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Writer:
Chernov Dmitrii

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Faculty supervisor:
Professor Ove Tobias Gudmestad
External supervisor(s):
Professor Anatoly Borisivich Zolotukhin (Gubkin University)

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NEW APPROACH TO THE TRANSPORTATION AND INSTALLATION OF HEAVY-WEIGHTED EQUIPMENT OFFSHORE

Chernov, Dmitrii Sergeevich, *master student*.
Faculty of Science and Technology, University of Stavanger
Faculty of Oil and Gas Field Development, Gubkin University of Oil and Gas, Moscow

ABSTRACT

Installation of offshore equipment is a huge branch of business in the oil and gas industry. Almost every offshore project requires heavy-weighted equipment, which should be installed on the seabed. Recently, oil and gas companies instead of producing from platforms prefer to develop fields as subsea factories. Mentioned changes result in growing opportunities for offshore service companies, working in the field of transportation and installation, as the workload constantly increases.

Currently, several techniques are used to carry out the full installation activities. The most used one is to transport the equipment by a subsea construction vessel (SSCV) and then transmit the equipment from the deck of the vessel to the seabed by a vessel’s crane. Such approach requires to hire a costly vessel – SSCV and have some limitations due to weather restrictions. Moreover, the most up to date SSCV’s are not able to operate with cargo’s weights more than 500 tons. To carry out the installation of heavy-weighted equipment, such as templates with integrated manifold, two vessels – barge and heavy lift crane vessel should be used. This leads to a significant increase in the installation cost.

However, service companies such as Subsea7, Aker, etc. have their own technologies, which could be classified as “wet” transportation and installation methods. Some of them already have practical applications. These methods have several pros and cons that will be reviewed in the paper.

The main aim of this work is to develop technical concept of a new wet transportation and installation approach, taking into account pros and cons of existing methods, make some approximate estimations of the processes from technical and economical points of view. Briefly, the idea is to implement adjustable bouncy compensators (BC) in the process of offshore transportation and installation of oil and gas equipment. Different equipment like subsea production systems, manifolds, templates and PLETs can be tooled up with a BC. This idea will help to eliminate use of offshore cranes during the process of installation, thus an enhanced operability and safety will be achieved due to elimination of the connection between vessel and equipment. The described technology allows one to carry out operations in harsh conditions with large wave height (with given level of safety) and heavy weighted equipment as well. Suggested innovation can be used in combination with other wet installation methods.

Key words: offshore, transportation, installation, dry and wet methods, heavy-weighted equipment, weather restricted operations

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Symbols

A - cross-section area;

α – angle between connection link and horizontal axis or alpha-factor (Chapter 5);

a – acceleration of submerging;

c - length of connection link;

C_D - drag coefficient;

d – duration of an operation (including contingency time);

F_{lift} - lifting force;

F_A – Archimedes force;

F_g - gravity force;

F_{draft} - draft force;

F_{drag} - drag force;

$F_D(d)$ - distribution function;

g – gravity acceleration;

H_s – significant wave height;

λ - parameter of the distribution (expected duration of weather window);

$m_{external}$ - mass of the system’s components (housing, pumps, etc.);

m_{gas} - mass of gas in the tank;

m_{water} - mass of water in the tank;

m_{BC} - mass of the BC system;

m_{cargo} - mass of the cargo;

$m_{template}$ - mass of the template in air;

n – expected number of weather windows for each month;

$\mathrm{OP}_{\mathrm{WF}}$ – operational limit for a significant wave height;

$\mathrm{OP}_{\mathrm{LIM}}$ – operational limit;

Q_p - capacity of injection pumps;

ρ_w - density of water;

ρ_{steel} - density of steel;

T_{POP} - time of operation;

T_{CT} - contingency time;

v - velocity of transportation;

V_w - volume of water inside BC;

V_{BC} – external volume of BC;

V_{cargo} – external volume of cargo;

$V_{template}$ – external volume of the tempalate;

$W_{template}$ – submerged weight of template;

x - coordinates along horizontal axis;

z - coordinates along vertical axis;

Abbreviations

1D – one-dimension;

BC - bouncy compensator;

CDTM - controlled depth tow method;

FAR – fatal accident rate;

GIR – group individual risk;

GPS – global positioning system;

HAZID – hazard identification;

IR – individual risk;

IRPA – individual risk per annum;

PCM – pairwise comparison method;

PIM – pendoulus installation method;

RAC – risk acceptance criteria;

ROV – remotely operated vehicle;

SSCV – subsea construction vessel;

Introduction

Installation of offshore equipment is a huge branch of business in the oil and gas industry. Almost every offshore project requires heavy-weighted equipment, which should be installed on the seabed. Recently, oil and gas companies instead of producing from platforms prefer to develop fields as subsea factories. Mentioned changes result in growing opportunities for offshore service companies, working in the field of transportation and installation, as the workload constantly increases.

Currently, several techniques are used to carry out the full installation activities. The most used one is to transport the equipment by a subsea construction vessel (SSCV) and then transmit the equipment from the deck of the vessel to the seabed by a vessel's crane. Such approach requires to hire a costly vessel – SSCV and have some limitations due to weather restrictions. Moreover, the most up to date SSCV's are not able to operate with cargo's weights more than 500 tons. To carry out the installation of heavy-weighted equipment, such as templates with integrated manifold, two vessels – barge and heavy lift crane vessel should be used. This leads to a significant increase in the installation cost.

The main aim of the work was to develop and prove applicability of a new approach of transportation and installation of heavy-weighted equipment offshore. The research is based on general studies in the fields of Marine Technology and Marine Operations.

After analyzing the existing methods of the full process of installation activity, author came up with a new idea, which is in his opinion, combine all pros and cons of aforementioned.

Scope of work:

- describe technical concept of a new method;
- deduce basic mathematical equations of the process;
- provide risk analysis of a new technology and give risk reduction measures to improve safety of the process;
- carry out the case study for the specific operation;
- estimate economical efficiency and give areas of applicability of the project in the context of existing methods;

Thesis organization:

Chapter 1 (Installation methods overview) provides general information about existing methods of transportation and installation of offshore equipment, theirs advantages and disadvantages, applicability in different weather conditions.

Chapter 2 (Technical description) compromises some technical information about innovation, its design basics, and gives mathematical equations to describe the process as well.

Chapter 3 (Risk analysis) gives risk assessment for the new technology and states basic risk reduction measures to improve the safety of an operation.

Chapter 4 (Case study) contains the solutions of the equations for the specific installation and give rough estimations of system’s dimensions. As an example, installation of Ormen Lange template was chosen.

Chapter 5 (Economic performance) addresses the statistical approach to the installation. Based on the statistics from northern part of North Sea, some economical evaluations were conducted for different methods and weather conditions.

Chapter 1. Installation methods overview

1.1. Transportation on barge

The most common way to transport and install underwater equipment or different structures is to use a barge. The object can be transported on the deck of the barge and then lowered down with a crane, for instance, installed on the barge. If the weight of the cargo is too large, the operation can be carried out by special heavy-lift crane vessels.

Such type of transportation is considered to be relatively fast, but at the same time this method is sensitive to weather conditions like wind and wave forces, slamming and current forces, affecting the cargo (Olsen, 2011). In addition, mentioned kind of transportation requires larger vessels to convey heavy equipment then wet methods do.

The overall installation operation comprises the following steps:

1. Loading of the cargo from shore onto the barge
2. Transportation to the location of installation
3. Lifting the cargo from the deck
4. Lowering the cargo through splash and current zones
5. Positioning of the cargo nearby the sea bed and final release

From a technical point of view, this method faces a great challenge while lowering the cargo through splash and current zone. As long as the structure moves down, it experiences strong slamming loads caused by waves and viscous forces. Furthermore, abrupt change in buoyancy may result in the wire slack and, subsequently serious snag loads. Regarding operations with light weight constructions, buoyancy changing effect can be neglected; however, lowering the heavy weight cargo in the same circumstances has an impact on vessel motion characteristics.

The main economic disadvantages of such approach are:

1) wasting of time while waiting for suitable weather conditions;

2) huge expenses for hiring large vessels, such as barge and heavy lift crane vessel.

Recently wet transportation method has appeared; it offers reasonable solutions overcoming named difficulties.

1.2. Wet transportation

In the wet transportation method, the cargo is immersed under the sea level at a protected location and then towed underwater to the location of installation. Thus, there is an opportunity to carry out all operations without removing the cargo from the water, and the necessity to hire large barges and crane vessels is partly eliminated. Moreover, the risk associated with pendulum motions of the cargo in the air and uplift loads disappears; and the safety of people on deck significantly increases.

Smaller vessels can be used to tow the objects than by barging, what means one more benefit of this method. Additionally, forces of the surrounding environment affecting the submerged cargo are weaker.

1.2.1. Pencil Buoy method

The Pencil Buoy method was developed and patented by Aker Marine Contractors and mainly concerned wet installation. At the same time, it can be applied to the process of structures removing from the seabed. By 2007, the Pencil buoy method has already been used for seven projects including seventeen tows. The wet tow using Pencil buoy method can be designed for an unrestricted summer storm, while the offshore lift operation is a typical weather window operation. Main customers of this technology were Statoil, Acergy and Teekay (Mork & Lunde, 2007).

The first prototype of a Pencil buoy was designed for tows of 150 tons of submerged capacity. Next investigations enhanced this criterion up to 350 tones, and in the future, buoys with 370 tones capacity will be available.

Here is represented the sequence of operations for Pencil buoy method:

1. Transportation of the equipment from fabrication site to load-out site by barge in order to minimize the wet tow distance and ensure better project economy.
2. Structure's lift from the barge to inshore transfer location with sufficient water depth with crane barge.
3. Transfer of the structure's weight from the crane barge to the installation vessel.
4. Connection of the structure's rigging to the installation winch wire and tubular buoyancy tank shaped as a pencil.

The pencil shape was chosen to give the tank a streamlined contour. It results in better performance during installation due to minimization of drag forces.

After all the above actions are completed, equipment gets ready for towing. Normal towing speed is 3-3.5 knots (Risoey, Mork, Johnsgard, Gramnaes, 2007). The Pencil Buoy set up is shown in Figure 1 below.

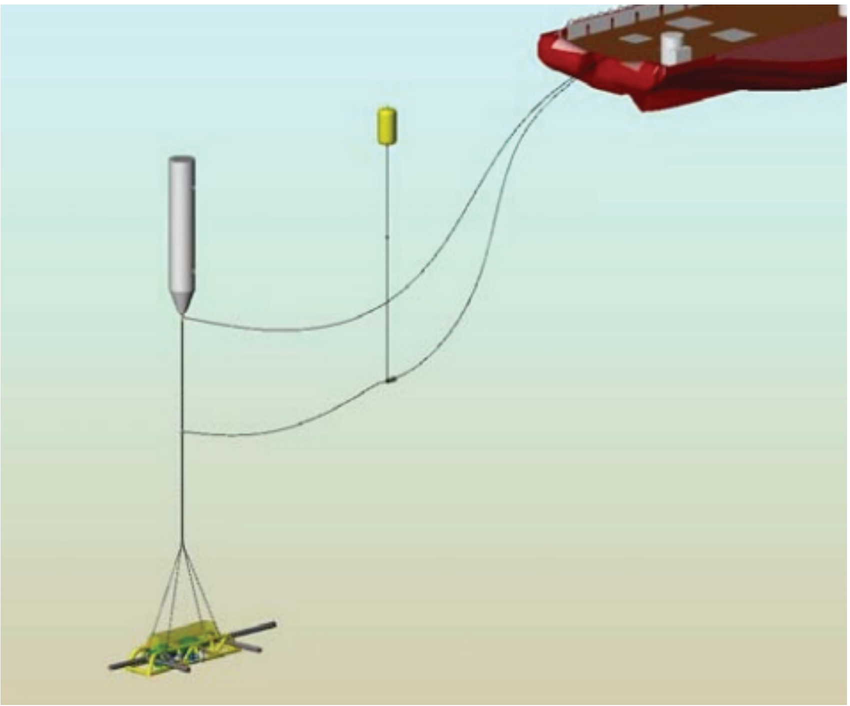


Figure 1.1. The Pencil Buoy set up (Mork & Lunde, 2007)

The Pencil buoy, or tubular buoyancy tank, is a steel structure with internal ring stiffeners. It has watertight compartments, which provide survival of the whole tank in case of one-compartment damage.

Aker proposed to transport subsea structures on the deck of a barge to the load-out location. This improves transportation time, as wet towing velocity is relatively slow. Afterwards, at the load-out site the cargo is lifted from the barge and connected to the installation winch and pencil buoy. The structure starts to sink and the rig's weight is carried by the pencil buoy.

At the installation site the structure's weight is transferred back to the towing winch wire and the buoy is disconnected. Therefore, the structure can be lowered and installed on the seabed. The lowering is implemented using a passive heave compensator.

This method has several advantages in comparison with traditional installation of subsea equipment:

1. There is no risk of cargo pendulum motions in the air.
2. Slamming/uplift loads during lowering through splash zone are excluded.
3. Large deck space for transportation is not needed.
4. Less crane capacity is required.

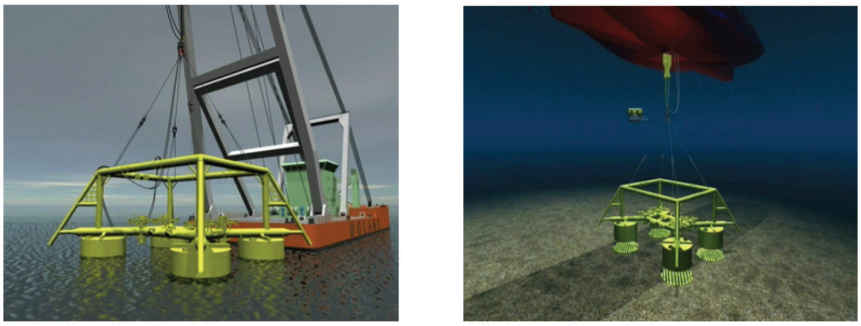
All mentioned negative aspects are eliminated, when the lift is done at the inshore sheltered area.

It has already been said that this approach can also be regarded as a method of structures recovery from the seabed. For instance, in 2006 a suction anchor was successfully lifted from the seabed and then wet towed to the inshore area.

