05	2.7016			1.644125951
																0
Conductors	9111	9112	37.00	0.61	0.6096	0.6096										25.6632
x12	9112	9113	37.00	0.61	0.6096	0.6096										25.6632
	9113	9114	37.00	0.61	0.6096	0.6096										25.6632
	9114	9115	37.00	0.61	0.6096	0.6096										25.6632

Table 12-1: Preliminary dimensions substructure

A preliminary check was done on the buckling of the legs. On the first page of the Table 12-1 (in red) the loads in the legs are calculated. This preliminary check on the leg dimensions shows that statically (weight of the topsides acting on the substructure) will not buckle the legs. UC show values smaller than 1. This means the legs could be dimensioned slimmer with respect to failing on buckling. Multiple failure mechanisms must be investigated before re-dimensioning.

$$F_{buckle} = \frac{2 \cdot \pi \cdot E \cdot I}{L^2}$$

Item	% Weight
Deck structure	5.0
Helideck	1.5
Living quarter	3.5
Topside equipment and facilities	60.0
Drilling rig	12.0
Hook load	6.0
Jacket support structure	12.0
Total Payload	**100**

Table 12-2: Distribution hand book offshore

Appendix E Suction anchor seizing – Iterative process

The total procedure vs the simplifications used for this research.

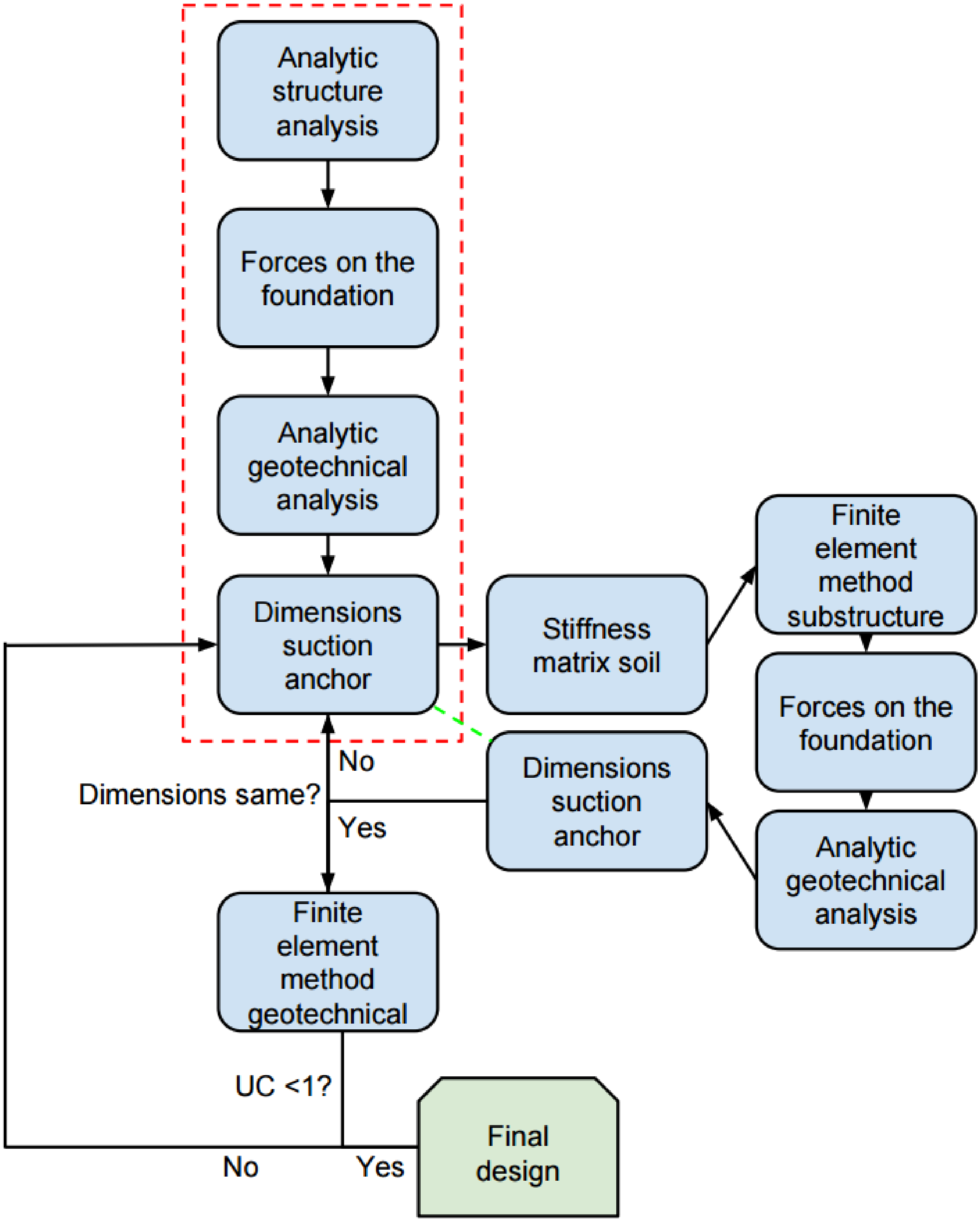

Figure 12-9: Total suction anchor procedure

In Figure 12-9 the total procedure of the seizing of a suction anchor is shown. The blocks in the vertical axis are the main steps. The dimensioning is a iterative process that might need a couple of loops. These are the blocks on the right. Starting at the top:
“Analytic structure analysis” is done to see what forces act on the structure. This will lead to the forces the foundation has to deal with, “Forces on the foundation”. With the “Analytic geotechnical analysis”

the soil properties will be used to gain insight in the bearing capacity of the soil. From the forces and the bearing capacity the “Dimensions of the suction anchor” can be calculated.
When the dimensions are known a “Stiffness matrix of the soil” is needed. Every layer of the soil will have a capacity. The stiffness matrix represents the soil with the suction anchor in-place. Now the forces and moments that the soil has to deal with can be calculated. A “Finite element method for the substructure” can be made to see how the substructure will react to the soil. Again “Forces on the foundation” will be calculated (differing from the earlier values due to the incorporated soil parameters and the structural analysis). A “Analytic geotechnical analysis” will be done with these new forces to gain new “Dimensions for the suction anchors”.
