Installation of two subsea templates at Ormen Lange

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This report evaluates the installation of two subsea templates at Ormen Lange and compares this operation with the installation of similar templates in the Barents Sea. The main differences are discussed. First an overview of all the subsequent phases of such a marine operation are given and briefly discussed. Secondly one phase in particular is tackled in more detail. The towing out on a barge of the templates, the lift-off by a crane vessel and the lowering of the template are handled in a detailed way. Weather windows are estimated. To conclude this report the landing of the template on the bottom is planned and calculated as an example for all the other phases. The interpretation of the problem statement was such that the emphasis of the report should not be calculations. Thus they are not the main focus of this work. A general overview and the link between the different phases, together with the differences between Ormen Lange and the Barents Sea were stressed in this work. A better and more detailed understanding of one specific phase was the second goal the authors tried to obtain.
1.0 Executive Summary

The installation of two subsea templates in the North Sea at the Ormen Lange site is fairly different than the installation in the Barents Sea. The different steps in the process, are mainly the same. Each step however requires a specific approach and planning. The phases of the operation are:

- Loading on the barge and towing
- Positioning, lift off and water entry
- Lowering through the water column
- Landing on the sea bottom

For each phase the critical issues and the differences between Ormen Lange and Barents Sea are discussed.

A very important matter for such kind of operations are the weather conditions. The sea state is characterised by the wave height. For each phase the maximum wave height is decided and the weather window is calculated and estimated.

The landing of the template on the sea bottom is a critical phase. A very high level of accuracy is required. The vertical oscillations due to the crane tip motions and the influence of the rapidly changing added mass when approaching the sea floor are two very critical aspects. They need to be checked and planned very carefully in advance. A attempt to make a calculation of this phase can be found at the end of this report.

Initially it was found that the oscillations may cause some problems when approaching the bottom. The amplitude is lower than the exciting wave amplitude, but remains significant. The added mass however increases rapidly when reaching the bottom. This damps any movement and makes sure a very smooth landing takes place.
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TABLE 3. Weather windows: values for Barents Sea 33
5.0 Introduction

The search for new oil and gas resources is an ongoing and never ending process. The last decade it has become clear through research that the traditional oil and gas reserves are slowly but inevitably reaching rock bottom. Energy reserves are found in less obvious places, from a technical point of view. With the discovery of offshore wells a new era was born. A whole new challenging world was yet to be discovered. The first steps into this world were offshore oil platforms. Today a new step has been taken. Ormen Lange will be exploited by means of subsea templates and an onshore plant. The use of subsea equipment is a great technical challenge, but has some major advantages like no visual pollution and no disturbance for the fishing industry.

The installation of these templates is a highly risky operation and needs to be planned and executed with a very high degree of accuracy. There for the preparation is a very important stage in the development of these manoeuvres. The planning for the installation at the Ormen Lange site took approximately one year.

The installation at Ormen Lange was a very particular one due to difficult environmental circumstances. In the Barents Sea some subsea equipment has been installed as well. The operations however are fairly different.
6.0 Different steps of the installation

6.1 The templates

The templates that need to be installed have following geometrical properties:

- length: 44 m
- width: 33 m
- height: 15 m
- weight: 1150 tonnes

There shape is irregular. The four corners are formed by 4 suction anchors.

The templates will be accompanied by a PLET (PipeLine End Termination) system. The real pipeline begins there. The final and total set-up will be as shown in the next figure:

![Final and total set-up](image-url)
6.2 SSCV Thialf

The SSCV (semi-submersible crane vessel) that will be used for the Ormen Lange operation is the Thialf which is owned by Heerema Marine Contractors. It is the largest deepwater construction owned by the company. Its tandem lift capacity is 14,200 metric tonnes. The SSCV is used for the installation of spars, foundation moorings and will be suitable for the lowering operations that are needed to install the different templates. The main dimensions of the Thialf are stated below and in figure 4 the relation between lifting capacity and lifting radius is shown. It is clear that the lifting capacity decreases severely when the lifting radius increases.

The dimensions of the Thialf are as stated in the figure below.

FIGURE 3. Thialf semi-submersible crane vessel (SSCV)

FIGURE 4. Capacities of Thialf
6.3 Ormen Lange

Ormen Lange is the second largest gas field ever discovered in the North Sea. It is located a 100 kilometres north west of the More coast, near Kristiansund.

The gas from this field will be brought on shore in Nyhamna where it will be processed. From Nyhamna the journey continues to Sleiper, to end in Easington, UK. Ormen Lange will provide the UK with 20% of there yearly gas needs for at least the coming 40 years.
Different steps of the installation

FIGURE 6.

Journey of the gas

Geographically Ormen Lange is a real challenge for the engineers. It is located just in the Storrega escarpment. 8500 years ago a part of the Norwegian main land with the size of Iceland slid into the sea, generating a huge tsunami and a canyon in the ocean bottom. There for stability had to be addressed to make sure that drilling up to 2000 m deep was still safe and stable. This causes the templates to be installed at a depth of 850 metres. This a new depth record for Norwegian industry! As the field is located in the Storrega escarpment, next to the depth, the steep slopes form a real problem for the pipelaying. Slopes of 35° are no exception. The following figure shows an idea of the slope and the emplacement of the templates.
Different steps of the installation

FIGURE 7. Storrega escarpment

The land slide 8500 years ago not only left a great depth, but made the sea-bed highly uneven with small hills from 30 to 40 metres high. The position of the templates must therefore be carefully chosen so it is located on a flat sea bottom. This hilly landscape provides a lot of trouble for the pipelaying.

Ormen Lange is the place where two currents meet. It is the ending of the Gulf stream which originates from the coasts of South-America. The temperature of this current is always above zero degrees. Cold polar currents mix with the Gulf-stream and cause temperatures that are below zero for most of the time. The current patterns are very flexible and change a lot through time and depth.

FIGURE 8. Current profile with 3 hours time difference and depth difference

The wind and waves in this area are harder than in any other deep water development area in the world. Waves can reach heights up to more than 30 m.

The depth, the steep slopes, the uneven sea bottom, the currents and the waves make this operation a true challenge and a milestone in the offshore development.
6.4 The Barents Sea

The Barents Sea is located North of the Russian - Norwegian border.

Although Ormen Lange is not so far from the Barents Sea the conditions for subsea installations are pretty different. There are three main influences on the water temperature:

- water from the North Atlantic drift: > 3°C
- Arctic water from the North: < 0°C
- coastal water: > 3°C

Due to the mix of these currents the water temperature is almost all year long above zero, around 1°C. The seabottom however is permafrost. The ports on the main land are ice-free during the whole year, but suffer from very cold temperatures and heavy winds. The different currents have also as an effect that in summer a lot of fog is always present. During the summer months, which are the months preferred for the installation of the templates, the midnight sun provides 24h light. This is a very big advantage for the planning and hence the cost of the operation. The fishing population is very extensive in this area and economically very important. This has to be taken into account when a decision is required on where and how the oil fields will be exploited.

The bottom of the Barents Sea is a regular one with an average depth of 250 m. No canyons or subsea mountains are found. A front called the Polar Front is formed between the Atlantic and Polar waters. This front is determined by the bottom topography and is therefore relatively sharp and stable from year to year.