1.2.2. Subsea 7 method

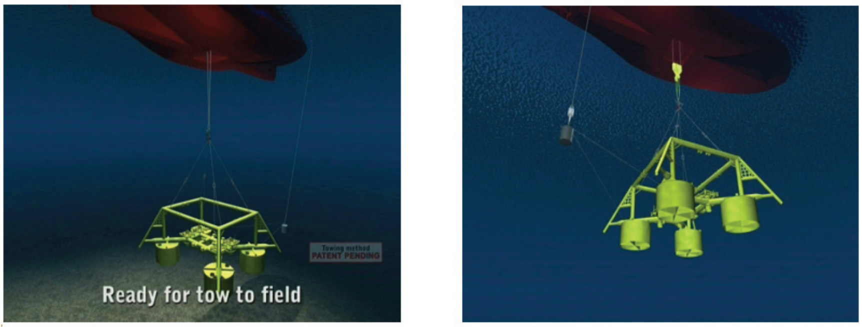
The Subsea 7 method is developed for installation of massive subsea structures in harsh environmental conditions. It enlists the service of a small monohull construction vessel and allows carrying out the installation in a single operation. Subsea 7 promotes this method as more reliable and cost efficient compared to the traditional transportation on the barge.

First implementation of the concept was practiced with light structures, and the transportation was held from the vessel side using the installation crane. Nowadays, towing is done through the moonpool of the vessel, which enables towing of heavy weighted cargos and improves the towing criteria. The hang-off point of the cargo should be as close to the vessels motion center as possible in order to decrease the effects of the vessels motions, what results in good performance in severe weather conditions. For that purposes, the hang-off tower is installed over the moonpool of the installation vessel. Some operational stages are depicted in Figure 2 below.



1. Wet store of the template

2. Pick up and hang-off



3. Tow to field

5. Installation

Figure 1.2. Illustration of four operation stages; wet-store, pick up and hang-off, tow to field and installation (Jacobsen & Næss, 2014)

There are several challenges related to this installation method. All of them can be divided into several groups:

- Geographic
  - Harsh environmental conditions
- Template properties
  - Massive weight
  - Large outer dimensions
  - Large hydrodynamic loads on the structures and suction anchors in case of closed structures creating large surface loads
- Operational
  - Heavy rigging
  - Working close to the vessel's crane capacity limit because of radius limitation for safe deployment

The overall installation process consists of following operations:

- Wet-store of template
- Pick up and hang-off
- Tow to field
- Transfer load to heavy lift winch system
- Landing of subsea template within the installation criteria

This method was successfully applied to install four massive templates for the Tyrihans project. Company reported that installation expenses were significantly lower than the cost of using a heavy lift vessel, and all operations were held in a safe manner. Consequently, the following conclusions were made (Aarset, Sarkar, Karunakaran, 2011):

- No manual handling of heavy rigging offshore
- All heavy lifts were performed inshore in sheltered waters
- Extremely limited exposure to personnel
- Cost-effective solution
- Depends on availability of vessels
- Limited use of "sophisticated" cranes and crane modes subject to higher risk of technical / software failures
- Increased tow speed is achievable at lower seastates

1.2.3. Pendulous Installation Method

The Pendulous Installation Method (PIM) was developed by Petrobras to install large manifolds in water depth of 1900 meters. PIM is a non-conventional technique, which was designed taking into attention the low availability and high cost of deepwater construction vessels and heavy lift vessels. This method involves small conventional deepwater construction or offshore support vessels, without special rigging systems. PIM is capable to deploy heavy manifolds or other equipment in water depth up to 3000 meters.

To install subsea structure onto the seabed, two small installation vessels are used. Vessels are equipped with a conventional steel wire winch system as a launch line to give the structure pendulous motion, while synthetic fiber rope is used for final deployment of the structure onto the seabed. During installation, two vessels are used. First vessel is equipped with crane to transfer the cargo from the vessel to a certain depth in water through the splash zone. Afterwards, the load from the crane is gradually transferred to the launch winch wire. To reduce the winching capacity requirement for both the launch winching system and the deployment winching system, the deployment rope is pre-rigged with the lifting slings of the manifold and fit out with a number of buoyancy elements. Finally, to deploy the manifold vertically, position and install it into the target zone on the seabed, the deployment winch is used.

The PIM is a cost effective solution in comparison with conventional methods of installation, for instance, installation with heavy lift vessels or expensive drilling rigs. However, due to the complex geometry of the manifold, hydrodynamic instability may occur during installation. Therefore, to prevent rotation of the cargo, an anti-rotation system such as counter weights should be installed. Installation process is shown in Figures 3 and 4 below.

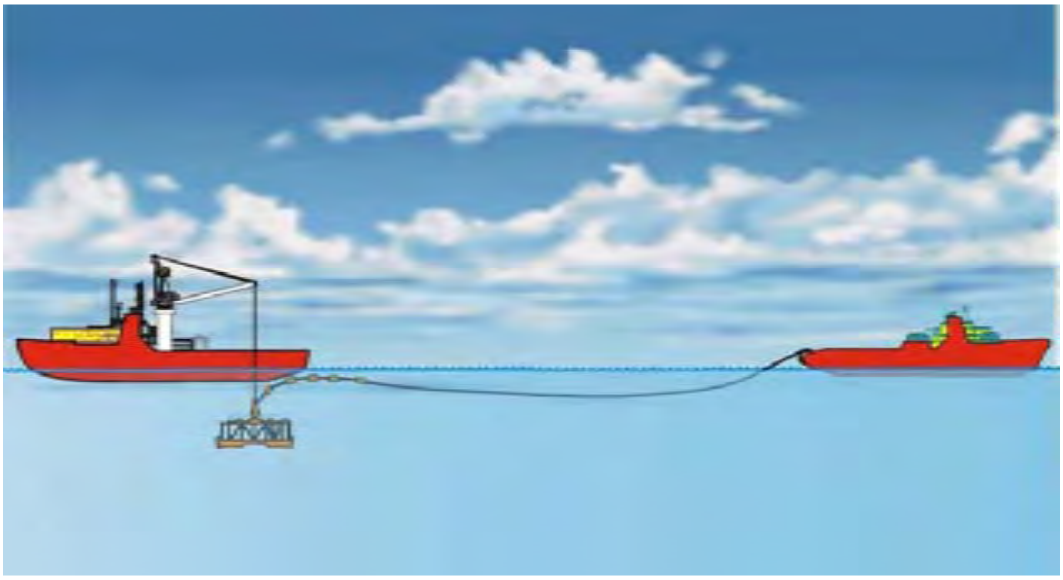


Figure 1.3. Illustration of Manifold Overboarding (Wang et al., 2012)

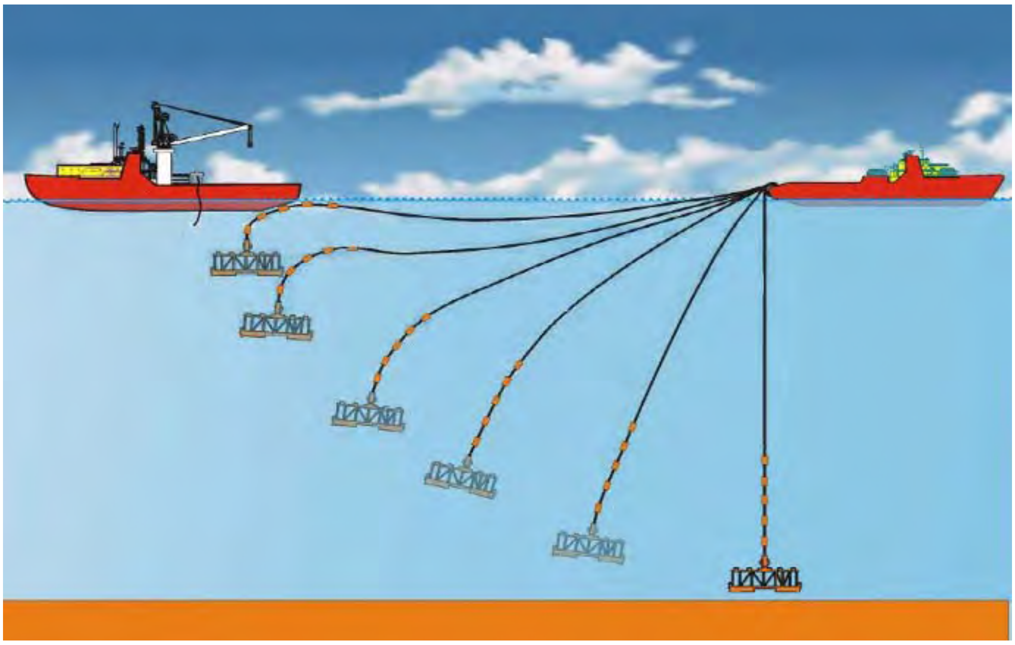


Figure 1.4. Illustration of Pendulous Motion to Lower Manifold (Wang et al., 2012)

1.3. Methods for transportation of pipelines

Various operations with pipelines like fabrication, welding and testing of them are preferably done onshore. It is obvious, that the same operations held offshore would be much more expensive because of high day rates of special pipe lay vessels. Solution of the problem can be found in wet towing of an already fabricated pipeline; which leads to the safe and controlled operation, well-qualified fully tested onshore product.

Tow technique depends on several factors, such as:

- submerged weight of the pipe
- length of the towed system
- weather conditions
- seabed properties
- existing pipelines along the towing route

There are three main techniques, which are widely used nowadays: off-bottom tow method, control depth tow method and catenary tow.

1.3.1. Off-bottom tow method

When the seabed conditions are well known and the location of installation is predetermined, off-bottom tow method can be used. The idea of this method is to control stability and submerged weight of a pipeline through installation of buoyancy tanks and chains at frequent intervals. This allows controlling the submerged depth of the bundle, Figure 5.

The Off-bottom towing method is only applied for limited water depth, as the cost of the method increases with water depth. In addition, the off-bottom towing method has relatively low towing velocity compared to other techniques. However, there is an essential advantage that fatigue damage is smaller because the pipe is located further away from the surface.

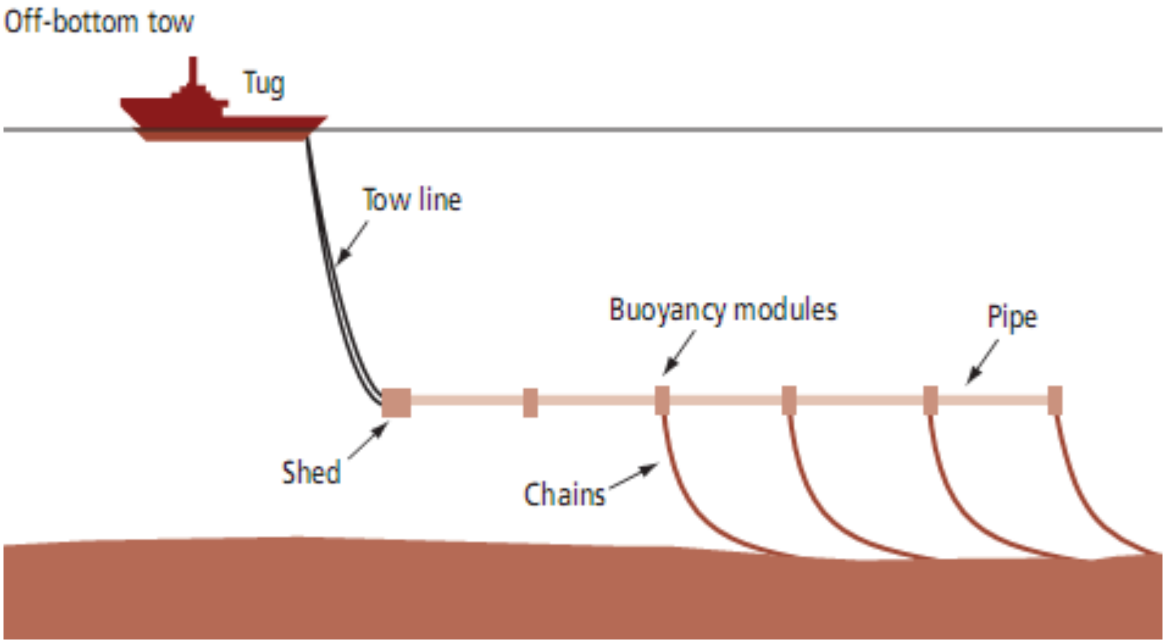


Figure 1.5. Off-bottom tow method (Olsen, 2011)

1.3.2. Controlled depth tow method

The controlled depth tow method (CDTM) is used for towing a pipeline from a predetermined point to a temporary location offshore. To transport a pipe, two tug boats are needed: leading and trailing tug. A bundle is kept between two mentioned vessels. Buoyancy elements and chains are still necessary; nevertheless, the overall buoyancy in this case is negative, Figure 6. It is important to figure out that the drag on chains creates a lift which affects the submerged weight. The lift produced by the chains depends on the speed of water, type of chains and number of links.

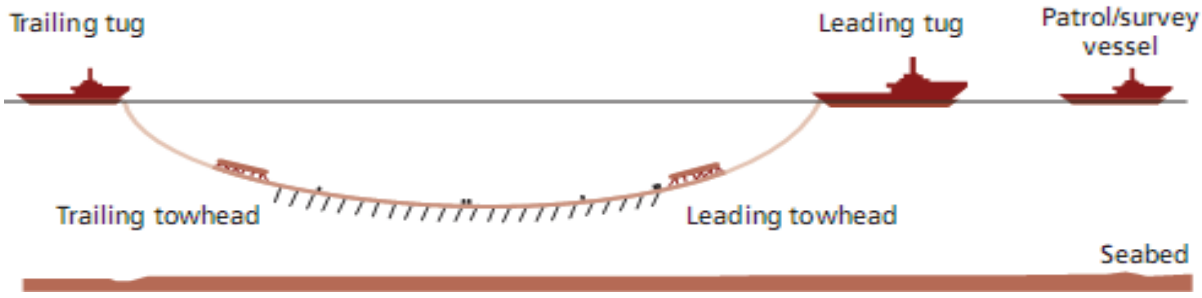


Figure 1.6. Controlled depth tow method (Olsen, 2011)

Several advantages of CDTM can be pointed out:

- towing velocity is higher than in the off-bottom tow method (up to 6.8 knots)
- no contact between pipe and the seabed (slopes and underwater rocks can be easily passed by)

1.3.3. Catenary tow

At the installation site buoyancy tanks and chains are removed and a catenary tow is performed. While the bundle is hanging between the two tugs, contact with the seabed should be avoided. Therefore, this method is not appropriate for shallow waters as the required horizontal bollard pull forces needed to keep the pipeline sag-bend off the seabed are too high for conventional tugs. The scheme of catenary tow is depicted in Figure 7 below.