This is the first loop. The green dotted line connects the blocks of the dimensions. If these are the same or lay within limits, a finite element method for the soil (“Finite element method geotechnical”) can be made. If the dimensions are not the loop needs to be repeated, till the values match. Until now the layered soil is simplified but a layered soil can be modelled in this finite element method. From the geotechnical finite element method a Unity Check will show if the capacity is sufficient. When it is sufficient the “Final design” is obtained. If not, the dimensions must be adjusted again.

Appendix F Brainstorm session

The results of the brainstorm executed for this research are shown in this appendix.

- *Jacket with bucket*: this is a normal jacket but the lower part of the jacket is an empty bin. After placement the bin can be filled with a material heavy enough to let the structure be gravity based. (So external foundation is not necessary)

Figure 12-10: Brainstorm session result, Jacket with bucket

- *Schuif 's an*: This concept was focussed on saving time on the installation of the foundation without extremely enlarging the strength at the bottom of the structure. When the foundation (gravity-based) is pre-installed, there will be a lot of weight at the bottom of the tower. For transportation and up ending of the structure a big ballast at the bottom is not convenient. With this variant the foundation is equally distributed over the height of the structure on a rail. When the structure is in place, the gravity based foundation is rolled down over the rail. (partly based on: http://www.monobasewind.com/)

Figure 12-11: Brainstorm session result, Schuif's an

- *Tension under pressure*: This platform will be making use of suction anchors at the bottom of the structure. The broad base will make sure that the overturning moment is taken care of. The relative slim upper section of the substructure will be strengthened with cables to save a lot of weight. Like the "*Suck it up"* the pumps can be installed above the waterline.