A problem typical to the Barents Sea is the presence of sunk Soviet submarines and German U-boats. Their locations are all well known, so they can be avoided. The Soviet government has used the Barents Sea a while for the dumping of toxic and radioactive waist. While drilling for oil, attention should be paid to avoid hitting this waist.
6.5 Different steps

In order to install subsea templates different steps need to be undertaken. First of all the location needs to be decided, so an extensive and detailed mapping of the sea bottom is needed. Once the location is determined the template can be ordered and constructed. the method to tow the template has to be decided, as well as the method of lowering it into place. The installation of the templates is a very precise event. The method of positioning is an important element of the installation.

6.5.1 Mapping and evaluating the seafloor

The surface of the earth consists 70% out of water. The surface that needs to be mapped is extremely large. Research vessels and their associated instruments and vehicles must travel quite slowly during mapping efforts (anywhere from 1 to 12 knots). In order to map the global ocean floor at this rate it would take approximately 125 years and $5 billion (Sandwell 1995; Yulsman 1996). Fortunately satellite determinations of the sea surface height give a first rough estimation of the seafloor. All discrete floor structures larger than 10 km horizontally and 1 km vertically are shown. This is by far not detailed enough for the operations under consideration. For both Ormen Lange and the Barents Sea these data were used to decide which method was needed for further investigations.

More detailed information is obtained by using multibeam swath mapping systems that are either mounted to the hull of a research vessel or towed behind the vessel as a vehicle. Depending on the specific equipment it has to be towed between 10 m and 60 m above the sea bottom to obtain the required accuracy and resolution. This denotes a limitation to the depth in which they can be used. The Barents Sea bottom could be mapped this way. The precise navigation of a towed vehicle however, 150 m below the ship is not easy. For the evaluation of the seafloor of Ormen Lange this method can not be used due to the large depths involved.

A third and state of the art method is the use of ROV’s and AUV’s. Both methods can be used in great depths up to 2000 m. The lack of an actual physical connection between the vessel and the AUV is an important advantage. They give very precise images of the seafloor as they can stay on an optimal altitude above the seabottom. On top of that AUV’s measure three times faster than a classic research vessel. This method was used at Ormen Lange with great success. In the Barents Sea oil fields AUV’s are used regularly for this effect.

The AUV’s are equipped with three sonars. Each of the three sonar devices on the AUV measures a distinctive aspect of the sea floor. Multibeam sonar collects bathymetry information for creating detailed relief maps, much like a hiker's topographic map. Sidescan sonar produces three-dimensional views of the bottom by bouncing sound waves off the bottom and measuring the strength of the reflected signals. These signals can detect subtle topographic features only a few centimeters high, and also indicate whether the seafloor is soft or hard, rocky, muddy, or silty. Sub-bottom sonar can show boundaries between layers of mud and rock below the seabed and therefore tell us about past geological events.

The AUV is programmed to follow a ‘lawn mower’ pattern and passes this pattern on an angle of 90° a few times as a redundancy check. In the following figure the red line denotes a previous determined route by a ROV survey. The exact position of the template and further details are obtained by the AUV lawn mower pattern, the black lines.
The NUI Explorer, a HUGIN 3000 AUV, was used together with more traditional ROV’s. Together, the data gave a very exact image of the sea-bed. The location could be chosen carefully and the best possible way for the pipes was decided. Thanks to the under water vehicles the following pipe route could be foreseen in great detail:
Different steps of the installation

6.5.2 Towing the template

Several methods can be used to tow the templates to their desired locations. The critical issues that influence the choice of method are the final depth of the template, the size/weight of the template and the expected weather. In Ormen Lange the templates were loaded onto barges in two pieces. The final assembly took place on the barge.
After the template was loaded on the barge, it was towed to Ormen Lange by tugs. Two different phases need to be distinguished. For the in-shore towing a high degree of manoeuvrability is needed. There for two tugs are used, as showed in figure 12. For the off-shore towing, the more traditional one tug - one barge set-up was used. Manoeuvrability is less important. The journey took four days. The towing method is closely linked to the method used to lower the template. In this case a crane vessel was used. The towing barge was manoeuvred next to this crane vessel.

Weather windows are very important for these kinds of operations. They will be discussed in chapter 5.

Snohvit is a recently discovered oil field in the Barents Sea. Subsea templates were installed. The towing method used however, was different. The heaviest structures, 240 tonnes, were installed using the subsea towing method. The structures were hooked up to a floating boy and towed out to the Snohvit field. Then, at 100 m below sea level, the templates were transferred to a crane vessel and lowered. This method has some advantages. Firstly it avoids the critical water entry phase. The template can be constructed in a dry dock that is filled once the template is attached to the towing vessels. The dry dock gives to opportunity to conduct this phase in controlled and thus optimal weather conditions. This method has however some limitations. The structure is towed under water which means that added mass has to be taken into account. The mass and the geometry of the template decide if this method can be used or not. Under water currents
Different steps of the installation

play their role in this operation. In the case of Ormen Lange all elements not to use this method are present. The template is heavy and big. A large added mass can be expected. To obtain a reasonable speed with reasonable needed forces towing on a barge seems better. On top of that the currents are not stable and influence the underwater towing. In the Barents Sea, Snohvit, this method could be applied without a problem.

6.5.3 Lowering the template

The lowering of the template was basically done in the same way both at Ormen Lange and Barents Sea. A crane vessel on which the template is hanged, lowers the template until it reaches the bottom. The suction anchors go deep in the ground and once the template is secured and fixed, the crane vessel lets go the template. A big difference is the lift of from the barge and the water entry phase.

In Snohvit the template was already under water. Once the template reached the exact location, the crane vessel took it over. The template was lowered and put into place. The only critical phase is the landing on the bottom.

In Ormen Lange the template arrived on a barge. The relative motion of the barge vs the crane vessel is highly important. When the crane lifts off the template, the barge will come up, the crane vessel will sink a bit deeper. There is a great risk of the template smashing back against the barge due this relative motion. On top of that the wave motion makes the operation even more critical. The weather windows in which this can be performed are much more severe than the first method. The time factor gets highly influenced by the available weather windows. Hence also the cost of the operation.

FIGURE 15. Lift of from the barge

There is a second very critical phase. The water entry of the template causes a lot of detailed planning and troubles. The added mass changes very rapidly. Due to the uneven and odd geometry the current around the template varies a great amount and very quickly. Again this has an important effect on the timing of the complete operation.
6.5.4 Positioning of the template

The positioning of the template must be done very accurately. Information about this topic only handles the Ormen Lange installation. Any information about Barents Sea installations was not found.

The requirements for the tolerance were very strict. The template had to be installed within +/- 2.5 m of the design location and within +/- 2.5° of the design heading. A fairly new method was applied by the company Sonardyne. Wideband telemetry was used. Two Sonardyne censors on opposite corners are enough to obtain precise data. For redundancy, censors were placed on the four corners. On the crane vessel as well, censors were placed. The template was also provided with several gyrocompass. All the data were collected wireless on the crane vessel. For more details, the authors refer to [1]. The positioning was done very meticulously and resulted in a very precise placing. The template was found to be less than 10 cm from the intended place and 0.03° from its intended heading.