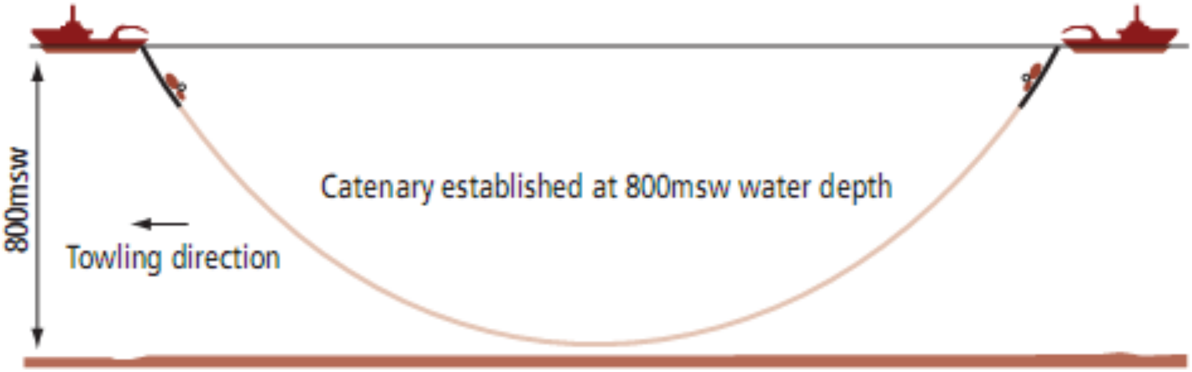


Figure 1.7. Catenary tow (Olsen, 2011)

Chapter 2. Technical description

2.1. Buoyancy compensator

In order to achieve a given buoyancy, a Buoyancy Compensating (BC) system can be used as well. In general, a ballasting system is a box-shaped tank filled with gas (air) and salt water (ballasting agent). Water or air is used to increase/decrease the mass of the system, thus buoyancy can be changed. To control the amount of water in the tank, pumps can be used. The main requirement for the pumps – they should be able to operate underwater and vary their capacity. Principle scheme of a BC is shown on the Figure 2.1.

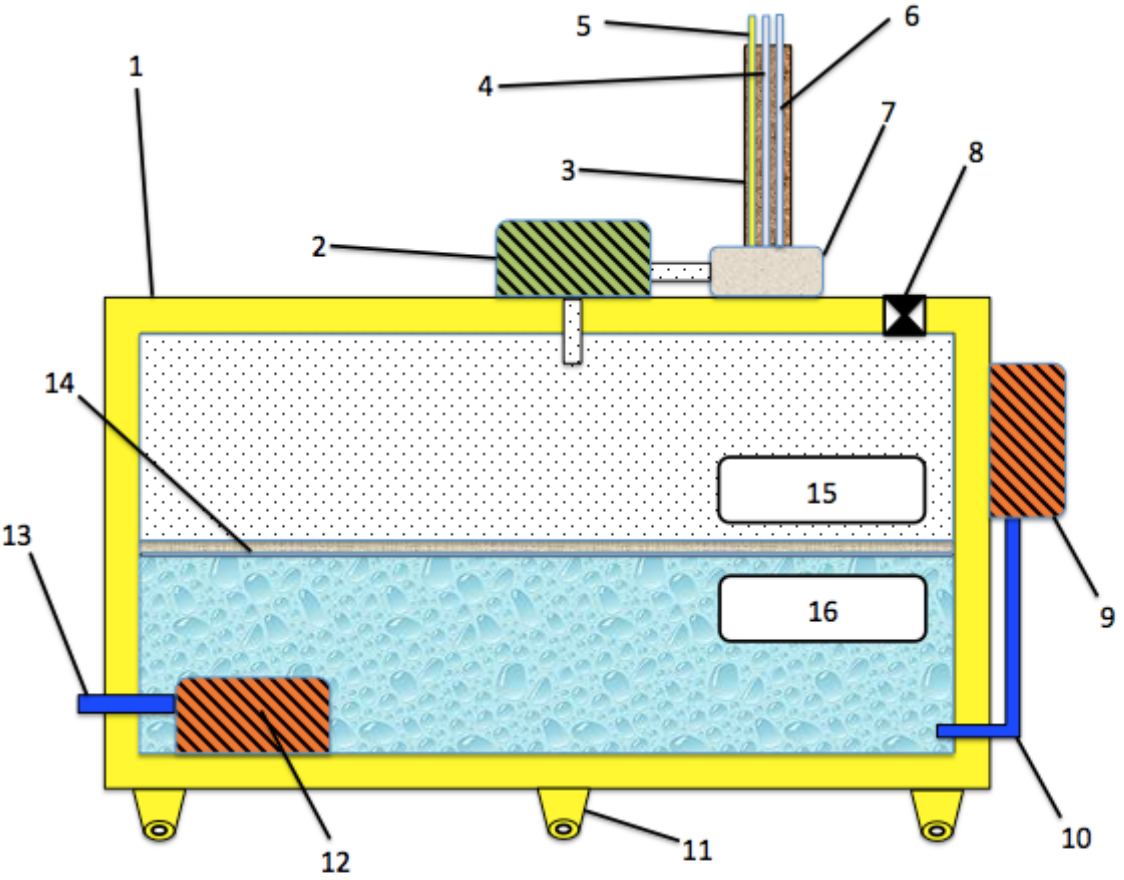


Figure 2.1. Buoyancy compensator, Principle Sketch

1- BC's body

2- Compressor

3 – Flexible Umbilical

4 – Electric cable

5 – Air line

6 – Optic fiber cable
7 – Umbilical connection device
8 – Pressure relieve valve
9 – Water injection pump
10 – Water injection line
11 – Connection device
12 – Water take off pump
13 – Water remove line
14 – Baffle
15 – Air
16 - Water

2.1.1. General description

To control and supply a BC with air and electric power, a flexible umbilical is used, which consists of:

-Air supply line

-Electric cable

-Fiber optics cable

In order to eliminate a rigid connection between the vessel and the BC, the umbilical should be flexible. As a result, the vessel's motions will not influence on the BC, which gives the opportunity to operate in more severe conditions. To connect the umbilical with the BC, a special devise is used. It comprises a control module and a distribution system to deliver gas or electric power to a compressor or the pumps respectively.

Inner space can be separated into sections to decrease effects induced by water movements inside the body, as well as giving the possibility to control the buoyancy partially, thus to manage the processes of installation and transportation more precisely.

Each section should be divided by a movable baffle, which separates gas from liquid, and be equipped with water injection/withdraw lines and a relief valve to control the amount of water and pressure inside the section.

The only way to manage all injection and withdraw operations of gas and water is to use underwater compressors and pumps due to response time, which could be significant in case, when pumps and compressors are installed on a vessel. As it was mentioned before, they should be able to work underwater. Moreover, all of them must be powered by electric power.

The transported cargo is linked with the BC by use of connection mechanisms. They may be designed in two ways. First is an ordinary mechanical system, which requires external force for disconnection. This force e.g. could be provided by a ROV. Another way is to hold the cargo by electric magnets. It gives us capability to disconnect the cargo remotely, but requires a big amount of electric power to operate the magnet, which could be an unsolvable task taking into account offshore conditions.

The steering system is of no small importance. It's consists of:

- positioning tracking device;
- dynamic positioning system (rotating propellers and system of blades);
- regulation of buoyancy.

The combination of three systems listed above gives us the ability to manage the submerged depth very accurate.

2.1.2. Physics behind

The difference between gravity force and Archimedes force is a lifting force. Following equation describes lifting force: $F_{lift} = F_A - F_g = \rho_w\, g\, V - mg$ (2.1);

As we can see from the equation, the lifting force can be changed by changing the volume of the buoyancy compensator or by changing the mass. A system with the ability to change the volume ("air balloon") requires the use of elastic materials and underwater compressors to operate the variation in volume. Moreover, in this case we should deal with compressible medium, which is hard to use. Thus, the second option will be considered in this work.

The overall mass of the system can be written as: $m = m_{external} + m_{gas} + m_{water}$ (2.2);

Where $m_{external}$ - mass of the system's components (housing, pumps, etc.);

m_{gas} - mass of gas in the tank;

m_{water} - mass of water in the tank;

The external mass will be constant in the process, when mass of the gas and water can be varied.

2.2. Ways to connect BC with cargo

There are 3 ways to realize the connection between the BC and the cargo:

1. To place the BC on top of the cargo.
2. Place the cargo inside BC.
3. Install BC along the edges of the cargo.

Each way has its own design and performances during operations. You can see these ways on the Figure 2.2.

Figure 2.2. Ways to connect BC with cargo

Lets compare these ways in respect to operations and design. The comparison is presented in the Table 2.1.

Table 2.1. Comparison of different ways to connect BC with cargo

	BC on the top	Inside BC	Along the edges
1. Design	Can be designed for useing the same BC with different cargos	Only for appointed cargos in respect to sizes (due to certain opening in the BC)	Only for appointed cargos in case of solid BC and for all types of cargos if clustered BC

2. Transportation	1. Larger drag forces due to larger cross-section area (normal to the direction of towing) 2. Buoyancy concentrated in the middle of the cargo, which results in good predicament to control the system during transportation	1. Medium (among three) cross-section area, so drag forces have intermediate values 2. BC is spread along the area of the cargo which results in perfect control ability	1. Lowest cross-section area, as a result low resistance to flow 2. The same control ability as in the case "Inside BC"
3. Installation	Cross-section area determined by the size of the cargo, drag forces and added mass have minimum values	Slight increase of the cross-section area leads to insignificant increase in drag forces, but added mass increase significantly	Drag forces and added mass increase significantly

As we can see from the comparison, each way has its own pros and cons. A satisfactory compromise will be a solution, where BC is spread along the whole top area of the cargo. Such asolution has a cross-section areas, which results in lower drag forces (extremely important in the towing operations), and has perfect controlling performances during transportation and installation.

2.3. Transportation

There are two options to carry out the transportation of the equipment.

First, the traditional way is to use a barge to deliver the equipment with the installed BC to the location. Such an approach requires hiring a costly vessel (barge) to transport the equipment. Furthermore, special weather conditions are claimed, which may result in increasing the cost of the transportation due to "waiting for the necessary weather".

Second, the innovative way, is to use tugs and transport the equipment on the sea surface or underwater. In this case we don't need expensive barges and, perhaps, we will be able to operate in more severe conditions.

First, the overall buoyancy of the system is positive. In this case, the towed equipment is floating on the sea surface. Such an approach has several pros and cons, which are in the Table 2.2.

Table 2.2. Pros and Cons of transportation by towing at the surface

Pros	Cons
1. No need to adjust buoyancy of the system. 2. Easy management of the transportation process.	1. Wave and wind impact. 2. Impossible to use in ice conditions. 3. Impacts from currents

The second way, is to tow cargo underwater. It allows us to eliminate wave or wind impact on the system. Moreover, it makes it possible to tow the equipment in ice conditions without risk of damaging. However, this method requires adjusting the buoyancy and use of dynamic positioning for the safe transportation, as well as computers to control at a certain depth of submerging and orientation in space.

2.3.1. Lifting operations within a harbor

All subsea equipment is fabricated on the shore in workshops. To transport it to the location of installation we need transfer the equipment from the harbor's pier to the sea surface.

In the case with a crane barge, we use onshore cranes to load the equipment on the deck of the barge. Main restrictions here are draft of the barge and suitable weather conditions. Normal draft for subsea construction vessels is 6.5-7 meters. For instance, Subsea 7's Scandi Acergy subsea construction vessel has a maximum draft 8.5 meters (Subsea 7, 2015). It is obvious that harbors should be able to accommodate such vessels and have enough water depth. You can see a photo of the Scandi Acergy vessel on Figure 2.3.

Figure 2.3. Scandi Acergy subsea construction vessel (Subsea 7, 2015)

In case of wet transportation, the most convenient way is to install the BC on the equipment in the workshop onshore and then transfer it to the sea surface by a crane. The main limitation here is the draft of the system, as our equipment is located under sea surface. In Chapter 4 "Case Study" we will calculate the exact draft of the system.

Nevertheless, if the water depth in harbor is not enough to accommodate wet system, several solutions could be applied.

2.3.1.1. Swiping from the pier

The first step is to install the BC on the equipment and lower the system to the sea. It can be done onshore with the help of a crane. After, we need to connect an umbilical and a towing line. To avoid the use of a huge crane, the cargo with the installed BC can be “swiped” to the sea on a slide rails by a tugboat and then submerged to a certain depth. This process is shown on the Figure 2.4.

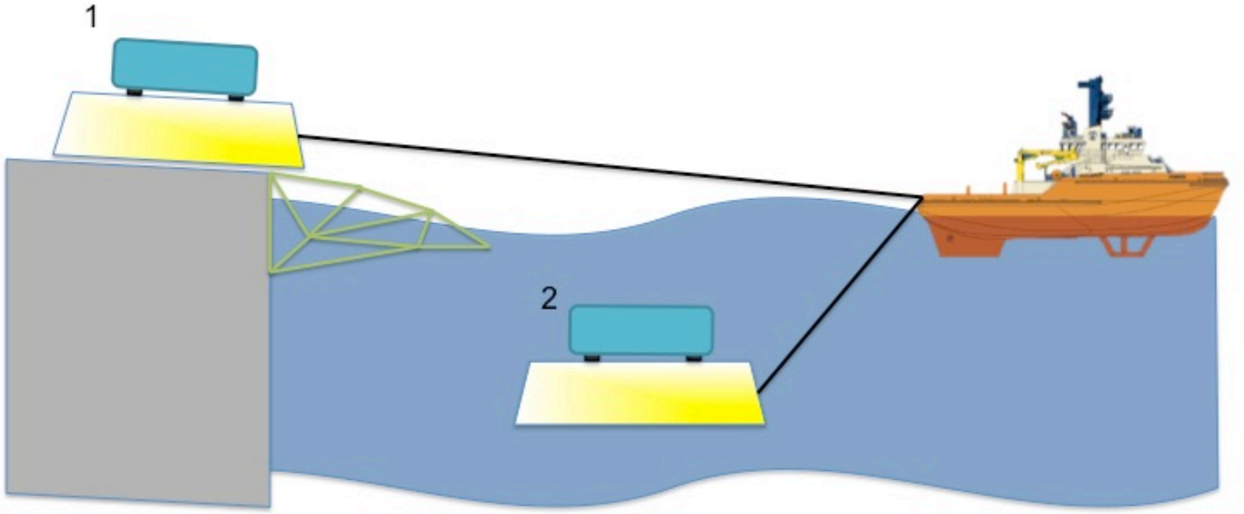


Figure 2.4. Swiping of the system to the sea

1 – pushing the equipment from the pier to the sea surface on rails

2 – submerging the equipment to a certain depth

2.3.1.2. Use crane vessel to transport the system to deeper area

The system with a pre-installed BC can be transported from a harbor’s shelter area to a deeper location and then lowered to the sea surface. At the position of offloading, the system with the BC should be connected with a tug boat for further transportation to the location of the installation.