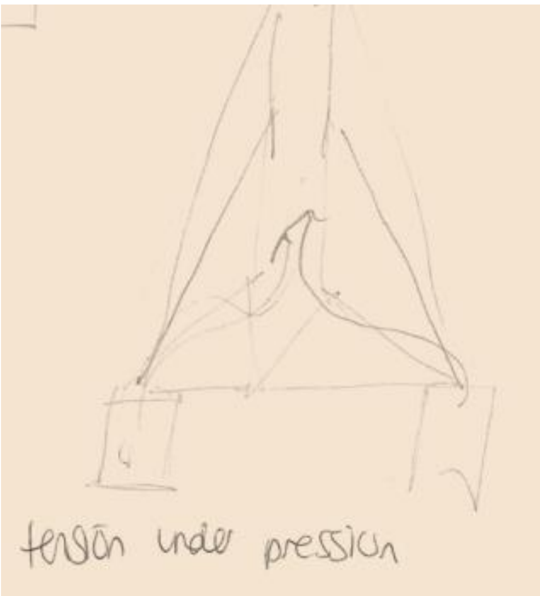

Figure 12-12: Brainstorm session result, Tension under pressure

- *Triangles*; One of the most rigid shapes is the triangle. This time the whole substructure is built up of triangles. This way the horizontal transport is also easier to realize. Probably the base will be very wide, which isn't always preferred.


Figure 12-13: Brainstorm session result, Triangles

- *Cone/cylinder*; It is all in the name. Cylinders or circles are strong shapes. On this principal the below substructure is designed. The way of transporting on a barge or on the JLS is also shown below. In the main picture there are two different basic shapes depicted, a cylinder and a cone. Circular pipe segments may be quite expensive.

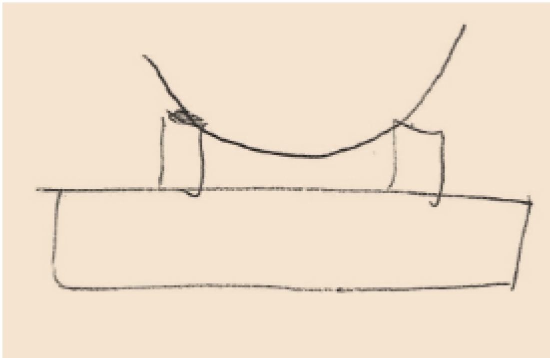

Figure 12-14: Brainstorm session result, Cone/cylinder

- *Hexagonal*; The Hexagonal is based on the Cylinder but no bended pipe sections are used. Due to the large slot of the PS this may be an option. If the base needs to be bigger the “Milk bottle can be used in combination with the Hexagonal. (See below)

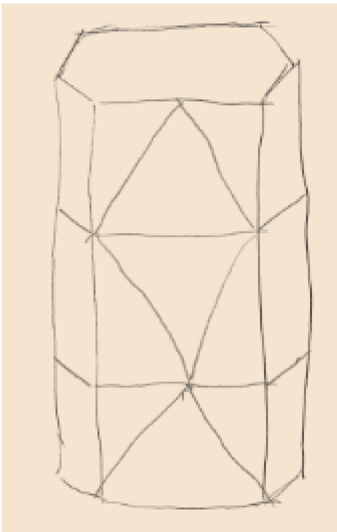

Figure 12-15: Brainstorm session result, Hexagonal

Appendix G Scatter diagrams

From met-ocean data wave scatter diagrams are obtained. There will be three scenarios that will be looked at: Year round, Worst case (December) and Low case (May). In Table 12-3 the percentage occurrence of significant wave height and mean zero-crossing period is given for year-round scenario.

All- year		Tz									
Hs		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10
0	0.5				11.614	3.017	0.044	0.002			
0.5	1				10.32	22.009	4.526	0.264	0.01	0.002	
1	1.5				0.103	13.279	9.204	2.113	0.175	0.007	0.002
1.5	2					2.8	7.586	2.271	0.785	0.087	0.003
2	2.5					0.005	3.922	1.547	0.645	0.181	0.007
2.5	3						0.714	1.16	0.255	0.164	0.062
3	3.5						0.056	0.53	0.113	0.05	0.041
3.5	4							0.12	0.06	0.024	0.005
4	4.5							0.026	0.048	0.015	
4.5	5							0.007	0.007	0.009	
5	5.5							0.002	0.002		
5.5	6								0.002		
		Total			3-6	Tz [s]					
		100.002		0-2	84.502	%					
				Hs [m]							

Table 12-3: Scatter year-round [source (Allseas, 2014))

The box in yellow shows the waves between three and six seconds and with a significant wave-height between zero and two meters. 84% of all the waves fall within this widow. Designing the suction anchor (and their reinforcements) for these sea-states will result in a workability of 84%. For the South China Sea the Pierson Moskowitch spectrum is used. (CHU, 2004)