FIGURE 16. Intended and final position of the template
Tow out on barge, lift off by crane-vessel and lowering

7.0 Tow out on barge, lift off by crane-vessel and lowering

7.1 Loading on the barge and towing

7.1.1 Description and critical issues

In this paragraph, the phase where the template is loaded as well as transported to its location will be described and the critical issues will be discussed. When a template is transported from an onshore facility to an offshore working area, this can be done in different ways. One way of transporting heavy structures is by using a barge and sailing it to the desired location (towing the barge). Another option is subsea towing, where the structure is towed to its location underwater, attached to a floating buoy. Both methods have their advantages and disadvantages. The ‘towing on barge’ method is more suitable if the offshore area is further from the yard, or when strong and unpredictable underwater currents exist. The advantage of the subsea towing method is that the water entry, which is one of the more critical phases can take place in calm weather, close to the shoreline.

In the first stage, the loading of the structure onto the barge, it is very important to maintain sufficient stability at all times. Therefore, it is important to have enough ballast tanks all over the barge so that the trim can be optimized and stability can be maintained. In the second stage, while the vessel is being towed out, many critical issues have to be analysed. Firstly the manoeuvrability of the barge-tug combination will be discussed. Afterwards, the required power will be estimated by using a DNV approximation formula.

Manoeuvrability

When the barge is close to the shoreline, manoeuvrability is more important than when the barge is far away from the coastline, far from marine traffic. For this, the propeller-barge interaction is quite important as long as the barge is close to the coastline because the lines can not be too long in order to maintain enough manoeuvrability. The extra resistance which occurs due to this propeller-barge interaction may be approximated using the following DNV [2] formula (Interaction efficiency factor):

\[ a_{re} = \left[ 1 + \frac{0.015 A_{np}}{L_{towline}} \right]^{-\eta} \]

-  \( A_{np} \) is the projected area of the cross sectional area of the towed object in \( \text{m}^2 \)
-  \( L_{towline} \) is the length of the towline in meters
-  \( \eta = 2.1 \) for barges.

It can be seen from the formula, that when the lines are longer, the added resistance will become negligible, which is the case by offshore, unrestricted towing. The configuration of the tugs will be chosen according to this and by keeping in mind that the manoeuvrability must be sufficient as well. For these reasons, the barge will be towed by two tugs when it is close to the coastline and at unrestricted offshore towing, the work will be done by a single tug.
Tow out on barge, lift off by crane-vessel and lowering

**Required bollard pull**

A first estimation of the wave drift component of the resistance for box shaped barges is found by using the following DNV approximation formula:

\[ F_{s(w)} = H \frac{H}{L} \left[ 0.52 L - 13 \right] \]

This formula can be used for box-shaped barges with a slow velocity only. In sheltered waters, manoeuvrability is more important than resistance and therefore short towing lines will be used and thus the resistance will increase. For unrestricted towing (offshore), DNV requires the following minimum breaking strength of the towing lines.

<table>
<thead>
<tr>
<th>BP (MT)</th>
<th>4BP</th>
<th>0.8BP + 3\sqrt{BP}</th>
<th>2BP</th>
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<tr>
<td>≤25</td>
<td>≤25</td>
<td>≤25</td>
<td></td>
</tr>
<tr>
<td>&gt;25, ≤130</td>
<td>&gt;25, ≤130</td>
<td>&gt;25, ≤130</td>
<td></td>
</tr>
</tbody>
</table>

In the formulas above, BP is the continuous static bollard pull in MT. Furthermore, according to DNV rules for marine operations, towing forces in open sea have to be sufficient to maintain zero speed under the following conditions:

| Wind velocity | \( V_w \) | 20 m/s |
| Head current velocity | \( V_c \) | 1 m/s |
| Significant wave height | \( H_s \) | 5 m |

For offshore towing, DNV requires a minimum length of the towing line given by,

\[ L_w = \frac{2000BP}{MBL_{\text{towline}}} \]

### 7.1.2 Ormen Lange vs. Barents sea

The installation of the Ormen Lange templates will be done by the use of a barge which is towed to its location and there the structure will be lift off by SSCV Thialf, the biggest crane vessel owned by Heerema Marine Contractors. On the other hand, the templates which have been used in the Barents sea at the Snohvit field, have been partially transported by barges, but the heaviest parts have been transported by the use of subsea towing.

The structures and manifolds for the Snøhvit field have all been fabricated by Nymo in Eydehavn and Grimstad. The majority of the structures has been loaded onto specialized barges were sailed to location. The biggest structures have been towed to the location using the subsea towing method. The structures were hooked up to a floating buoy and towed out to the snohvit field by the *Boa Deepsea* vessel, which is operated by *Aker offshore contractors*. When they arrived at location, at a depth of 100 meters, the structures were transferred to the crane and lowered to the seabed. If the subsea towing method is used, it is very important to maintain a constant speed when the template is towed to its location. The template will be towed by a few sea tugs and the template itself will be underwater at all times.
7.2 Lift off

7.2.1 Description and critical issues

In this part, the lift off operation will be described. During lift off, it is important that the structural resistance of the crane is large enough, so that the crane can withstand all stresses and forces which are applied to the construction in total. The total load which the crane has to support equals the static load and a dynamic load. The size of the dynamic load is taken into account by using an amplification factor. In case of a tandem crane, the total load to be supported by the crane number $i$ is then according to DNV (Dynamic hook load):

$$ DHL_i = DAF \left( \left( \alpha_{CoG} \cdot SKL \cdot W \right) + W_{rig} \right) + F \left( SPL \right) \right) , $$

where:

- $DAF$ : Dynamic amplification factor
- $\alpha_{CoG}$ : maximum theoretical part of the total load at hook ‘i’ with CoG in extreme point
- $SKL$ : factor expressing the increase in hook load ‘i’ due to tilting of the object
- $W$ : Object weight
- $W_{rig}$ : rigged weight
- $F \left( SPL \right)$ : Additional hook load due to special load such as wind loads

Furthermore, it is important to make sure that the structure is lifted with a large velocity, so that the chance of an impact after the lift off with the barge is minimal. The SSCV Thialf, which is used for the operation has a large initial velocity. The structure is lifted to 5 meters above suavely in 90 seconds. When the structure hangs at 5 meters above the mean sea-level, there is still a risk of impact with the barge or...
with waves and therefore it will be lifted higher to around 20 meters with a speed of 1.5 cm per second.

In principal, the lift off operation would be analysed analytically as a problem with 12 degrees of freedom (12 DOF), but because tugger lines are being used, the rotations of the template are eliminated and the problem becomes a problem with 9 degrees of freedom. Tugger lines are extra lines which are connected between the template and the crane vessel.

7.2.2 Ormen Lange vs. Barents sea

The template which has been used for the Ormen Lange gas field, has been towed on a barge to its location, while the templates which have been used in the Barents sea for the Snohvit field have been transported using the subsea towing method. For this reason, the lifting off of the Ormen Lange template will be more critical than the lifting off operation of the Snohvit operation, where the template is transferred from the buoy to the crane vessel at a depth of around 100 meters below sea level.