Such approach minimizes the time of using highly cost crane vessel, as the distance between the shelter area and a deeper one is usually not very long. Moreover, if possible, the crane installed on the vessel, could be used to transfer equipment from the pier to deck of the vessel. It is a useful option, if the onshore crane is not available.

2.3.1.3. Use semi-submersible barges for transportation to deeper area

As in previous method, the system is loaded on the barge by means of onshore cranes and then transported to the deeper area. On the location of transfer of the loading, the system should be connected with the tug boat and then the barge submerges, making the system with BC to float. At this point all work is carried out by the BC and the tug.

Such an approach eliminates the offshore crane operations and is supposed to be a cheaper option, as a semi-submersible barge is normally less expensive, than a subsea construction vessel. However, semi-submersible barges are designed to transport heavy cargos, for instance, jack-ups. As a result they are large vessels and may not be available for rent. A schematic view of the transportation process is shown on the Figure 2.5.

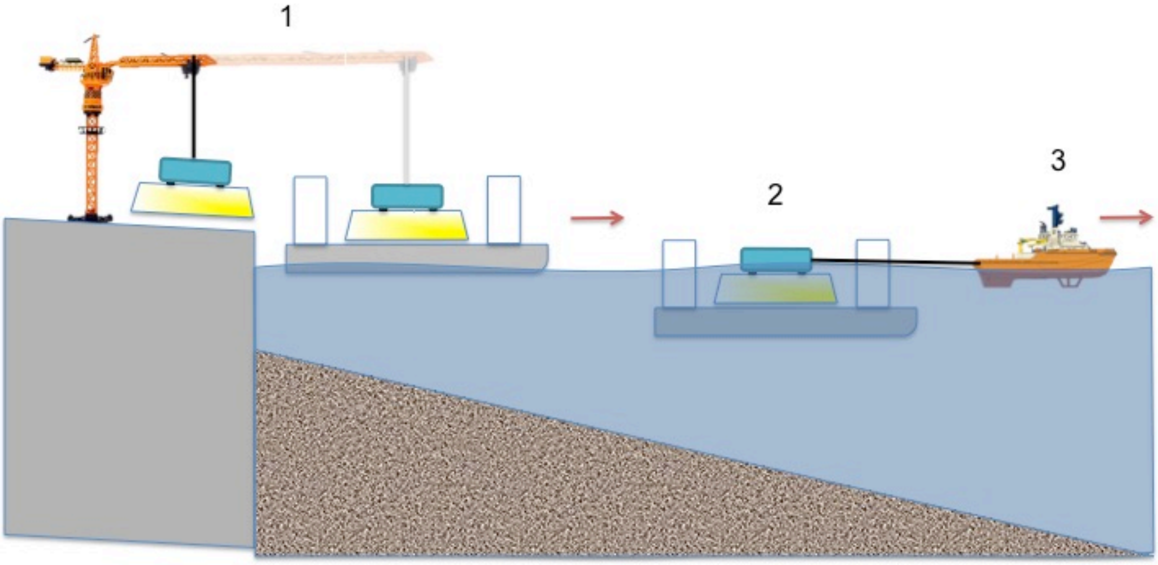


Figure 2.5. Transportation by semi-submersible barge

1 – loading the equipment on the deck of semi-submersible barge

2 – transportation to the deeper location or to the location of installation

3 – towing the equipment away from the barge

One of the examples of semi-submersible barges could be the vessel Teras 002, which belongs to Teras Offshore. Specification of the vessel is listed in Table 2.3.

Table 2.3. Teras 002 specification (Teras Offshore, 2015)

Year built	2009
Gross tonnage, t	9741

Net tonnage, t	12922
Deadweight, t	19300
Deck Strength, t/m^2	20
Length, m	116,8
Breadth, m	36,58
Draft, m	7,6
Submersible depth (above main deck), m	7

Figure 2.6. Teras 002 semi-submersible barge (Teras Offshore, 2015)

Figure 2.6 shows Teras 002 semi-submersible barge in normal and submerged positions.

Obviously, the main purpose of such vessels is to transport heavy topsides or drilling rigs. But the construction of smaller vessels of such type could be reasonable in respect to installation of subsea equipment.

In addition, transportation of the system with pre-installed BC could be done not only to the deeper locations within a harbor, but to the installation point offshore as well. In such case, transportation is held traditionally – a dry method. On the position of the installation, barge submerges and further work is done by the BC. Using thrusters, installed on the BC system, equipment could also be towed outside the barge.

Main advantage is time for transportation and absence of offshore lifting operations. Such carriers could achieve relatively fast speed (up to 15 knots), and when wet methods are used, only within 3-5 knots. It will result in better economic performance. However, small semi-submersible barges are not existing on the market and should be additionally engineered and constructed.

2.3.2. Towing force

As our system is in water we can start towing. First of all we need to find the sufficient draft force to carry out the transportation. You can see the forces acting on the system on the Figure 2.7.

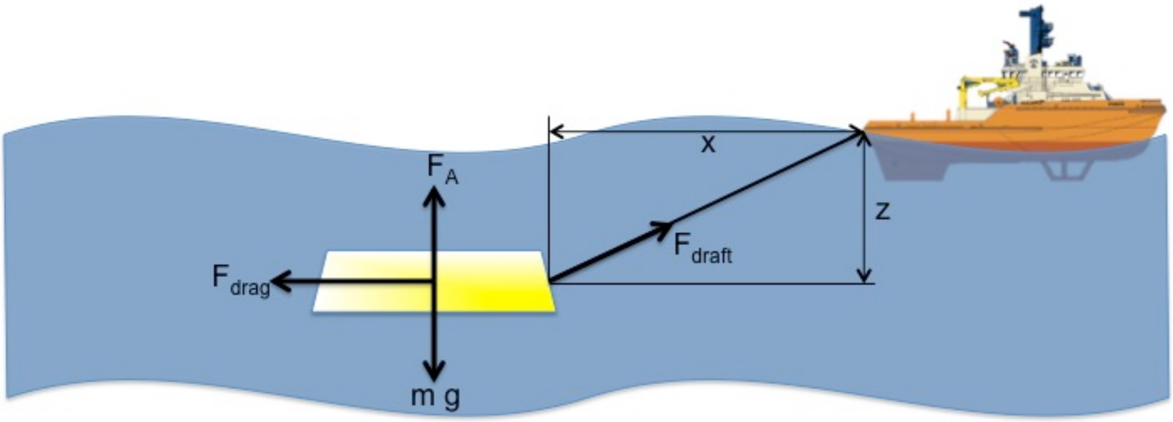


Figure 2.7. Forces acting on the system

In general, from the equation of motion we have:

$$F_{draft} \cos\alpha - F_{drag} = ma \ (2.3)$$

For the simplicity we will consider that our motion is uniform, thus there aren't any accelerations in our system and the velocity is constant. It could be a good approximation when there are no waves. The angle α is an angle between the rope and the horizontal axis. Thus, we have:

$$a = 0 \ (2.4)$$

$$\text{tg}\,\alpha = \frac{z}{x} \rightarrow \cos\alpha = \cos\left(arctg\ \left(\frac{x}{z}\right)\right) (2.5)$$

$$F_{drag} = \frac{1}{2}\rho_w\ C_D\ v^2\ A \ (2.6)$$

$$F_{draft} = \frac{F_{drag}}{\cos\alpha} = \frac{\rho_w\ C_D\ v^2\ A}{2\ \cos\ (\text{arctg}\ (\frac{z}{x}))}\ (2.7)$$

where ρ_w is a density of water, C_D - drag coefficient, v - velocity of transportation, A - cross-section area, z – horizontal distance between points of connection of the rope, x - vertical distance between points of connection of the rope.

The projection of the forces on a vertical axis gives us condition to keep the system at a certain depth.

$$F_{A.cargo} + F_{A.BC} + F_{draft} \sin\alpha - m_{cargo} g - m_{BC}\, g = 0 \ (2.8)$$

Note that the force from thrusters is not included. The most work will be performed by the BC, and the propellers are just for dynamic positioning. As only the mass of the BC can be varied in the equation above, the condition of stability will be:

$$m_{BC} = m_{external} + m_{gas} + m_{water} \ (2.9)$$

Mass of the gas is negligible compare with the masses of other components:

$$m_{BC} = m_{external} + m_{water} = m_{external} + \rho_w\, V \ (2.10)$$

$$V_{water.BC} = \frac{F_{A.cargo} + F_{A.BC} + F_{draft} \sin\alpha - m_{cargo} g - m_{external}\, g}{\rho_w\, g}$$

$$= \frac{\rho_w g\, V_{cargo} + \rho_w g\, V_{BC} + \frac{1}{2}\rho_w\, C_D\, v^2\, A \operatorname{tg}\alpha - m_{cargo} g - m_{external}\, g}{\rho_w\, g}$$

$$= V_{cargo} + V_{BC} + \frac{1}{2\, g} C_D\, v^2\, A \operatorname{tg}\alpha - \frac{m_{cargo} + m_{external}}{\rho_w}$$

$$= V_{cargo} + V_{BC} + \frac{z}{2\, g\, x} C_D\, v^2\, A - \frac{m_{cargo} + m_{external}}{\rho_w} \ (2.11)$$

During transportation, the vessel will face some motions due to waves. As our system is linked with the tugboat, it will be influenced as well. More detailed, the draft force, which is applied to the cargo at a certain angle, will try to push the system upwards, thus our system with zero buoyancy will aspire to the top. This process should be studied more precisely by means of using computer software, like OrcaFlex etc. However, these phenomena can be managed by real time regulation of buoyancy and dynamic positioning.

The weakest element in the system is the rope between the vessel and the cargo and the connection points with the rope. It is obvious that the rope should be able to stand against the loads.

2.3.3. Immersion depth control

One of the main challenges of wet transportation is to control the depth of immersion during operation. As it was described in the previous section, due to neutral buoyancy and link between vessel and BC, the system will tend to emerge to the sea surface. This process is shown on the Figure 2.8.

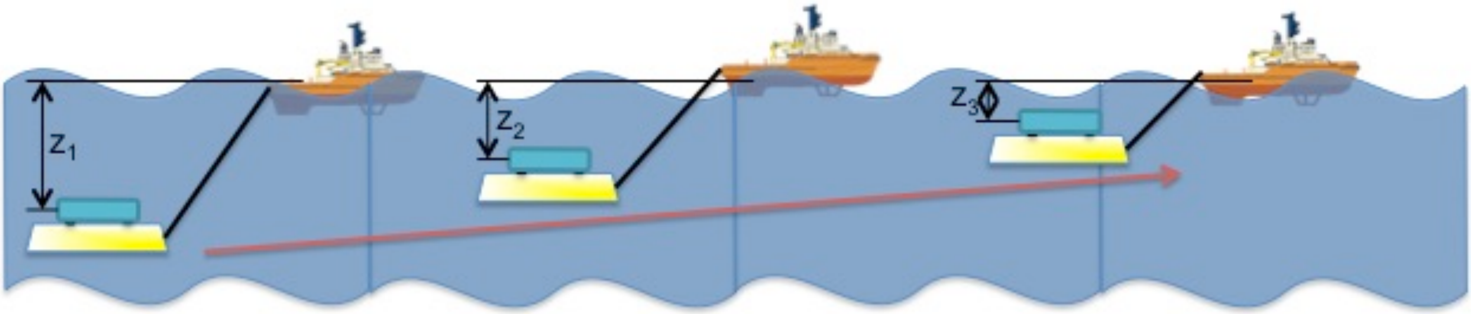


Figure 2.8. Immersion depth changes

We assume that our subsurface system is neutral buoyant (gravity and Archimedes' forces are compensated), so the only forces acting on the system are the draft force coming from the vessel through the link and the drag forces due to system's motions in water. Acting forces are shown on Figure 2.9. Note that the picture is made not at scale.

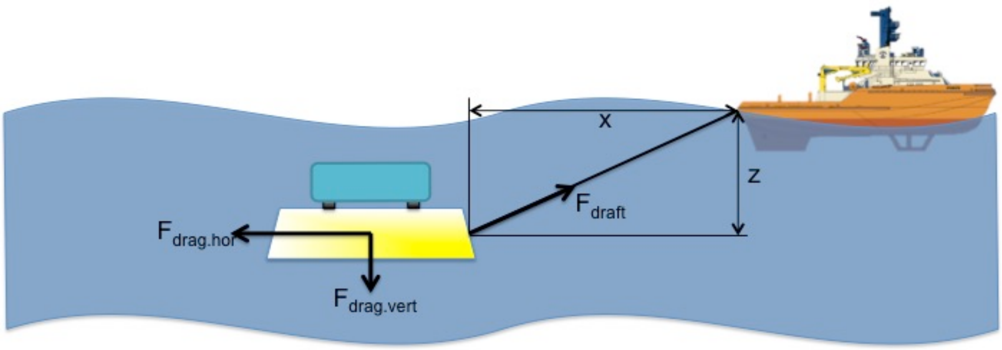


Figure 2.9. Force balance

Lets write the force balance equations for horizontal and vertical axes.

The force balance for the horizontal axis:

$$\overrightarrow{F_{draft}} - \overrightarrow{F_{drag.hor}} = m\vec{a} \text{ (2.12)}$$

where F_{draft} is a draft force, coming from the vessel through the link, $F_{drag.vert}$ - drag force in vertical direction, m - total mass of the system, a – acceleration.