The model used for calculating the accelerations use the following parameters:

$$\frac{z_a}{\zeta_a}(\omega): RAO\ PS$$

$$S_\zeta(\omega) : Wave\ spectrum\ Pierson\ Moskowitz\ (T_p, H_s)$$

$$S_{PS\ acceleration}(\omega) = S_{PS}(\omega) \cdot \omega^2$$

$$m_0 = \int_0^\infty S_{PS\ acceleration}(\omega) \cdot d\omega$$

$$n = \frac{T_{operation}}{T_p}$$

$$Most\ probable\ maximum\ acceleration\ PS = \sqrt{2 \cdot m_0 \cdot \log(n)}$$

The most probable maximum acceleration of the PS is used in the report. The wave data is of the one in 10 years wave.

This appendix gives an overview of the different procedures developed for installation with PS. The comparison between the conventional way and the new developed procedures is correctly done when using equivalent numbers to quantify the cost and duration of each sub-procedure.
The numbers are sown in Table 12-4.

Conventional		
	Vessel	**Day rates [$/day]**
	Crane vessel	400,000
	Barge	10,000
	Tug	15,000
	Support vessel	100,000
	Semisub dry dock	300,000
	Lanch barge	30,000

Table 12-4: Conventional numbers used

These numbers leads to the following cost for the conventional procedure.

KBB		duration [days]	Cost [$]
Launch barge	Mobilisation of jacket barge	7.0	210,000
Launch barge	Load out jacket on barge	1.0	60,000
Launch barge	Sail barge to installation location	7.6	458,333
Launch barge	Lanch jacket	0.25	15,000
Crane vessel	Mobilization of crane vessel	7	2,800,000
Crane vessel	Install jacket	1	400,000
Foundation barge	Mobilization foundation barge	7	70,000
Foundation barge	Sail to install location	5.6	222,222
Foundation barge and crane vessel	Install 12 piles	18	7,920,000
Crane vessel	Horizontally level the legs	1	400,000
Boatlanding barge	Mobilise boatlanding barge	7	70,000
Boatlanding barge	Sail to install location	5.6	222,222.22
Crane vessel and boatlanding barge	Install boatlading	0.5	200,000
Boatlanding barge	Demobilise boatlanding barge	7	70,000
Crane vessel	Demobilise Crane vessel	7	2,800,000
Semisub dry dock	Mobilise semisub	7	2,100,000
Semisub dry dock	Load out topsides on semisub	1	300,000
Semisub dry dock	Sail to float-over location	2.8	916,666.67
Semisub dry dock	Float-over	2	660,000
Semisub dry dock	Demobilise Semisub	7	2,100,000
KBB		Duration [days]	Cost [$]
	Total installation time and cost	**31.4**	**21,990,000**

Table 12-5: Conventional

The new developed procedures use the numbers mentioned in .

Vessel		**Day rates [$/day]**
PS		1,000,000
Barge		10,000
Tug		15,000
Support vessel		100,000

Table 12-6: Numbers PS procedures

For the difference between mobilization for one project and multiple projects, a 5 day mobilization and 5 day demobilization period will be used for comparison. (10 days extra)

Safe haven		**No extra mobilization costs**		**With extra mobilization costs**	
		duration [days]	Cost [$]	duration [days]	Cost [$]
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
Jacket barge	Sail barge to safe haven	7.6	305,555.56	7.6	305,555.56
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Jacket barge and PS	Load jacket from barge on PS	1.5	1,560,000	1.5	1,560,000
Jacket barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	PS sail to install location	0.5	500,000	0.5	500,000
PS	Install substructure	1.0	1,000,000	1.0	1,000,000
PS	Install foundation	1.0	1,000,000	1.0	1,000,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge	Sail barge to safe haven	5.6	222,222.22	5.6	222,222.22
PS	PS sail to safe haven	0.5	500,000	0.5	500,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	-
PS	Sail to location	0.5	500,000	0.5	500,000
PS	Install topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
Safe haven		Duration [days]	Cost [$]	Duration [days]	Cost [$]
	Total installation time and cost	**16.5**	**12,820,000**	**16.5**	**22,750,000**