7.3 Water entry

7.3.1 Description and critical issues

In this chapter the critical issues concerning the water entry of the template will be discussed. When the water entry phase is discussed it is important to look at the slamming forces and to make sure that these forces. It is important that these forces remain low, so that the template will not be damaged by them. Using the DNV standards for marine operations, the following formulas are valid to calculate the total forces which act on the template during water entry.
When more accurate information is needed about the actual forces which act on the template, the following formula, which is derived by Faltinsen [3] (1990) can be used to find the forces in the heave-direction.

\[ F_3 = \frac{dA_{33}}{dh} \dot{V}^2 + A_{33} \ddot{V} + \rho g \Omega \]

For this kind of operation it is very important to choose a good weather window, so that the risk on damaging the template or other kinds equipment is minimized. When the structure is lowered and it reaches the splash zone and water entry commences, the buoyancy of the template will result in less tension in the lifting wire and for this ballast water has to be pumped out, because in heavy lift operations the use of a heave compensator is almost never used.

### 7.3.2 Ormen Lange vs. Barents sea

For this critical phase, where the weather window is very important the Ormen Lange towing method, towing on a barge, has many disadvantages compared to subsea towing. When the subsea towing method is used, the water entry phase can be operated in perfect conditions close to the shoreline. When the template arrives at its final location, it is already under the water surface and therefore this critical phase can be skipped when the subsea towing method is used.

### 7.4 Lowering

#### 7.4.1 Description and critical issues

The template hangs from the crane vessel down, attached by a cable. The template is lowered until above the sea-bed. This is a system with two free moving objects. This system has 12 degrees of freedom. The rotation of the template however is stopped by the use of tugger lines. These are two lines attached from the sides of the template to the crane vessel. 9 DOF are left.

![Tugger lines](image)

At first sight this phase seems pretty straight forward and simple. There are however some difficulties that need to be analysed closely.
Currents cause a horizontal offset while the load is hanging in currents. This lift operation is however a heavy lift. There for it is assumed that this offset can be neglected. On top of that, data show that the deeper you go, the less strong the currents are. Even if there would be a small offset, it will reduce when the template gets deeper.

The currents can have a second effect: vortex-induced resonance oscillations of the wire. [3] The vortices take place with a frequency that is dependent on the velocity of the current and the geometrical form of the submerged body, in this case the hoisting line. A second important factor is the natural frequency of the hoisting line. When vortex frequency reaches the natural frequency of the line, the line will start to oscillate. The hoisting line enters the lock-in region. Even with higher current speeds, the line will still oscillate with her natural frequency. Once the wire has started vibrating, it is very hard to make it stop.

The template hanging on the wire can be seen as a pendulum, due to the finite stiffness of the wire. As mentioned before the template has only three degrees of freedom. The rotations are excluded due to the tugger lines. To obtain a first idea of the movements of the template the natural periods can be calculated:

\[
T_1 = 2\pi \sqrt{\frac{(M + A_{11})L}{\eta mg - \rho gV}}
\]

\[
T_2 = 2\pi \sqrt{\frac{(M + A_{22})L}{\eta mg - \rho gV}}
\]

\[
T_3 = 2\pi \sqrt{\frac{(M + A_{33})L}{\eta \alpha EA}}
\]

For a more precise idea, the template needs to be coupled to the crane motion. More specifically the influence of the vertical motion of the crane tip on the vertical oscillation of the template will be discussed further.

A last critical issue is the possibilities of Matthieu instabilities. A Matthieu instability is a uncontrolled horizontal motion due to a controlled vertical motion. In this case the coupling between the heave motion of the crane tip and the surge motion of the load. The dynamic equations are given by [4]:

\[
m\ddot{\eta}_1 + B_{11}\dot{\eta}_1 + \frac{T}{l}\eta_1 = 0
\]

\[
m\ddot{\eta}_3 + B_{33}\dot{\eta}_3 + k\eta_3 = k\eta_3 T
\]

with \(m\) the weight of the wire per unit length, \(B\) the coefficients of the damping matrix, \(\eta\) the motion vector, \(T\) is the tension in the wire, \(l\) is the length of the wire and \(k\) is defined as

\[
k = \frac{\alpha}{C_L} \text{ with } C_L = \frac{EA}{\eta m}
\]
It is assumed that the crane tip executes a harmonic vertical motion, given by
\[ \eta_{3T} = \eta_{3Ta} \exp(i\omega t) \]
If the surge equation is solved it is seen that for
\[ \omega = \frac{n}{n} \omega_0 \]
\[ n = 1, 2, 3, \]
\( \omega_0 \) is the natural frequency of the pendulum.
These instabilities can cause trouble during a break in the lowering operation or when approaching the seabottom, as the speed goes to zero. The length of the cable is constant and the Matthieu instabilities can take place.

7.4.2 Ormen Lange vs. Barents Sea

The lowering of the template is done in the same way in both geographical places. The principles will be the same. The same critical issues need to be investigated. The currents influence the horizontal offset and the vortex-induced oscillations. They play an important role in the planning and need to be looked into carefully. The temperature of the water can have its importance as well. The presence of icebergs needs to be avoided at all times. This can sometimes be a problem for the Barents Sea. The difference in depth basically doesn’t change the principles of this operation.

7.4.3 Information needed for analysis and description of analysis

Three entities are involved in this phase: the crane vessel, the template and the hoisting lines. The tugger lines are involved as well, but it can be assumed that their influence is limited to the decrease of the number of degrees of freedom. No further details are thus needed about the tugger lines and the deadman anchors.

The Thialf, the largest crane vessel in the world, was used for this operation. In chapter 3.2, all the technical details of the Thialf are shown. The response of the Thialf on the wave motions is important. For this a RAO would be needed. This is used to calculate the effect of the crane tip motion on the motion of the template. To check the assumption that the crane vessel doesn’t move during the lowering operation the displacement of the crane vessel needs to be compared with the displacement of the load. The GRT DWT of the Thialf is 136,709 tonnes. The DWT ratio of the load vs. the crane vessel is 0.84%. It is safe to assume that the position of the crane vessel isn’t influenced by the motions of the template.

The hoisting lines play an important role in this operation. The strength has to be sufficiently high. The elasticity needs to be known and checked. The configuration used to lift the template is a tandem configuration. Two cranes and two attaching points are used. The following figure shows clearly the two hooks.
There are different kinds of hoisting lines that can be used, six different types to be exact:

- chain
- wire rope
- metal mesh
- natural fibre rope
- synthetic fibre rope
- synthetic web

Each kind of line has its own particularities. In order to choose the correct line different aspects need to be considered:

- weight of the load
- shape of the load
- environmental conditions applicable to the line

The weight carried by the hoisting lines is the dry weight, 1150 tonnes, plus the added mass. On top of that weight impact loads need to be taken into account. Impact loads happen e.g. when landing on the bottom or sudden horizontal displacements. The safest choice is probably steel wire rope. A rope is made out of twisted strands, which are made of twisted individual wires. The core can be of fibre or again a wire rope strand. After a careful evaluation of the strength, the resistance to fatigue, aggressive environments and abuse the correct hoisting line can be chosen.

As for the whole operation all the properties of the template need to be known. The geometrical properties are used to calculate the added mass. This is a very important factor throughout the whole lifting and installing operation. Further in this report the added mass will be studied in greater detail.