As in the previous section, we will assume that transportation is held in still water conditions (no waves), so the movements of the system are uniform ($\vec{a} = 0$). According to the statement above, force balance can be re-written in next form:

$$\overrightarrow{F_{draft}} - \overrightarrow{F_{drag.hor}} = 0 \text{ (2.13)}$$

The same equation can be written for vertical axis:

$$\overrightarrow{F_{draft}} - \overrightarrow{F_{drag.vert}} = 0 \text{ (2.14)}$$

Lets decompose each component in the equations and combine these into one system:

$$F_{draft} \cos\alpha - \frac{1}{2}\rho_w \, C_D \, {v_x}^2 \, A_1 = 0 \text{ (2.15)}$$

$$F_{draft} \sin\alpha - \frac{1}{2}\rho_w \, C_D \, {v_z}^2 \, A_2 = 0 \text{ (2.16)}$$

From the system above, from second equation let us find the velocity of ascending v_z:

$${v_z}^2 = \frac{2 \, F_{draft} \sin\alpha}{\rho_w \, C_D \, A_2} \text{ (2.17)}$$

From the equation 2.17 let uss find draft force F_{draft}:

$$F_{draft} = \frac{\rho_w \, C_D \, {v_x}^2 \, A_1}{2 \, \cos\alpha} \text{ (2.18)}$$

Now, we can substitute the last equation into the equation of velocity of ascending. The resulting equation will be:

$${v_z}^2 = \frac{A_1}{A_2} v_x \operatorname{tg}\alpha = \frac{A_1}{A_2} v_x \frac{z}{x} \text{ (2.19)}$$

In the equation above, the velocity v_x - is the towing velocity. We will assume that this velocity is constant during transportation. Next step, is to differentiate last equation in odder to obtain changing of immersion depth in time. For that purpose we should exclude x component from the equation. As z and x are the legs of a rectangular triangle, we can write $c^2 = z^2 + x^2$ or $x = \sqrt{c^2 - z^2}$ (2.20). Note that c is the length of the connection link. We will consider that the rope is stiff enough, so its length will not change during operations. Thus, the final equation will be:

$$v_z{}^2 = \frac{A_1}{A_2} v_x \frac{z}{\sqrt{c^2 - z^2}} \quad (2.21)$$

As $v_z = \frac{dz}{dt}$, the last equation will transform to:

$$(\frac{dz}{dt})^2 = \frac{A_1}{A_2} v_x \frac{z}{\sqrt{c^2 - z^2}} \quad (2.22)$$

The exact solution is hard to find analytically, we will use numerical methods to solve this equation in Wolfram Mathematica. The programs script is in Appendix 3. They will be shown in Chapter 4 “Case study”.

Shown physics of the process documents that our system will tend to ascend during transportation. To prevent this effect, several techniques can be implemented.

2.3.3.1. Immersion depth control using BC

The BC system can be divided into several slots, each slot will have its own water injection/removal system. This allows to change buoyancy partly, for instance, the front part of the towing system will have negative buoyancy, while the tail will remain neutral buoyant. This will help to compensate the largest draft forces coming from the tug boat through the connection link.

As the draft forces are not constant, due to unstable weather conditions and complexity of the vessel’s motions, the BC system should be able to vary the buoyancy of the slots. Level of water in slots will be controlled by a computer system and buoyancy adjustments will be done automatically, based on the data obtained from the sensors, installed on the BC and the vessel.

However, such an approach will not give full control of the depth of immersion, due to impossibility of the system remaining at a the certain depth, when it has zero buoyancy. Even a small change in force balance will lead to changes in depth. Moreover, changing of level of water in slots has response time and instant adjustment of buoyancy is not possible. Nevertheless, it is possible to compensate a major part of the draft force, coming from the vessel.

2.3.3.1.1. Mathematical model

The main idea of the method is to increase the mass of the part of the system, which will give the opportunity to keep all forces acting on the system in balance. For that purpose we will inject additional amount of water in the slot, located near the connection point of the BC and the towing line. Normally, when a system is neutral buoyant, all forces, such as gravity force and buoyancy force, compensate each other. When we apply draft force through connection link (during transportation), the system will be misbalanced. To compensate such an effect we will add certain amounts of water to the BCs slots. Force balance during transportation is shown on the Figure 2.10.

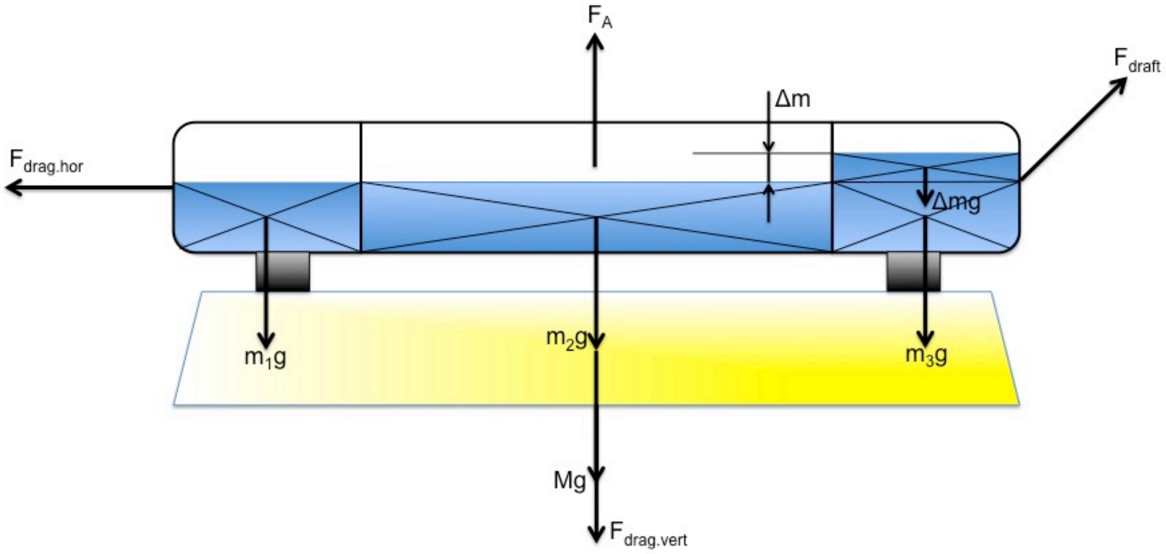


Figure 2.10. Added mass for draft compensation

The resulting system of the equations will be almost the same, as shown in previous section. The only difference is in the added mass component in equation 2.22. The resulting equation is:

$$(\frac{dz}{dt})^2 = \frac{A_1}{A_2} v_x \frac{z}{\sqrt{c^2 - z^2}} - \frac{2\,\Delta m\, g}{\rho_w\, C_D\, A_2} \quad (2.23)$$

where Δm - added mass of the slot. Note, that added mass is a time dependent variable. Its value is based on the capacity of the injection pumps. We can calculate the added mass using next formula:

$$\Delta m = \rho_w Q_p\, t$$

$$(\frac{dz}{dt})^2 = \frac{A_1}{A_2} v_x \frac{z}{\sqrt{c^2 - z^2}} - \frac{2\, Q_p\, t\, g}{C_D\, A_2} \quad (2.24)$$

where Q_p - capacity of injection pumps (m^3/s), t – pump working time (sec).

Our goal is to obtain a constant depth during transportation, thus $\frac{dz}{dt} = 0$. Lets re-write equation 2.23 with a new condition and find the additional mass of the water in system.

$$\frac{A_1}{A_2} v_x \frac{z}{\sqrt{c^2 - z^2}} - \frac{2\,\Delta m\, g}{\rho_w\, C_D\, A_2} = 0$$

$$\Delta m = \frac{A_1\, \rho_w\, C_D}{2\, g} v_x \frac{z}{\sqrt{c^2 - z^2}} \quad (2.25)$$

2.3.3.2. Blades system

In previous section it was described that immersion depth control by means only of the BC system is difficult due to the impossibility of balancing buoyancy forces during transportation. Thus, the system should be somehow improved to achieve the requirements of controlled depth towing. One of the possible solutions is to supply the BC with a rotating blades system. The same principle is used in submarines to control the immersion depth. The configuration of a blades system is shown on the Figure 2.11.

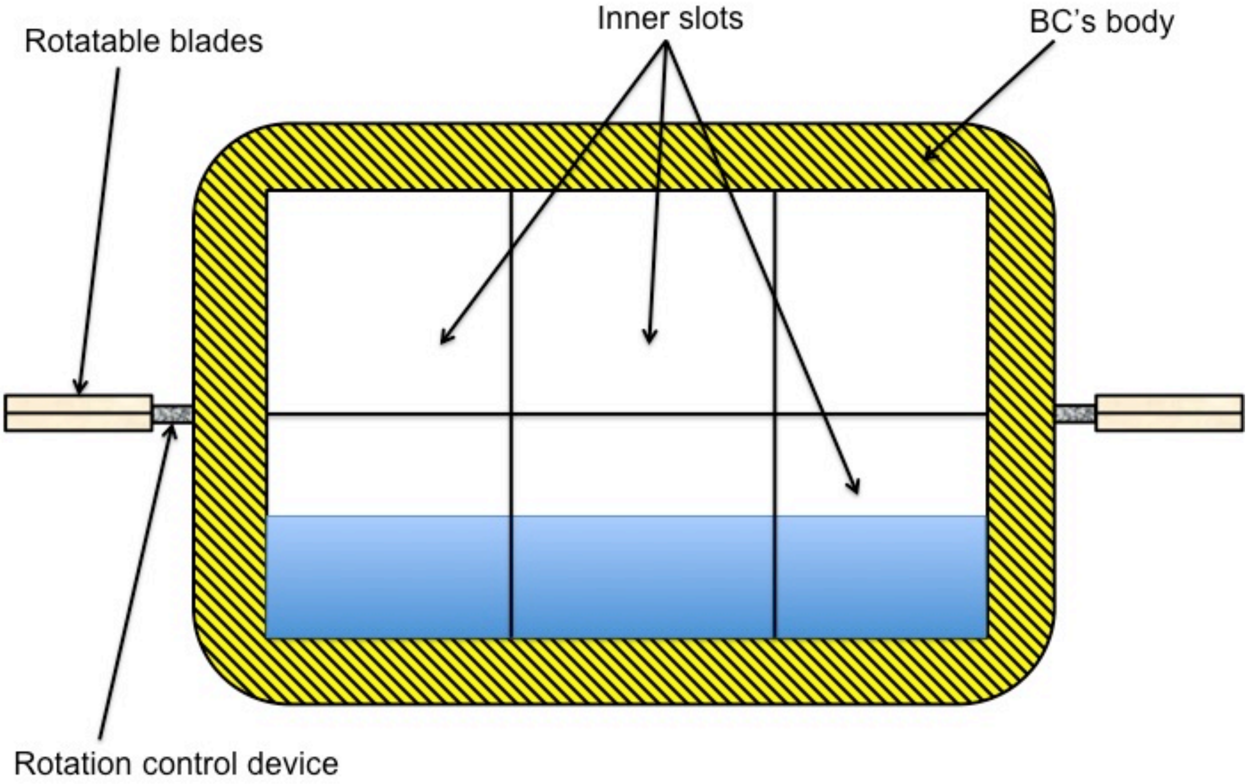


Figure 2.11. Cross-section views of blades system

Such a system enables us to control the immersion depth with sufficient precision by means of rotatable blades.

2.3.3.3. Heave compensator for the winch

One more device, which is reasonable to use is a heave compensator for the winch, installed on the deck of the tug. During transportation the tug boat will move up and down, due to waves. This creates additional draft force on the subsurface system, transmitted to the BC system via the connection link. As the movements of the tug boat in wave conditions are not uniform, thus the draft force will have a non-uniform distribution. Methods, described in sections before, state basic tools to compensate such effect coming from the subsurface equipment. Implementation of heave compensator, installed on the deck of the tug, will solve the problem coming from tte surface equipment.

The main principle is to vary the length of the connection link during transportation. When the tug boat will go up on the wave's crest (draft force on the BC will subsequently increase), the length of the link should be increased. During vessel's "falling" to the wave's trough, the length of the link will steadily decrease. Thus, the distribution of forces will have more uniform profile. Hence, the variable amount of water in BC's slots will be less, which results in decreasing the power of the pumps, needed to fill the slot in a certain time.

2.3.3.4. Discussion

Combination of all methods, described in previous sections, will give us the opportunity to control the immersion depth with sufficient precision. Note, that they are applicable only for the transportation case. During installation we will have positioning troubles, which are described in Section 2.4. However, some of the methods can be upgraded to solve positioning tasks during installation.

2.4. Installation

When the vessel and equipment are at the position, the rope should be disconnected. Use of a flexible cable is necessary to compensate the heave motions of the vessel. As the length of the umbilical will vary with the depth of immersion, a reel should be installed on the vessel.

There are several ways to connect the umbilical:

- using submerged buoy
- without buoy

When the first system is better for the deepwater conditions, the second is for shallow water. You can see the principle schemes of ways of connection of the umbilical on the Figure 2.11.