Table 12-7: Safe haven, calculation

Safe haven for topsides, jacket from yard					
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Jacket barge and PS	Load jacket from barge on PS	1.5	1,560,000	1.5	1,560,000
Jacket barge	Demobilise barge	7.0	280,000	7.0	280,000
PS	PS sail to install location	3.9	3,884,181	3.9	3,884,181
PS	Install jacket	1.0	1,000,000	1.0	1,000,000
PS	Install foundation	1.0	1,000,000	1.0	1,000,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge	Sail barge to safe haven	5.6	222,222.22	5.6	222,222.22
PS	Sail to safe haven	0.5	500,000	0.5	500,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Sail to location	0.5	500,000	0.5	500,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
Safe haven for topside, jacket from yard		Duration [days]	Cost [$]	Duration [days]	Cost [$]
	Total installation time and cost	**12.2**	**16,110,000**	**12.2**	**26,110,000**

Table 12-8: Safe haven for topsides, jacket from yard

No safe haven, both on PS		**duration [days]**	**Cost [$]**	**duration [days]**	**Cost [$]**
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Jacket barge and PS	Load jacket from barge on PS	1.5	1,560,000	1.5	1,560,000
Jacket barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	PS sail to topside yard	1.1	1,059,322.03	1.1	1,059,322.03
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	PS sail to install location	2.8	2,824,858.76	2.8	2,824,858.76
PS	Install jacket	1.0	1,000,000	1.0	1,000,000
PS	Install foundation	1.0	1,000,000	1.0	1,000,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
No safe haven, both on PS		Duration [days]	Cost [$]	Duration [days]	Cost [$]
Total installation time and cost		**11.2**	**14,680,000**	**11.2**	**24,680,000**

Table 12-9: Both the topsides and the substructure will put on PS in at the yard

PS with conventional piles					
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Jacket barge and PS	Load jacket from barge on PS	1.5	1,560,000	1.5	1,560,000
Jacket barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	PS sail to install location	3.9	3,884,181	3.9	3,884,181
PS	Install jacket	1.0	1,000,000	1.0	1,000,000
Foundation barge	Mobilization foundation barge	7	70,000	7	70,000
Foundation barge	Sail foundation barge to install location	5.6	222,222.22	5.6	222,222.22
PS with foundation barge	Install foundation	18.0	18,180,000	18.0	18,180,000
Foundation barge	Demobilise foundation barge	7	70,000	7	70,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge	Sail barge to safe haven	5.6	222,222.22	5.6	222,222.22
PS	Sail to safe haven	0.5	500,000	0.5	500,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Sail to location	0.5	500,000	0.5	500,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
PS with conventional piles		Duration [days]	Cost [$]	Duration [days]	Cost [$]
	Total installation time and cost	**29.2**	**33,440,000**	**29.2**	**43,440,000**

Table 12-10: Safe haven and skirt piles by PS

PS with conventional launch barge, foundation install by PS, topside safe haven					
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
Jacket barge	Sail launch barge to install location	7.6	305,555.56	7.6	305,555.56
Jacket barge	Launch jacket	0.3	10,000	0.3	10,000
Jacket barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge	Sail barge to safe haven	5.6	222,222.22	5.6	222,222.22
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Sail to location	0.5	500,000	0.5	500,000
PS	Install jacket	0.4	400,000	0.4	400,000
Foundation barge	Mobilization foundation barge	7	70,000	7	70,000
Foundation barge	Sail to install location	5.6	222,222	5.6	222,222
Foundation barge and PS	Install 12 piles	18	18,180,000	18	18,180,000
Foundation barge	Demobilise foundation barge	7	70,000	7	70,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
Boatlanding barge	Mobilise boatlanding barge	7	70,000	7	70,000
Boatlanding barge	Sail to install location	5.6	222,222	5.6	222,222
PS and boatlanding barge	Install boatlading	0.5	500,000	0.5	500,000
Boatlanding barge	Demobilise boatlanding barge	7	70,000	7	70,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
Total installation time and cost		**29.6**	**27,310,000**	**29.6**	**38,080,000**