7.5 Landing on the sea bottom

This phase will be discussed in greater detail in section 6.5. A detailed analysis shall be made.
8.0 Weather windows and duration

The principles used to determine the weather windows are the same for the Barents Sea and Ormen Lange. Two main differences have however a big influence on the estimated duration of the different phases and hence on the needed weather windows. The first difference is the distance from shore to the drilling locations. The Barents Sea locations are generally further than Ormen Lange. The duration of the towing will be longer. The needed weather window will have to be longer as well. This makes the whole planning more complicated.

A second difference is the difference in depth. Ormen Lange is 850 m deep, the Barents Sea 300 m. It will take more time to lower the template in Ormen Lange than it will in the Barents Sea. Again this influences the available weather windows and the planning. In the following paragraphs the duration and weather windows will be estimated for the Ormen Lange field. As mentioned, the principles stay the same for any other location in the Barents Sea.

8.1 General theory

Weather statistics are crucial for the decision on weather windows. The most important statistics are the extreme value statistics. They can be based upon a long term approach or a short term approach. The three hour stationary sea state is considered independent of all the previous and coming sea states. Hence this is the most important parameter. A complication in this kind of operations is that once a certain phase has started it can not be stopped. The weather window must be guaranteed for the whole phase. As a result of this the duration of each phase must be kept as short as possible.

A sea state is determined by several influences: temperature, wind,... The question remains how we can describe the sea state with as few parameters as possible. A fairly good approximation is obtained by measuring and using the wave heights. With just this one parameter a certain sea state is well characterised. Next to the wave heights, information about the persistence of the sea state is needed. Occurrence and duration are the two factors that need to be observed. A certain maximum limit in occurrence is decided. This limit may not be passed during the operation. The duration of the operation must be smaller than the time between two following surpasses of the maximum wave height. A value for the maximum wave height is given in the Lecture notes in Marine Operations by Finn Gunnar Nielsen.

\[ H_{(s, \text{max})} = 4 \text{m} \]

The sea states are measured every three hours, for twenty minutes. Consequently it is pretty hard to obtain information about shorter sea states than three hours. Interpolation can be used. Once these measurements are executed statistic calculations can be applied. A distribution of the average duration of calm sea states can be calculated. Based on empirical data it is found that the cumulative probability of the duration of a calm period may be written as a two parameter Weibull distribution:

\[ P(t) = 1 - \exp \left( - \frac{t}{t_c} \right)^\beta \]

\( P(t) \) is the probability that the duration of a calm period will be less than \( t \). The parameters \( t_c \) and \( \beta \) depend on the significant wave height and the geographical area. The average duration of calm periods can be described as follows:

\[ \bar{\tau}_c = \frac{1}{\beta} A[-\ln(P(H_s))]^{-\frac{1}{\beta}} \]
This expression shows the average duration of periods where the significant wave height is smaller than the maximum limit of the wave height. Comparing these values with the duration of the different phases shows if the needed weather windows are available.

This theory can be found in Lecture notes in Marine Operations by Finn Gunnar Nielsen and in the DNV regulations [2]. Due to the lack of more precise measurements, this will be used further on in this report to estimate the weather windows.

First the duration of the different phases will be calculated. After that it will be checked if there are weather windows available for the needed duration. If this is not the case then the phase needs to be replanned and adopted.

8.2 Duration of the phases

Mapping of the seafloor
This has been executed in great detail during two years prior to the installation of the templates (2000 - 2002).

Towing to location
The duration is mainly decided by the speeds of the towing vessels and the distance from shore. For Ormen Lange the towing took 4 days. The length of the needed weather window is hence 96 hours.

Positioning of the barge and the crane vessel
In the lecture notes [4] it is found that this phase is divided in two sub phases:
- hold vessel in position: 2 hours
- Run and test anchor lines: 2 hours
- Total: 4 hours

Lift of from barge
This operation needs to done very fast to avoid the template to smash to the barge again. The Thialf has a ballast pump capacity of 20,800 m³/h. This capacity is used the flood the right ballast tanks and hence changing the trim of the vessel. The template is lifted in a minimum of time to approximately 5 m (estimated based on video material found on www.ormenlange.com). This takes approximately 90 seconds. These 5 metres are not enough for the template to be safe. The tandem cranes hoist the template even higher at a speed of approximately 1,5 cm/sec. The wave height is limited to 4 m and based on the videos on www.ormenlange.com, the template is hoisted up to 15 m above sea level. The total duration of the lift of is:

\[
T_{\text{lift}} = 90 + \frac{1500 - 500}{1.5} = 757 \text{ s} = 12,62 \text{ min}
\]

Water entry
The template have a height os 15 m. It is assumed that it is lowered at the same hoisting speed as mentioned before.

\[
T_{\text{entry}} = \frac{1500}{1.5} = 1000 \text{ s} = 17 \text{ min}
\]
Weather windows and duration

Lowering to the bottom
Again the lowering speed is assumed to be 1.5 cm/sec, the depth is 850 m. This gives a total time for this operation of:

\[ T_{\text{lowering}} = \frac{85000}{1.5} = 57,000 \text{ sec} = 950 \text{ min} = 16 \text{ hours} \]

Landing on the bottom
Based on chapter 2.4. in the Lecture Notes in Marine Operations by Nielsen, the landing phase consists of two sub phases:

- Positioning of template: 17 hours
- Landing and intrusion of the suction anchors: 6 to 24 hours

Next to the phases mentioned additional weather windows need to be calculated. This is for instance the case for following phases:

- attaching the transponders
- attach the tugger lines and the deadman anchors
- deploy of the ROV (used to check during the landing and to remove the hoisting lines after landing)
- preparation on barge
- template levelling
- swaging and cutting
- template levelling
- swaging and cutting
- survey of the work

All these phases were not discussed so far in this report. For the sake of consistency the authors have chosen not to go in detail of these phases now. The estimated duration and needed additional required duration can be found in [4]. In this report only the main phases are discussed.

8.3 Weather windows

The duration of each phase is known. As mentioned before the two parameter Weibull distribution can now be used to estimate the significant wave height which will occur during the operation. This \( H_s \) must be smaller than a certain maximum limit. The DNV rules [5] propose the following model:

\[ H_{s, \text{char}} = H_1 \left( \frac{2}{2 + j} \cdot f_1 \right)^{\frac{1}{j}} \text{ with} \]

\[ f_1 = \ln(R \cdot N) + (d-1) \ln(\ln(R \cdot N)) \]

\[ R = \frac{\sqrt{2\pi}}{\Gamma(d-1/2)} \left( \frac{2}{j+2} \right)^d \left( \frac{L}{j+2} \right)^{d-\frac{1}{2}} \]

and with:

- \( H_1 \) and \( j \) are the two Weibull parameters
- \( N = 14,400 \ d_n \) where \( d_n \) is the design operational period, expressed in days
Weather windows and duration

- $d = 1.5 - 1/2j$
- $\Gamma$ is the Gamma-function

The Weibull parameters are given by DNV [6]:

<table>
<thead>
<tr>
<th>TABLE 1.</th>
<th>Weibull parameters for Ormen Lange and Barents Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ormen Lange</td>
</tr>
<tr>
<td>$j$</td>
<td>1.53</td>
</tr>
<tr>
<td>$H_f$</td>
<td>2.84</td>
</tr>
</tbody>
</table>

This model gives the characteristic significant wave height in function of the number of days the operation takes. This model however does not take into account the variations between winter and summer. They will be exaggerated for the summer waves. For the North Sea the model gives the following significant wave heights:

<table>
<thead>
<tr>
<th>FIGURE 21.</th>
<th>Characteristic significant wave heights in function of days of exposure - North Sea</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>FIGURE 22.</th>
<th>Characteristic significant wave heights in function of days of exposure - Barents Sea</th>
</tr>
</thead>
</table>
The shorter the operation takes, the lower the wave heights will be. The wave heights need to be lower than certain design wave heights. These design wave heights are displayed in table 2. They are taken from [4]. On top of that, due to the uncertainties linked to weather forecasting DNV defines a coefficient $\alpha$ [7] which reduces these design wave heights even more. In this way a fair amount of certainty is obtained. This parameter $\alpha$ depends on the duration of the operational phase and the design wave height and is given by DNV. The exact values can be found in table 2. The operational wave heights must be smaller than $\alpha H_{\text{des}}$. Table 3 gives the same values as table 2, but for the Barents Sea. The following tables summarize:

<table>
<thead>
<tr>
<th>TABLE 2. Weather windows: values for Ormen Lange</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase [ ]</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Towing to destination</td>
</tr>
<tr>
<td>Positioning</td>
</tr>
<tr>
<td>Lift of from barge</td>
</tr>
<tr>
<td>Water entry</td>
</tr>
<tr>
<td>Lowering</td>
</tr>
<tr>
<td>Landing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 3. Weather windows: values for Barents Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase [ ]</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Towing to destination</td>
</tr>
<tr>
<td>Positioning</td>
</tr>
<tr>
<td>Lift of from barge</td>
</tr>
<tr>
<td>Water entry</td>
</tr>
<tr>
<td>Lowering</td>
</tr>
<tr>
<td>Landing</td>
</tr>
</tbody>
</table>

The calculations for the duration were not performed as thoroughly as for the Ormen Lange case. Several assumptions were used:
- Distance shore - location: 145 km (the length of the Hammerfest to Snohvit - as it was not clear whether the towing started in Murmansk or Hammerfest)
- Towing speed: 3 kn
- Crane vessel used: Thialf with the same lifting speed as before
- Template: 15 m high
- Depth: 300 m

The values in the table clearly show that the characteristic wave height to be expected higher is then the maximum allowed wave height. First of all the seasonal variations are not included in this model. This will make a big difference as the installation will be planned during the calmer summer period. Secondly this model is just an approximation. For such kind of important operations much more detailed data are needed! The values obtained in this paragraph are just to show how a possible analysis could be performed. As an example the authors hope they are good enough.
9.0 Landing on seafloor

This phase of the operation will be analysed in much greater detail. A more detailed choice of material will be discussed, together with relevant modifications needed. Relevant dynamic forces and responses will be estimated. The influence of the vertical crane tip motion will be analysed. When a template comes close to the bottom the added mass changes very rapidly. This as well will be looked into closely.

9.1 Introduction

This final phase of the installation process is of great importance. Two main criteria will decide the success of this operation:

- the precision of the final location of the template
- the “softness” of the landing

If the template lands hard on the seafloor, an impact load will take place. This can be very important regarding the hoisting lines. They are not conceived to withstand impact loads. On a first approach of the problem, this seems to be not such a great issue due to the growth of the added mass. The theory about this subject learns that once the template approaches a fixed structure, as the bottom, the added mass becomes function of the distance to this structure and the asymptotic results tends to infinity. This means that the added mass while approaching the bottom becomes bigger and bigger and theoretically goes to infinity. Practically this means that the speed of the template will decrease and the acceleration will become negative, thus help the template to land softly on the bottom.

The precision in this case is very important. Once the template is installed the wells will be drilled through the previewed hatches in the template. They have to be on precisely the right position. On top of that, pipes will be attached to the template and go to the PLET-module. The connection on both ends of the pipes need to be within very precise boundaries.

This operation consists of three main phases:

- approach to the bottom
- touchdown and insertion of the suction anchors
- removal of the hoisting lines by means of a ROV

During the approach of the bottom vertical oscillations need to be checked. These oscillations can be induced by the motions of the crane tip and by the elasticity of the wire. As mentioned before a close eye needs to be held on the added mass.

For the next phase, the anchors need to touch to bottom at exactly the right position. Once they have started to suck themselves into the ground, it is almost impossible to remove them. Only one chance is given for absolute accuracy. Therefore the speed needs to be acceptable.

A lot of experience exists for the last phase. This doesn’t constitute a major risk. The right ROV needs to be selected and foreseen with the right equipment. Skilled personnel is of course needed to perform this operation without damage.

This phase of the operation is very similar for both Ormen Lange as the Barents Sea. The only possible differences lay in the bottom and the different kind of template. Depending on the material the bottom is made from, the time needed to insert
the suction anchors varies. The principles and the encountered problems are however completely the same. The analysis shall only be performed for the Ormen Lange case.

9.2 Equipment and modifications needed

9.2.1 Positioning

A short introduction on this topic has been given in paragraph 3.4.4. As mentioned the method used was slightly different than usual. Wideband telemetry was used instead of long base line acoustic transmission.

The first option was to use GPS positioning, but it was soon found out that the range in water wouldn’t be sufficient. A second option was acoustic transmission of the data. Due to environmental conditions (salinity of the water, currents, temperature and pressure variations,...) this proved to be very difficult. Great deflections were to be expected and the time to transmit the data was too long. Latter was just a key issue to obtain a highly precise positioning. Sonardyne sensors were placed on the four corners and on the Thialf. As mentioned the precision was very high for the Ormen Lange case.

9.2.2 ROV

During the installation process a ROV is used. The positioning equipment communicates from the Thialf to the ROV. On top of that the ROV provides live video images which help the operators a great deal. The most important task however of the ROV is to unhook the hoisting lines once the template has landed and is installed. This the operation that will determine which ROV will be used. The educational pages of Remotely Operated Vehicles Committee of the Marine Technology Society categorize ROV systems according to: size, depth, on board horsepower and whether it’s all-electric or electro-hydraulic.
The operation is carried out 850 m to 1,000 m deep. Unhooking the hoisting lines can be characterized as medium heavy work. The best choice is a Medium (Electro/Hyd) ROV.

### 9.2.3 Tugger Lines

The use of the tugger lines has been discussed previously in this report. They are attached to the template before lowering. Normal and common steel wires will fit the purpose of the tugger lines perfectly.

### 9.2.4 Hoisting Lines

The choice of the hoisting lines was explained and made in section 4.5.3. A steel wire rope was chosen among the possibilities.

---

**TABLE 4.** ROC Committee categorization of ROV systems (ROV, 2004) [11]

<table>
<thead>
<tr>
<th>Class</th>
<th>Capability</th>
<th>Power [hp]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCROV (Electric)</td>
<td>Observation (&lt; 100 m)</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Small &amp;/#/9 (Electric)</td>
<td>Observation (&lt; 300 m)</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Large (Electric)</td>
<td>Observation/Light work (&lt; 3,000 m)</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Ultra-Deep (Electric)</td>
<td>Observation/Data Collection (&gt; 3,000 m)</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>Medium (Electro/Hyd)</td>
<td>Light/Med Heavy Work (&lt; 2,000 m)</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Large (Electro/Hyd)</td>
<td>Heavy Work/Large Payload (&lt; 3,000 m)</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>Ultra-Deep (Electro/Hyd)</td>
<td>Heavy Work/Large Payload (&gt; 3,000 m)</td>
<td>&lt; 120</td>
</tr>
</tbody>
</table>

---

**FIGURE 24.** Lowering of the templates with hoisting lines
9.3 Theoretical background

The system considered is a two body system with 9 degrees of freedom. The load hangs in water and is handled as a point mass. Motions of the vessel are referred to an earth fixed coordinate system \((x,y,z)\) which is in origin of the vessel at rest. The motions of the load are referred to the centre of the load.