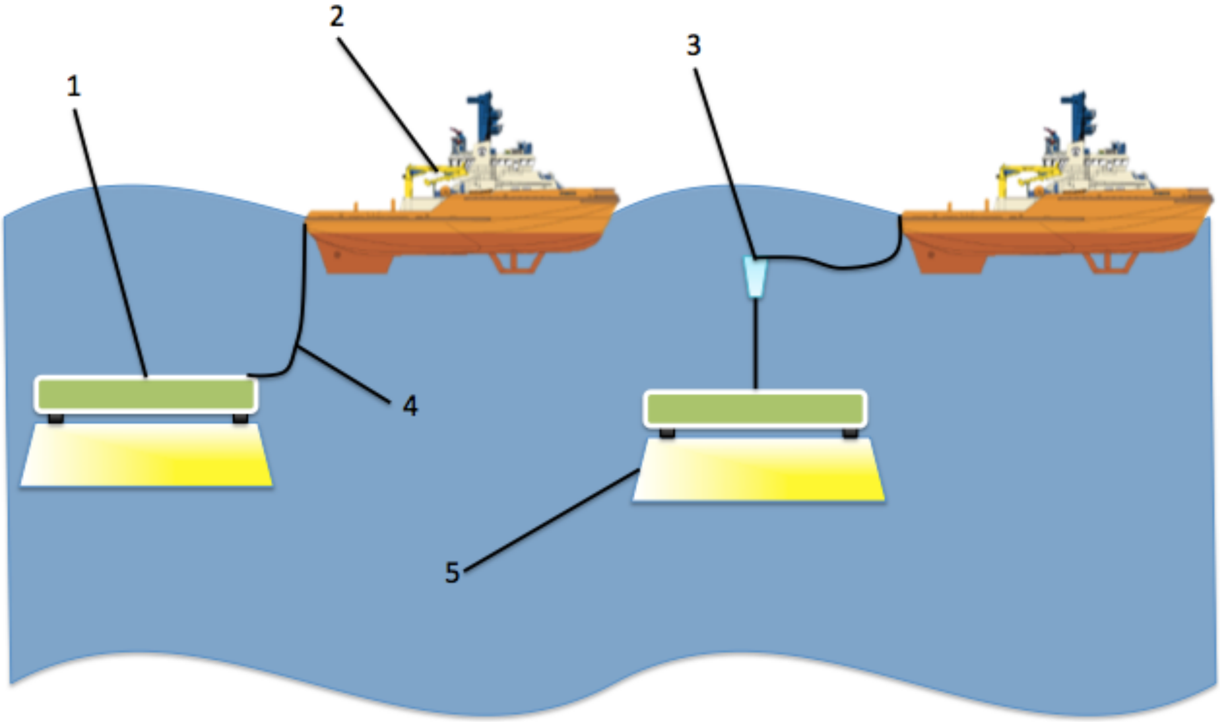


Figure 2.12. Connection of the umbilical

1 – BC;
2 – Tugboat;
3 – buoyancy buoy;
4 – Umbilical;
5 – Cargo;

BC components should be installed over the entire area of the production system to control the velocity and the symmetry during the dive. To monitor the process, ROVs can be used as well. To orient the system in the space, thrusters are used. Crucial point here is positioning tracking. As it was mentioned before, we can install a GPS module on the BC, but it is not enough to have only one tracking device to record a rotation, so at least two such devices should be installed. When the equipment has reached the bottom, the BC system can be removed; this gives us the ability to reuse it.

2.4.1. Equation of motion

According to the equation of motion $\vec{F} = m\vec{a}$.

The forces, which are acting during installation are following:

- gravity force of the cargo;
- gravity force of the BC system;
- buoyancy force;
- drag force;

We will consider 1D case, when all the forces are acting along the z-axis and our cargo and BC are box-shaped. So, the task is to determine the height of the BC system. From the equilibrium of forces we have:

$$F_{A.cargo} + F_{A.BC} - m_{cargo}g - m_{BC}\, g = 0 \text{ (2.26)}$$

where $F_{A.BC}$ - buoyancy force from the BC, $F_{A.cargo}$ - buoyancy of the cargo, m_{cargo} - weight of the cargo in air, m_{BC} – weight in air of the BC system and water inside. Lets define all components in the equation above.

$$\rho_w g\, V_{cargo} + \rho_w g\, V_{BC} - m_{cargo}g - m_{BC}\, g = 0 \text{ (2.27)}$$

$$V_{BC} = \frac{m_{cargo} + m_{BC}}{\rho_w} - V_{cargo} \text{ (2.28)}$$

Note, that the volume of the BC is filled with air, which mass is negligible.

With such volume of the BC filled with air, the system will stay on the position due to zero overall buoyancy. However, by adding water to the system we will increase the mass of the system, thus the system will start to sink. Let us study this process more precise. First, let us write the equation of motion of the system.

$$-F_{A.cargo} - F_{A.BC} - F_{drag} + m_{cargo}g + m_{BC}\, g = m_{total}\, a \text{ (2.29)}$$

$$-\rho_w g\, V_{cargo} - \rho_w g\, V_{BC} - 0.5\, \rho_w v^2 C_D\, S + m_{cargo}g + m_{BC}\, g$$
$$= \left(m_{cargo} + m_{BC}\right)a \text{ (2.30)}$$

As we have added the water into the BC, the mass of the BC will be sum of the masses of the components, plus mass of the water.

$$-\rho_w g\left(V_{cargo} + V_{BC}\right) - 0.5\, \rho_w v^2 C_D\, S + \left(m_{cargo} + m_{BC} + \rho_w\, V_w\right) g$$
$$= \left(m_{cargo} + m_{BC} + \rho_w\, V_w\right) v\, \frac{dv}{dz} \text{ (2.31)}$$

To solve this equation lets re-write it in the next form.

$$A = \left(m_{cargo} + m_{BC} + \rho_w\, V_w\right) g - \rho_w g\left(V_{cargo} + V_{BC}\right) \text{ (2.32)}$$

$$B = 0.5\, \rho_w C_D\, S \ (2.33)$$

$$C = m_{cargo} + m_{BC} + \rho_w\, V_w \ (2.34)$$

$$A - B\, v^2 = C\, v\, \frac{dv}{dz} \ (2.35)$$

Physical meaning of the components:

A – difference between weight and buoyancy force (weight in water);

B – drag component;

C – weight of the system in air.

The exact solution of the equation above is hard to find analytically. We will solve this equation numerically in Wolfram Mathematica using initial condition that in the beginning velocity is zero.

As you can see from the formulas above we have used the fact that acceleration $a = \frac{dv}{dt} = \frac{dv}{dt}\frac{dz}{dz} = \left|\frac{dz}{dt} = v\right| = v\ \frac{dv}{dz}$, obtained function will be velocity of the BC over submerged depth. To obtain same function in velocity-time domain we will use $a = \frac{dv}{dt}$. Resulting equation in time domain will be:

$$A - B\, v^2 = C\frac{dv}{dt} \ (2.36)$$

To obtain the displacement of the system we should solve next second-order differential equation:

$$A - B\left(\frac{dx}{dt}\right)^2 = C\frac{d^2x}{d\,t^2} \ (2.37)$$

Note, that all equations above doesn’t include the work of pumps. It means that the water enter tank immediately, which is not realistic case. Lets add varying mass variable into equations 2.35 and 2.36.

The work of pump can be described using next formula

$$V_w = Q_p\, t \ (2.38)$$

where Q_p - capacity of injection pumps (m^3/s), t – pump working time (sec).

Thus, components A and B in the equations will be time dependent. The resulting equations for the velocity and displacement will be:

$$A(t) - B\,v^2 = C(t)\frac{dv}{dt} \quad (2.39)$$

$$A(t) - B\left(\frac{dx}{dt}\right)^2 = C(t)\frac{d^2x}{d\,t^2} \quad (2.40)$$

$$A(t) = (m_{cargo} + m_{BC} + \rho_w\,Q_p\,t)\,g - \rho_w g\left(V_{cargo} + V_{BC}\right) \quad (2.41)$$

$$B = 0.5\,\rho_w C_D\,S \quad (2.42)$$

$$C(t) = m_{cargo} + m_{BC} + \rho_w\,Q_p\,t \quad (2.43)$$

In the equations 2.38-2.42 capacity of pumps is constant and condition of finite volume of the BC doesn't fulfill. It means that pumps will carry out the work even with the full BC. We will implement piecewise functions for the coefficients A and C in the equations 2.38-2.39 in order to obtain a realistic result. Final systems of equations to calculate the sinking velocity and displacement will be.

$$A(t) = \\ = \begin{cases} (m_{cargo} + m_{BC} + \rho_w\,Q_p\,t)\,g - \rho_w g\left(V_{cargo} + V_{BC}\right), & Q_p\,t \le V_{BC} \\ (m_{cargo} + m_{BC} + \rho_w\,V_{BC})\,g - \rho_w g\left(V_{cargo} + V_{BC}\right), & Q_p\,t > V_{BC} \end{cases} \quad (2.44)$$

$$C(t) = \begin{cases} m_{cargo} + m_{BC} + \rho_w\,Q_p\,t, & Q_p\,t \le V_{BC} \\ m_{cargo} + m_{BC} + \rho_w V_{BC}\,, & Q_p\,t > V_{BC} \end{cases} \quad (2.45)$$

The results of calculations are presented in Chapter 5 "Case study".

2.4.2. Positioning during installation

One of the difficulties of all wet methods is the problem with installation of the equipment at a certain location on seabed. When the installation is held by means of the crane on the barge, we can easily adjust coordinates of installation by regulating the position of a crane boom. In our case, there is no possibility to operate positioning of the subsurface system through changing the position of surface tools. Thus, the system should be self-contained to change the position in space. To solve this problem we will divide the process into two parallel stages:

- Regulation of position
- Monitoring the installation

2.4.2.1. Regulation of position

When the structure is on the position and ready for installation, blades should be vertically oriented. By injecting the water into BC's tanks we will change the buoyancy of the system from neutral to negative, so our system will start sinking along vertical axis. However, due to currents our system could dislocate in horizontal plane. By changing the angle of blades incidence we could manage such disorientation. If currents are too strong, and displacement cannot be changed only by means of regulating the angle of blades incidence, a dynamic positioning system could be applied. Dynamic positioning should consist of rotatable thrusters, which will orient the system in the horizontal plane. The schematic view of the system is shown on the Figure 2.12.

Hence, the amount of water in BC's tanks will influence on the velocity of sinking/ascending and a combination of rotatable thrusters and blades will orient the structure in the horizontal plate, thus full three dimensional positioning is provided.

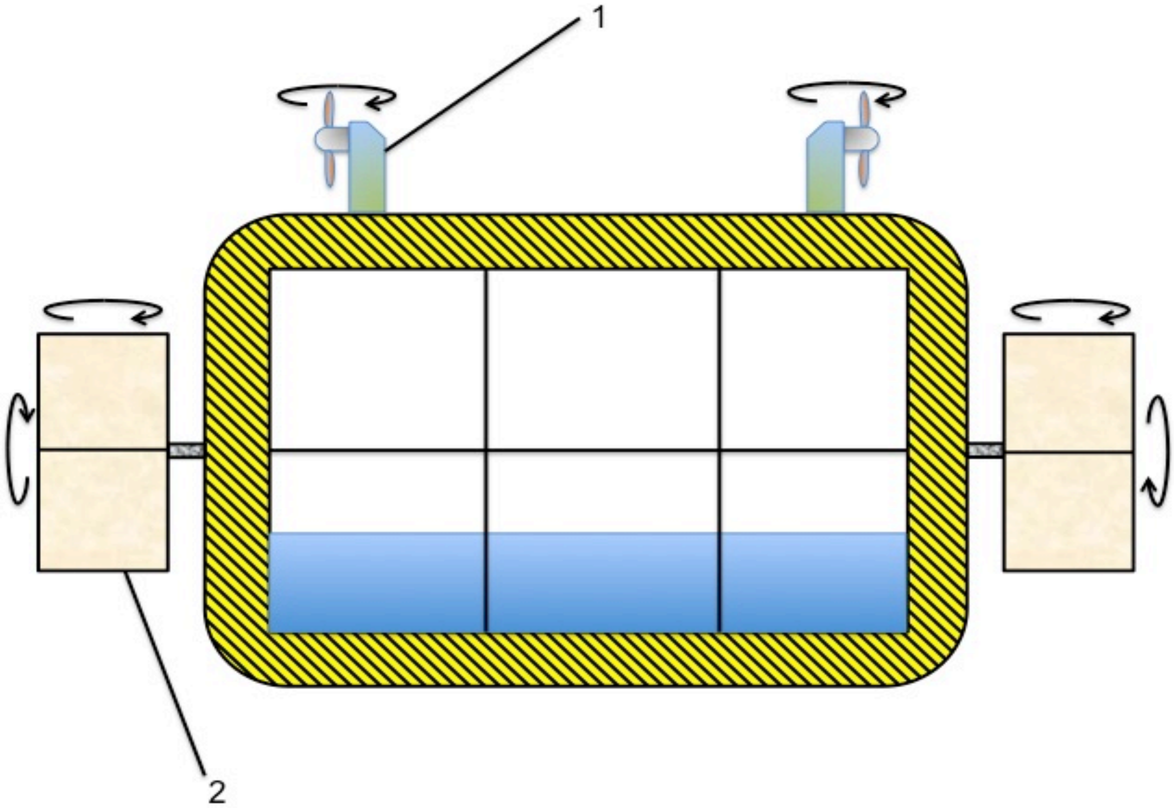


Figure 2.13. System of rotatable thrusters and blades

1 – Rotatable thrusters (dynamic positioning)

2 – Rotatable blades

2.4.2.2. Monitoring of position

One of the possible solutions is to use ROV in the process of installation. Implementation of ROVs gives us the opportunity to carry out visual inspection of the system, identify possible accidents and to take measures to prevent them. At the same time, the ROV will transmit information about the location of the equipment in space, thus the ROV allows managing the process. A schematic view of ROV monitoring is shown on the Figure 2.13.

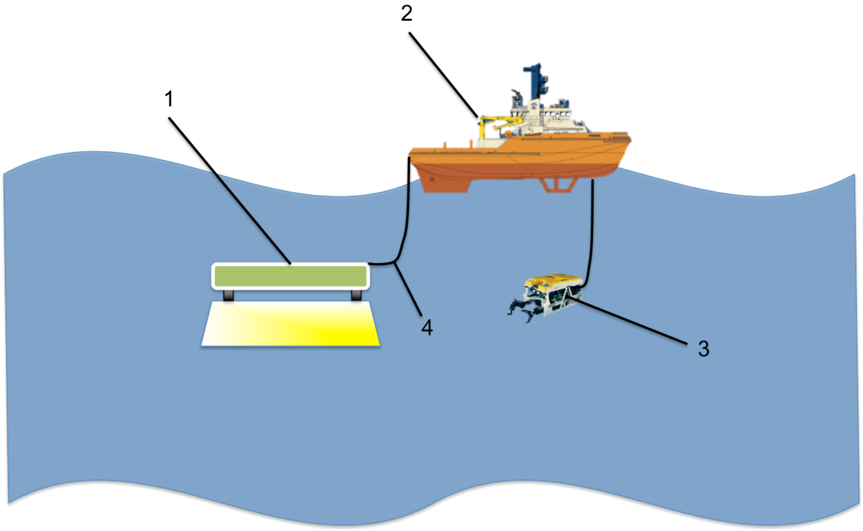


Figure 2.14. Monitoring by ROV

1 – Buoyancy compensator

2 – Tug vessel

3 – ROV

4 – Flexible line

2.5. Combination with different methods

Synergy of a new concept and existing installation methods could lead to increase in performance of towing and installation processes. The main restriction in existing methods is the weather window requirement to perform the work. Usually, when installation is held by a subsea construction vessel (SSCV) with involvement of offshore crane operations, the requirement is a value of significant wave height, which shall be less, than 2.5 meters. From the other hand, to transport the equipment to the location of installation on the deck of the vessel, less time is required. Section 2.3.1.3 documents a reasonable approach to combine these two facts into one concept. However, at the moment, such vessels do not exist.