Table 12-11: Launch barge, suction anchor, topsides safe haven

PS with conventional launch barge, topside at yard					
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
Jacket barge	Sail launch barge to install location	7.6	305,555.56	7.6	305,555.56
Jacket barge and PS	Launch jacket	0.3	10,000	0.3	10,000
Jacket barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Sail to location	2.8	2,824,859	2.8	2,824,859
PS	Install jacket	0.4	400,000	0.4	400,000
Foundation barge	Mobilization foundation barge	7	70,000	7	70,000
Foundation barge	Sail to install location	5.6	222,222.22	5.6	222,222.22
PS with foundation barge	Install foundation	18.0	18,000,000	18.0	18,000,000
Foundation barge	Demobilise foundation barge	7	70,000	7	70,000
Boatlanding barge	Mobilise boatlanding barge	7	70,000	7	70,000
Boatlanding barge	Sail to install location	7.0	280,000.00	7.0	280,000.00
PS and boatlanding barge	Install boatlading	0.5	505,000	0.5	505,000
Boatlanding barge	Demobilise boatlanding barge	7	70,000	7	70,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
PS with conventional launch barge, topside at yard		Duration [days]	Cost [$]	Duration [days]	Cost [$]
Total installation time and cost		**29.6**	**30,060,000**	**29.6**	**40,060,000**

Table 12-12: Launch barge, topsides at yard

PS with conventional launch barge, foundation install by crane vessel topside safe haven					
Launch barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Launch barge	Load out jacket on barge	1.0	40,000	1.0	40,000
Launch barge	Sail barge to installation location	7.6	304,000	7.6	304,000
Launch barge	Lanch jacket	0.25	10,000	0.25	10,000
Crane vessel	Mobilization of crane vessel	7	2,800,000	7	2,800,000
Crane vessel	Install jacket	1	400,000	1	400,000
Foundation barge	Mobilization foundation barge	7	70,000	7	70,000
Foundation barge	Sail to install location	5.6	222,222.22	5.6	222,222.22
Foundation barge and crane vessel	Install 12 piles	18	7,920,000	18	7,920,000
Crane vessel	Horizontally level the legs	1	400,000	1	400,000
Boatlanding barge	Mobilise boatlanding barge	7	70,000	7	70,000
Boatlanding barge	Sail to install location	5.6	222,222.22	5.6	222,222.22
Crane vessel and boatlanding barge	Install boatlading	0.5	205,000	0.5	205,000
Boatlanding barge	Demobilise boatlanding barge	7	70,000	7	70,000
Crane vessel	Demobilise Crane vessel	7	2,800,000	7	2,800,000
Launch barge	Demobilise Jacket barge	7	70,000	7	70,000
Foundation barge	Demobilise foundation barge	7	70,000	7	70,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge	Sail barge to safe haven	5.6	222,222.22	5.6	222,222.22
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Sail to location	0.5	500,000	0.5	500,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
Total installation time and cost		**30.2**	**22,519,000**	**30.2**	**32,519,000**

Table 12-13: PS Topsides safe haven, launch barge, skirt piles by crane vessel

No safe haven, both on PS				duration [days]	Cost [$]
Jacket barge	Mobilisation of jacket barge	7.0	70,000	7.0	70,000
Jacket barge	Load out jacket on barge	1.0	40,000	1.0	40,000
PS	Mobilisation of PS	2.0	2,000,000	7.0	7,000,000
Jacket barge and PS	Load jacket from barge on PS	1.5	1,560,000	1.5	1,560,000
Jacket barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	PS sail to install location	3.9	3,884,181	3.9	3,884,181
PS	Install jacket	1.0	1,000,000	1.0	1,000,000
PS	Install foundation	1.0	1,000,000	1.0	1,000,000
PS	Horizontally level the legs	1.0	1,000,000	1.0	1,000,000
Topside barge	Mobilisation of topside barge	7.0	70,000	7.0	70,000
Topside barge	Load out topside on barge	1.0	40,000	1.0	40,000
Topside barge	Sail barge to transfer location	5.6	222,222	5.6	222,222
PS	Sail to save haven	0.3	250,000	0.3	250,000
Topside barge and PS	Load topside on PS	1.0	1,040,000	1.0	1,040,000
Topside barge	Demobilise barge	7.0	70,000	7.0	70,000
PS	Sail to location	0.3	250,000	0.3	250,000
PS	Install Topsides	0.8	833,333	0.8	833,333
PS	Demobilise PS	2.0	2,000,000	7.0	7,000,000
	Total	**11.7**	**15,400,000**	**21.7**	**25,400,000**

Table 12-14: Topsides and Tower on PS, no safe haven

The deferment cost per day is multiplied with the duration of the total operation and added to the total.