The sea is never as smooth as a mirror. Waves are always present. Each sea has its own typical wave spectrum. Every vessel that floats on a sea experiences these wave motions and as a response, conduct motions themselves, due to the hydrodynamical forces. Such is the case for the Thialf at Ormen Lange. The crane vessel conducts motions in its 6 degrees of freedom while being held on place by dynamical positioning. The complete vessel is seen as a rigid structure. The crane tip will execute the same motions as the complete vessel. The template however is hanging on a cable from this tip. It will be influenced by the crane tip. The 9 degrees of freedom will interact with each other. This means that the motion in the direction of 1 degree of freedom is not purely due to forces in that direction. It’s a result of motions according other degrees of freedom as well. The is known under the name of coupled motions.

A dynamic analysis of the coupled system leads to the motions of equations of the system. These equations consist of:

- a mass matrix
- a total stiffness matrix with three main contributions:
  - restoring forces
  - hydrostatic effects due to the dynamic positioning system
  - vessel-load coupling effects
- a damping matrix
- external and exciting force components

The damping components will be neglected in this analysis. With these matrices known we can obtain a first idea of the behaviour of this system, by calculating the undamped eigenfrequencies and eigenmodes of the coupled system. For this the following equation can be used:

\[
(-\omega^2 M + C)x = 0
\]

The eigenvalues are given from:

\[
\lambda x = M^{-1}Cx
\]

with:

- \(x\) the unknown
- \(M\) the mass matrix
- \(C\) the stiffness matrix
- \(\lambda\) the eigenvalues

With each eigenvalue an eigenvector corresponds. This vector shows the relative contribution of each degree of freedom in the total motion if the body is excited in a certain resonance mode, given by the eigenvalue. This short analysis learns what happens if the system is excited in its resonance areas. These areas should be avoided. For a more thorough analysis of the system, damping must be included,
just as the exciting forces. The forces are written in a complex form:

\[ F = Re\{F_n \exp(i\omega t)\} \]

where \( F = (F_1, F_2, ..., F_9)^T \) is the complex excitation force vector and \( \omega \) is the frequency of oscillation. (For a complete theoretical background a linear damping term \( B \) is assumed.) The motion response of the vessel - load system is obtained as:

\[ \eta = (-\omega^2 M + i\omega B + C)^{-1} F \]

The equations so far give theoretical background on how to calculate the coupled motions. The interest of this chapter however is the motion of the template, under the influence of the crane tip motion. It is assumed that the crane tip will only perform a purely heave motion. The pitch will be neglected.

In deep water operations, the elasticity as well as the mass of the wire may be important to consider in determining the dynamic loads and hence the motions. The system will be modelled as a vertical oscillation of a wire including a mass. The vertical motion of a point of the wire can be described by solving:

\[ EA \frac{\partial^2 \eta}{\partial x^2} + m \frac{\partial^2 \eta}{\partial t^2} = \rho g \]

with \( EA \) the stiffness per unit length and \( m \) the weight per unit length of the wire.

This equation is the result of the consideration of dynamic equilibrium of the point of the wire and the stress-strain relation for the element. The equation can be solved by applying the mathematical technic of separation of the variables. The solution of the dynamic displacement and force in the cable are given by:

\[
\eta(x, t) = \eta_d \left[ \cos(kt) + \frac{1 + \frac{m}{kM} \tan(kL)}{\frac{m}{kM} - \tan(kL)} \sin(kt) \right] \cos(\omega t)
\]

\[
F_d(x, t) = E A k \eta_d \left[ -\sin(kt) + \frac{1 + \frac{m}{kM} \tan(kL)}{\frac{m}{kM} - \tan(kL)} \cos(kt) \right] \cos(\omega t)
\]

These equations will be used in the next paragraph to calculate the response of the template on a sinus movement of the crane tip.

### 9.4 Template movement influenced by the crane tip motion

First of all it is important to check if there is a possibility that the wave excitation brings the Thialf into resonance. Therefore the natural frequency of the Thialf needs to be checked. The effect of hydrostatic pressure and the horizontal offset will be neglected. On top of that small motions will be assumed. The natural period is calculated with the following formula:

\[ T_{n, \text{Thialf}} = 2\pi \frac{M_{eq}}{K_{eq}} \]

with \( M_{eq} = V \rho + A_{33} \) sum of the added mass and the dry mass. \( K_{eq} \) is the equivalent waterplane stiffness. The formula is found in [3]: \( K_{eq} = \rho g A_w \). The submerged volume of the Thialf is estimated by looking at pictures, combined with geometrical data. Two pontoons are completely submerged. They are linked by one underwater pontoon. On the pontoons 8 columns are positioned. The dimensions are estimated as follows:
Landing on seafloor

Installation of two subsea templates at Ormen Lange

FIGURE 25. Thialf

The added mass is the unknown factor. It can be calculated with a formula found in Pettersen (2004), for a 2D approach. For a 3D value the formula needs to be multiplied with the length:

\[ A_{33}^{2D} = 1,36\pi\rho D_{pontoon}^2 \]
\[ A_{33} = 1,36\pi\rho D_{pontoon}^2 L_{pontoon} = 35471665, 47\text{ kg} \]

The added mass has been checked using [8] using the methods of Ursell and Grim. Results in the same range were found, but can not be published due to a significant lack of precision, due to undetailed graphics, used for the different coefficients. A better way of obtaining the added mass are model tests. Of course these require financial and time resources.

The natural period of the Thialf can be calculated:

\[ M_{eq} = V\rho + A_{33} = 158766496, 5\text{ kg} = 1,6\times10^8 \text{ kg} \]
\[ K_{eq} = \rho g A_w = 18099450\text{ kg/s}^2 \]
\[ T_{Thialf} = 18, 61\text{s} \Rightarrow \omega_{Thialf} = \frac{2\pi}{T} = 0, 3376 \]

The wave spectrum of the North Sea can be modelled by the JONSWAP spectrum [8]. This spectrum was the result of an extensive measuring programme between 1968 and 1969 in the North Sea. In general it is representative for seas with wind-
generated waves with a limited fetch. It has 5 parameters. A simplification of the spectrum is the BRECHTSNEIDER spectrum, also valid for the North Sea, but with some restrictions. This spectrum gives the modal peak frequency that can be expected in function of the 1/3 significant wave height. This is known as the maximum wave height is decided for the weather window. This value, while not being the 1/3 significant wave height, is however used. This will give a small exaggeration of the modal frequency.

$$\omega_{m, \text{max}} = \left( \frac{4}{5} B \right)^{\frac{1}{4}} = 0.79$$

$$B = \frac{3.31}{H^2} = 0,4976$$

These calculations show that it is safe to assume that the Thialf will be far from resonance at all time.