2.5.1. Combination with Subsea 7 method

Subsea 7 approach is to transport heavy equipment under the hull of the vessel nearby its center. As a result, less deck space and less vessel capacity is required to carry out transportation and installation. Moreover, problems with positioning of the equipment near the seabed are solved by implementation of additional rope to control the rotation and position of the equipment. However, such a method doesn't solve the problem of transportation and installation in harsh conditions and the weather limit for operation is typically 2.5 meters. In addition, transportation to the location of installation is carried out in "wet" position, thus the velocity of the vessel is relatively low – 4-5 knots.

Adding buoyancy compensator to the system will lead to increase in operational wave limit.

2.5.2. Combination with PIM

Originally, transportation to the location of installation is done by a SSCV. Then, equipment is connected to another leading vessel through the wire and by a crane transmitted to the sea surface. After, the SSCV releases the equipment into free fall.

Implementation of buoyancy compensators could expel the need of SSCV for transportation, thus installation could be done by means of one vessel. Such an approach also excludes the need of offshore crane operations.

From the design of the buoyancy system, there is no need of dynamic positioning (rotatable thrusters) in the process. Moreover, the BC will not go deep, thus the complexity of the system is reduced.

Chapter 3. Risk Analysis

During transportation and installation operations, some undesirable events may occur. Each of these events has their own probability and consequences. In order to assess risk, which is, generally, the product of probability and consequence, as low, medium or high, risk acceptance criteria should be defined.

In this chapter we will be focused on the proposed concept of wet installation to define basic possible hazards in the process. We will consider an option with transportation by a tug boat and further installation by the BC system. As a result, several risk mitigation measures were defined to improve the system's safety.

3.1. Acceptance criteria

Risk acceptance criteria (RAC) – the parameter, which is used to describe risk in respect to certain category. Regarding chosen method for analysis, the RAC could be qualitative or quantitative.

In our case, the analysis will be based on the following categories of RAC:

1) *safety for people;*
2) *environmental impact;*
3) *assets (including loosing of reputation);*

As was mentioned previously, risk is defined by probability and consequences. In order to avoid misunderstanding, both parameters should be categorized and each category should be described. They are shown below.

Consequences categories

1) Safety for people:	2) Environmental impact:	3) Assets:
A – Negligible injury	A – Insignificant harm	A – Insignificant damage
B – Minor injury	B – Minor harm	B – Minor damage
C – Severe injury	C – Moderate harm	C – Moderate damage
D – One fatality	D – Considerable harm	D – Considerable damage
E – Several fatalities	E – Serious harm	E – Serious damage

Based on the frequency of hazards occurrence, the probability categories are:

1 - rarely occurred

2 - happened several times per year in industry

3 - has occurred in operating company

4 - happened several times per year in operating company

5 - happened several times per year in location

For quantitative analysis, all RACs must be described by numbers. Such parameters as FAR, GIR, IR or IRPA are representative for personal safety estimations. Environmental impact can be defined as the period of recovery time or amount of pollutants released to the environment. Assets – level of lost money (for reputation – losses in share value).

3.2. HAZID

Hazard Identification Analysis (HAZID) – a method, which is used to identify and evaluate hazards early in a project, being conducted at the conceptual and front-end engineering design.

According to NORSOK Z-013, a HAZID analysis has several objectives:

a) to identify hazards associated with the defined system(s), and to assess the sources of the hazards, events or sets of circumstances which may cause the hazards and their potential consequences;

b) to generate a comprehensive list of hazards based on those events and circumstances that might lead to possible unwanted consequences within the scope of the risk and emergency preparedness assessment process;

c) identification of possible risk reducing measures.

The HAZID analysis is presented in Table 3.1.

Table 3.1. HAZID table

Activity	Hazard Identification	Cause	Possible consequence
1.Lifting operations within a harbor	1. Collision of the equipment with the pier	- Break of the crane's rope; - Fault of a crane-operator; - Poor weather conditions (strong wind); -Failure of a crane systems.	- Damage of the equipment; - Damage of the pier; - Leakages of technical liquids. -Personal injures and fatalities.
	2. Sinking of the system in the harbor	- Failure of the BC system - Failure of the BC's control system (installed on the tug).	- Damage of the equipment; - Harm to environment.
	3. Capsize of the equipment with installed BC	- Poor design (Incorrect weight distribution); - Unreliable weather forecast; - Improper personal training;	- Damage of the equipment; - Harm to environment.
2. Transportation to the location of installation	4. Collision of the equipment with the tug boat	- Immersion depth control system failure; - Vessel's positioning failure; - Poor weather forecast.	- Damage/loss of the equipment; - Damage to the tugboat; -Personal injuries and fatalities.

	5. Sinking of the vessel (tugboat) under heavy weight of the equipment	- Uncontrolled entry of water into BC (leakage); - Immersion depth control system failure; - Leakage in the control hose;	- Personal injuries or fatalities; - Damage to the vessel; - Damage to the equipment; -Environmental pollution.
	6. Loss of the equipment	- Wire rupture; - Destruction of the cargo's fasteners; - Failure of the wire drum (on the vessel);	- Loss of the cargo; - Environmental pollution.
	7. Falling from height	- Violation of HSE standards; - Nighttime operations.	- Personal injuries or fatalities.
	8. Impossibility of carrying out an operation	- Poor logistic; - Absence of a responsible person; - Weather conditions; - Lack of sources.	- Delay in operation.
3. Installation of the equipment onto the seabed	9. Collision of the equipment with the vessel	- Immersion depth control system failure; - Vessel's positioning failure; - Poor weather forecast.	- Damage/loss of the equipment; - Damage to the tugboat; -Personal injuries and fatalities.

	10. Uncontrolled sinking (with high velocity)	- Immersion depth control system failure; - Uncontrolled entry of water into BC (leakage);	-Damage to the BC system due to fast pressure change
	11. Displacement from the position of installation (missing the target window)	- BC's positioning failure - ROV failure (transmission of wrong coordinates)	- Delay in operation; - Loosing of the equipment.

3.3. Probability and consequences

For each category of RAC we should build our own probability and consequence matrix. Inside the matrix we will place serial number of the hazard from HAZID analysis. Results of such analysis are highly dependent on the opinion of an expert. Moreover, an important challenge is to define the probability and consequence for each specific event. In terms of qualitative analysis for each event we should define which event is most probable (or has worst consequences) among others and rank them into 5 groups. In order to do that, the pairwise comparison method (PCM) can be applied (Thomas, 2012, . The results of PCM comparison you can see in the Table 3.2.

Methodology for PCM is the next:

1. Build a comparison table, where 1st column and row represent the hazards from HAZID analysis.
2. Make pairwise comparison of hazards, based on the next principle: if event N is more probable (or has worst consequences) than N+1, give 1 point to event N, otherwise give 1 point to N+1 (if probabilities are equal – 0.5 to N and 0.5 to N+1).
3. Calculate sum of the points.

4. Find the results.

Table 3.2. PCM matrix

Serial number	1	2	3	4	5	6	7	8	9	10	11
1	-	0	0	1	0	0	1	1	1	1	1
2	1	-	0	1	0	0	1	1	0	0,5	1
3	1	1	-	1	1	0	1	1	1	1	1
4	0	0	0	-	0	0	1	1	0,5	0	1
5	1	1	0	1	-	0,5	1	1	1	1	1
6	1	1	1	1	0,5	-	1	1	1	1	1
7	0	0	0	0	0	0	-	0,5	0	1	0,5
8	0	0	0	0	0	0	0,5	-	1	1	0,5
9	0	1	0	0,5	0	0	1	0	-	0	1
10	0	0,5	0	1	0	0	0	0	1	-	1
11	0	0	0	0	0	0	0,5	0,5	0	0	-
Total score	4	4,5	1	6,5	1,5	0,5	8	7	6,5	6,5	9

Now, we can sum up all the scores and divide events into 5 probability groups.

As we can see from the Table 3.2, the highest values 12.5 and 12 corresponds to events 12 and 13 respectively. Let us consider 5 groups of probabilities:

-Group 1 (rarely occurred): total score 0-2

-Group 2 (happened several times per year in industry): total score 2.5-4

-Group 3 (has occurred in operating company): total score 4.5-6.5

-Group 4 (happened several times per year in operating company): total score 6.5-8

-Group 5 (happened several times per year in location): total score 8.5-10

In accordance with that, final splitting will have following form:

-Group 1: events 3, 5, 6

-Group 2: event 1

-Group 3: events 2, 4, 9, 10

-Group 4: events 7, 8

-Group 5: event 11

For consequence determination we can use terms described in Section 3.1. “Acceptance criteria”.

Now we can build the probability and consequences matrix for the defined hazards. The result is given in Table 3.3.

Table 3.3. Probability and consequences matrix (Risk matrix)

Consequences						
E	🟨 5,6	🟨	🟥 4,9	🟥	🟥	
D	🟩 3	🟨 1	🟨 10	🟨 7	🟥	
C	🟩	🟩	🟨	🟨 8	🟨 11	
B	🟩	🟩	🟩 2	🟨	🟨	
A	🟩	🟩	🟩	🟩	🟨	
	1	2	3	4	5	Probability

Conclusion:

Most events are located in “green” and “yellow” zones, which can be determined as acceptable risk. Events 4 and 9 – collision of the equipment with the vessel – are situated in “red” zone, thus these events should be discussed further.

3.4. Uncertainties in the process of transportation and installation

In each operations there are a lot of possible consequences, which are the result of uncertain conditions, thus our analysis faces a lot of uncertainties. Among them:

- Unreliable weather forecast. It is very important to have accurate forecast to carry out weather-restricted operations. To grade down this uncertainty we can rely on at least two sources of information;

- Design of offshore operations is based on data from databases, which could be uncertain;
- Different points of view from different experts;
- Companies have different standards for the same operation. Also, these standards might be wrongly constructed;
- One big undesirable event could be the sum of small hazards, which is hardly predicted;

3.5. Bow-tie diagrams

As was shown in Section 3.3 "Probability and consequences", events 4 and 9 are in red zone, thus it should be discussed in more detail. Some technical upgrades should be performed to increase the reliability of the system. Results can be presented by a bow-tie diagram. Figure 3.1 illustrates the bow-tie diagram.

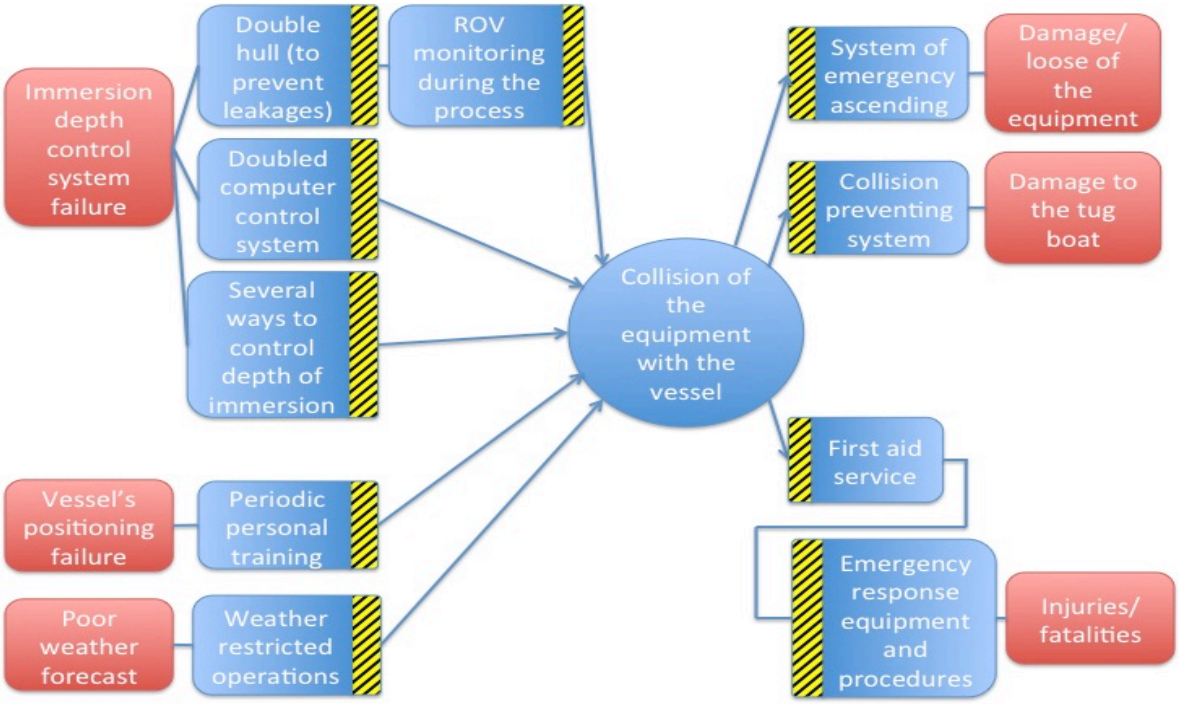


Figure 3.1. Bow-tie diagram

3.6. Risk reducing measures

As we can see from the diagram above, each cause and consequence has its own barrier in order to reduce the risk.

Probability part:

1. Immersion depth control system failure: probability of occurrence

can be reduced by implementation of double hull of the BC system to prevent leakages to the system. This will eliminate uncontrolled changes of depth. In addition, the process should be inspected by ROV in order to identify possible failures. Simultaneous implementation of blade system and rotatable thrusters is reasonable in order if one of the system will break. All computer equipment in the control room on the vessel should be duplicated for the emergency cases.

2. Vessel's positioning failure: vessel's crew should consist of best specialist. Periodic training of the team is essential.
3. Poor weather forecast: if the weather is over the weather window for the operation, all works should be stopped.

Consequences part:

There are three possible consequences in this operation:

- injure/death
- damage/loose of the equipment
- damage to the tug boat.