After these first evaluations and maintaining the same assumptions an oscillation is assumed for the crane tip. The frequency will be set to resonance to assume the worst case, even though it has been shown that this case will almost never appear. Several amplitudes will be checked. The maximum wave amplitude for this operation is 1,25 m. Higher values will be checked to illustrate the principle.

$$\eta_{\text{crane}} = \eta_a \cos(0,3376t)$$

Some characteristics of the template need to be calculated. The geometrical dimensions are given in chapter 3.1.

$$M_{\text{template}} = 1150000\text{kg}$$

$$V_{\text{template}} = 44 \cdot 33 \cdot \frac{15}{20} = 1089\text{m}^3$$

$$M_{\text{wet}} = M_{\text{template}} \cdot g - \rho g V_{\text{template}} = 331332,75\text{N}$$

The volume is estimated based on pictures and drawings. It is definitely not precise, but for the sake of this report it will suffice, just to show how the analysis can be preformed.

The wire needs to be calculated as well. The assumption is made that the wire is made from pure steel. This is a clear simplification that doesn’t affect the principles of the analysis. Further it is assumed that 8 wires were used of 8 cm diameter each time. The length is set to 850 m. The density of steel is 7800 kg/m³. The Young modulus $E$ is 1,95 x $10^{11}$.

$$A_{\text{wire}} = 2\pi r^2 \cdot 8 = 0,08m^2$$

$$AE = 1,568E10$$

$$m_{\text{wire}} = A_{\text{wire}} \cdot L_{\text{wire}} \cdot \text{density} = 530400\text{kg}$$

The wave number $k$ is given by:

$$k = \sqrt{\frac{2 m}{\eta \cdot EA}}$$
All the parameters for the formulas in paragraph 6.3. are now known. The response of the template can now be plotted. The plots were generated in Maple and shown below.

**FIGURE 26.**
Response of template, wave excitation = 1 m (thick line = template motion, thin line = wave motion)

The template will oscillate, but the amplitude is smaller than the wave oscillation. The elasticity of the wire acts as a kind of damper system. When the crane tip moves upwards, the wire will stretch and the template will only follow later. The amplitude of the template is still fairly big. This is due to the large depth. The comparison can be made with a depth of 300 m instead of 850 m:
The stretching of the wire has reached its maximum when oscillating at 850 m deep. That’s also why the relative difference between 1 m waves or 2.5 m waves is not existing.

In general it is found that at great depths the displacement of the template can be significant. It should be taken into account.

9.5 Influence of added mass near the sea bottom

In this paragraph, the influence of added mass in heave will be discussed in detail. In order to make calculations, simplifications have been made. All the assumptions are discussed below and finally some graphs and discussions on the results will be given. With these simplifications and idealisations, it is possible to get an idea of the real situation, where the situation is far from ideal. The following idealisations and assumptions have been made:

- the template hangs still on a distance $h$ above the sea-bed.
- buoyancy has been estimated
- circular area instead of rectangular
- template is assumed to be flat
- viscosity has been neglected

In order to transform the rectangular shape of the template into a circular disk, the surface of the rectangular box, which has a length of 44 m and a breadth of 33 m (1,452 m$^2$) has been transformed in a comparable circular area. The size of the area is kept constant at 1,452 m$^2$, so that the radius of the circular area equals 21.5 m. Furthermore it is known that the added mass of a circular disk as a function of the distance from the bottom is given by the following formula’s:

- for $r << h$

$$A_{33} = \frac{8}{3} \rho r^3$$

- for $h/r << 1$

$$A_{33}(z) = \frac{\pi \rho r^4}{8h} + \left\{ \log \left[ \frac{8\pi r}{h} \right] - \frac{5}{3} \right\} \frac{\rho r^3}{2}$$
Using the formula which is valid close to the bottom of the sea ($h/r << 1$), the following graph is made. It is very clear that the added mass goes to infinity when the distance between the idealized template and the bottom of the sea goes to zero.

**FIGURE 29.**
Ormen Lange template simplified to a circular disk

![Graph showing added mass as a function of distance](image)

Now the landing speed of the template will be analysed. To find the landing speed of the template, conservation of energy is used, which means that the following formulas is being used in this part:

$\left( E_{\text{kin}} + E_{\text{pot}} \right)_{\text{start}} = \left( E_{\text{kin}} + E_{\text{pot}} \right)_{\text{bottom}}$

When the template hangs still on a distance $z$ to the seafloor, the kinetic energy equals zero and the potential energy at the starting point equals the submerged weight times the distance to the seafloor. When the template lands on the seafloor, the potential energy will be zero and so the velocity at impact can be calculated easily, using the following formula:

$0 + mgz_{\text{start}} = \frac{1}{2} Mv_{\text{bottom}}^2 + 0 \quad v_{\text{bottom}} = \sqrt{\frac{2mgz}{m + A_{33}}}$

It is known from previous discussions that the added mass ($A_{33}$) will go towards infinity when the distance between the template and the seafloor ($z$) goes towards zero. For that reason, the impact velocity will go towards zero as the structure touches the seafloor. In the following graph, which has been made with Matlab, the speed of the template is visualized as a function of time. There is assumed that the template is dropped from a distance $h = 5m$ from the seafloor with an initial velocity of 1.5 cm/s, which equals the lowering speed of the crane. In reality, the template will not be dropped but be put gently on the seafloor. The purpose for this analysis is to get an idea of the influence of added mass when a structure reaches the bottom.
FIGURE 30. Height vs. time close to the seafloor

FIGURE 31. Speed vs. time close to the seafloor
FIGURE 32. Acceleration vs. time close to the seafloor
10.0 Conclusion

The installation of the template at Ormen Lange was performed successfully last August. It took one week-end. The planning and preparation however took more than two years. Different aspects of this process were briefly discussed. The complete installation is an extremely complex and difficult task. A subsea installation on such a great depth, is a victory for man.
11.0 Enclosures

11.1 Maple script to determine the characteristic wave heights

restart:
H1:=2.33;
j:=1.33;
N:=14400*dn;
d:=1.5-1/(2*j);
gam:=evalf(GAMMA(d-1/2));
R:=sqrt(2*Pi)/GAMMA(d-1/2)*((2/j)**(d-1)*((j/(j+2))**(d-1/2));
Hs:=H1*(2/(2+j)*f1)**(1/j);
plot(Hs,dn=0..15, color=black, thickness=2);

11.2 Maple script to obtain the template movement

restart:with(plots):with(plottools):
eta_a:=2.5;
M:=331332.75;
L:=300;
EA:=1.5682831*10**10;
m:=530400/9.81;
omega:=0.3376;
k:=sqrt(omega**2*m/EA);
eta:=eta_a*(cos(k*L)+(1+m/(k*M)*tan(k*L))/(m/(k*M)-
tan(k*L)))*sin(k*L)*cos(omega*t);
A:=plot(eta,t=0..50,thickness=3):
B:=plot(eta_a*sin(omega*t),t=0..50,thickness=1):
display(A,B);
12.0 References


[5] *Rules for Planning and Execution of Marine Operations*: Part 1 - Chapter 3 - Section 2.3.3.5., Det Norske Veritas, 1996