To reduce the effect of the first, all vessels and structures must be equipped with good First Aid Service equipment in order to organize quick access to the first aid. To eliminate death of personal in a situation, when first aid is not enough, people should be evacuated to shore, where they can be provided with the best care. Availability of helicopter deck on the vessel is a great advantage.

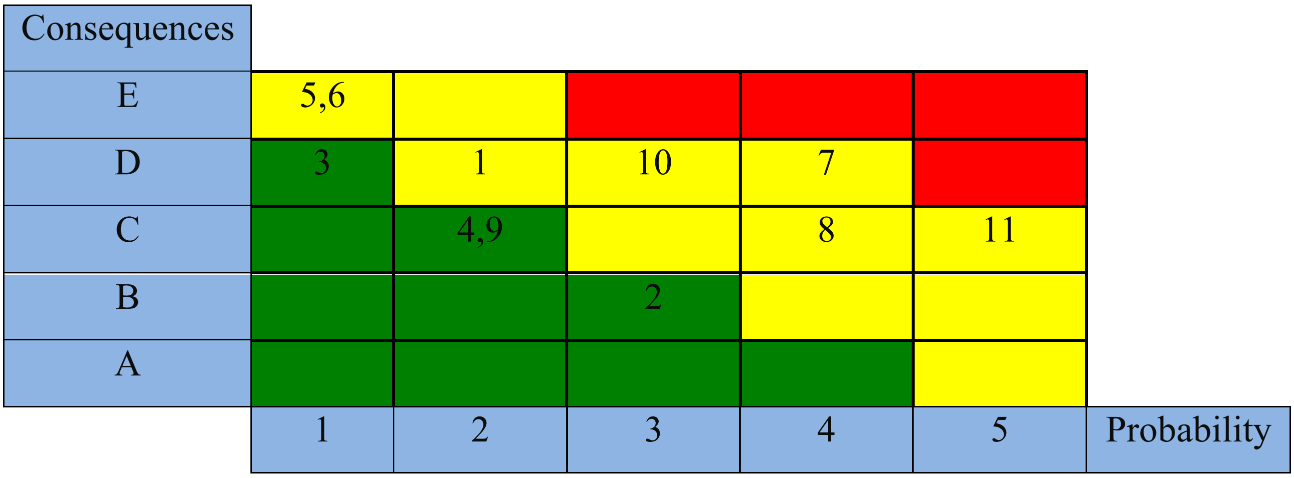
To prevent damage or loss of the equipment, as well as damage to the vessel, the system of emergency ascending is required. The system has several components:

- accumulators with compressed air, for emergency empty of ballasted water in slots (making system ascend);
- accumulators of electric power for thrusters, enough for drawing the equipment aside the vessel.

As a result, the equipment with the BC system will ascend not far from the vessel and could be grabbed by another vessel.

The resulting risk matrix, after implementation of all measures is presented in Table 3.4.

Table 3.4. Risk matrix after implementation of risk reducing measures



Consequences						
E	🟨 5,6	🟨	🟥	🟥	🟥	
D	🟩 3	🟨 1	🟨 10	🟨 7	🟥	
C	🟩	🟩 4,9	🟨	🟨 8	🟨 11	
B	🟩	🟩	🟩 2	🟨	🟨	
A	🟩	🟩	🟩	🟩	🟨	
	1	2	3	4	5	Probability

Chapter 4. Case study

As an example we will consider transportation and installation of Ormen Lange's template with integrated manifold. You can see a view of the template on the Figure 4.1. The Template has following parameters (Glomnes et al., 2006, p. 3):

- Dimensions – a x b x h = 44m x 33m x 15m;
- Weight in air - 1150 tons;

Sea state and weather conditions:

- no waves and currents;
- no wind;
- density of sea water – 1027 kg/m^3.

Figure 4.1. Ormen Lange template (Glomnes et al., 2006, p.14)

Let us calculate the submerged weight of the template. For that calculation we will assume that all voids of the template are filled with water and it is made of steel with density 7800 kg/m^3.

$$V_{template} = \frac{m_{template}}{\rho_{steel}} = \frac{1150 * 10^3}{7800} = 147.44\ m^3$$

Now we can find weight of the template in water.

$$W_{template} = m_{template}\, g - \rho_w\, g\, V_{template}$$
$$= 1150 * 10^3 * 9.81 - 1027 * 9.81 * 147.44$$
$$= 11281500 - 1485438.833 = 9796.06\, kN \approx 998.58\, tons$$

4.1. BC system dimensions

The first step is to roughly dimension the BC system. As it was mentioned in section “Ways to connect BC with the cargo”, the BC system should cover the whole top area of the manifold. We will consider that our manifold and BC are box-shaped. So, the task is to determine the height of the BC system. Lets use formula 2.28, obtained in Chapter 2.

$$V_{BC} = \frac{m_{template} + m_{BC}}{\rho_w} - V_{manifold}$$

To calculate the volume of the BC we need to know the mass of the system. The mass includes masses of the compressor, pumps, housing, etc. For our rough calculations we will assume that overall mass is 100 tons.

$$V_{BC} = \frac{(1150 + 100) * 10^3}{1027} - 147.44 = 1069.70\, m^3$$

As was mentioned before, the BC should cover the top area of the manifold. For our case we will diminish that values to obtain more or less sleek shape, so the length and width will be 40 m and 30 m respectively. The height for our particular case will be 0.89 m. To give safety margin for operation we will consider the height of the BC as 1 m.

Important parameter for harbors is the draft of the system. Let us calculate the draft for our particular case.

$$(W_{template} + m_{BC})\, g - \rho_w g V_{BC.submerged} = 0$$

$$V_{BC.submerged} = \frac{W_{template} + m_{BC}}{\rho_w}$$

$$S_{BC}\, d = \frac{W_{template} + m_{BC}}{\rho_w}$$

$$d = \frac{W_{template} + m_{BC}}{\rho_w S_{BC}} = 0.89\, m$$

Thus, the total height of underwater part will be 15.89 meters.

4.2. Transportation issues

4.2.1. Calculation of sufficient draft force

Now, lets determine sufficient draft force for towing operations from formula 3.5, where v - is velocity of towing. We will assume that this velocity is 6 knots, which is approximately 3 m/s. Also, we will assume that the distances z and x are 30 and 100 m respectively.

$$F_{draft} = \frac{\rho_w \, C_D \, v^2 \, A}{2\cos\left(\mathrm{arctg}\left(\frac{z}{x}\right)\right)} = \frac{1027 * 1.05 * 3^2 * 33 * 15}{2\cos\left(\mathrm{arctg}\left(\frac{30}{100}\right)\right)} = 2.5\ MN$$

So, our tugboat should be able to reach such capacity.

4.2.2. Displacement of the system under draft force

In Chapter 2 we have discussed the phenomena of displacement of the system during transportation. Equation 2.22 describes changes in depth under a draft force for different transportation velocities. For our calculations we assume the following initial conditions:

- initial depth is 30 meters;
- velocities of transportation are 2, 6, 10 knots;
- no waves.

The results are present on the graph below (Figure 2.4.). V_{tr} – velocity of transportation.

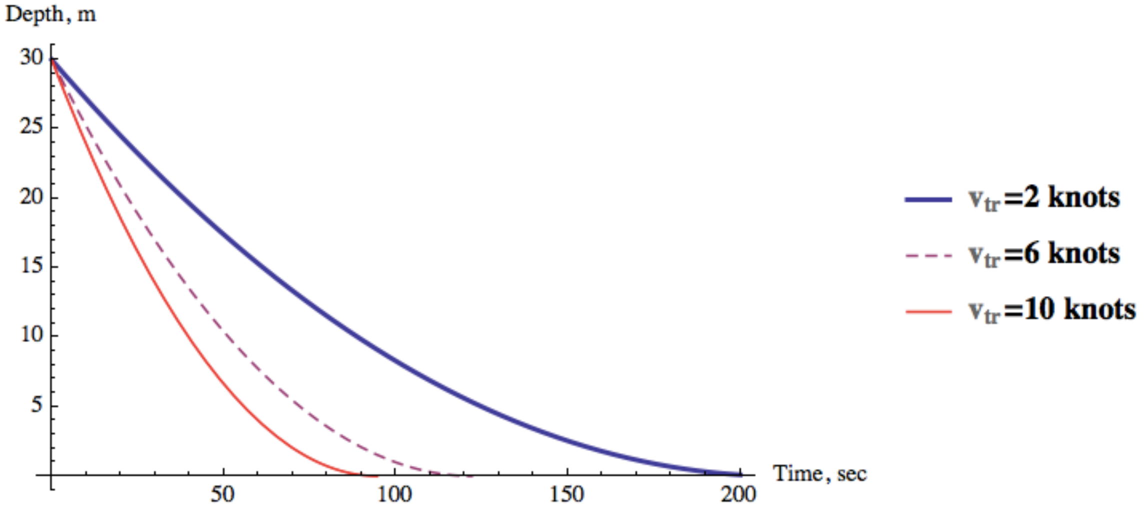


Figure 4.2. Ascending of the system in time under constant draft force

Conclusion:

- for transportation velocity 2 knots, without adjusting of buoyancy, the system will ascend to the sea surface after 200 seconds;
- for transportation velocity 6 knots, without adjusting of buoyancy, the system will ascend to the sea surface after 120 seconds;
- for transportation velocity 10 knots, without adjusting of buoyancy, the system will ascend to the sea surface after 95 seconds;

So, adjustment of buoyancy is required for the system to stay at a certain depth.

Now we can calculate the amount of water need to be added to the BC in odder to remain the system at a certain depth. For instance, we will take the same depth of immersion, as in the previous example – 30 meters. Transportation velocities are 2, 6 and 10 knots, which is 1, 3, 5 m/s respectively. Formula 2.25 describes the mass.

$$\Delta m_1 = \frac{A_1\,\rho_w\,C_D}{2\,g} v_x \frac{z}{\sqrt{c^2 - z^2}} = \frac{44 * 33 * 1027 * 1.05}{2 * 9.81} * 1 * \frac{30}{\sqrt{100^2 - 30^2}} =$$
$$= 757158\,kg$$

$$\Delta m_2 = \frac{A_1\,\rho_w\,C_D}{2\,g} v_x \frac{z}{\sqrt{c^2 - z^2}} = \frac{44 * 33 * 1027 * 1.05}{2 * 9.81} * 3 * \frac{30}{\sqrt{100^2 - 30^2}} = = 2271475\ kg$$

$$\Delta m_2 = \frac{A_1\,\rho_w\,C_D}{2\,g} v_x \frac{z}{\sqrt{c^2 - z^2}} = \frac{44 * 33 * 1027 * 1.05}{2 * 9.81} * 5 * \frac{30}{\sqrt{100^2 - 30^2}} = = 3785790\ kg$$

These are very important results, because our BC could accommodate only 1069.7 m^3 of water. The calculations document the fact that the height of the BC should be increased, thus the volume will increase, to operate with higher velocities of transportation.

4.3. Installation issues

4.3.1. Calculation of sinking velocity

As we have the volume of the BC, we can start to add water in the system in order to increase its weight, thus initiate sinking. Using formulas 2.35-2.37 we will calculate the velocity of sinking and displacement of the system in respect to depth and time.

Initial data for the calculations is in the Table 4.1.

Table 4.1. Initial data for calculation of sinking velocity and displacement of the system

Parameter	Units	Value
Mass of the template, kg	kg	1 150 000
Mass of the BC, kg	kg	100 000
Density of water, kg/m^3	kg/m^3	1027
Gravity acceleration, m/s^2	m/s^2	9,81
Volume of the BC, m^3	m^3	1069.7
Volume of the template, m^3	m^3	147.44
Volume of water inside the BC, m^3	m^3	100/500/1000
Drag coefficient	-	1.05
Cross-section area, m^2	m^2	1452

Note, that we will consider that the water in the system is filled immediately. Moreover, the drag coefficient C_D is a function of Reynolds number. As our sinking velocities are not very high, we can assume that C_D is constant and has a value of 1.05 (for the cube shape) (Gudmestad, s.a.).

The obtained function is a function of velocity over a certain depth. You can see these relations in Figures 4.3, 4.4 and 4.5.

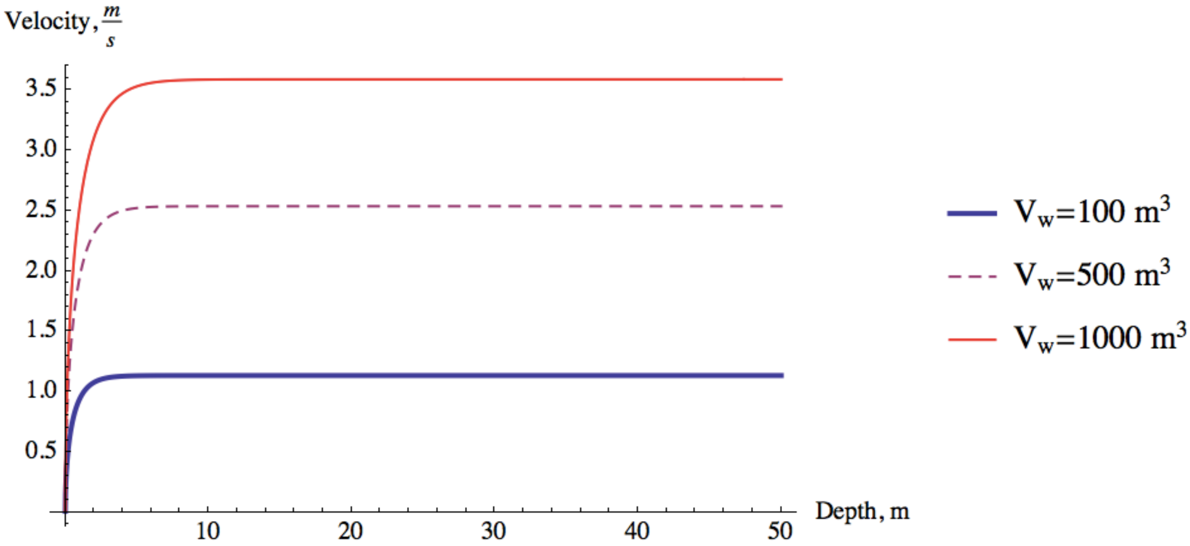


Figure 4.3. Relation between sinking velocity and depth

V_w *– amount of water in the BC*

In time domain the graph will be:

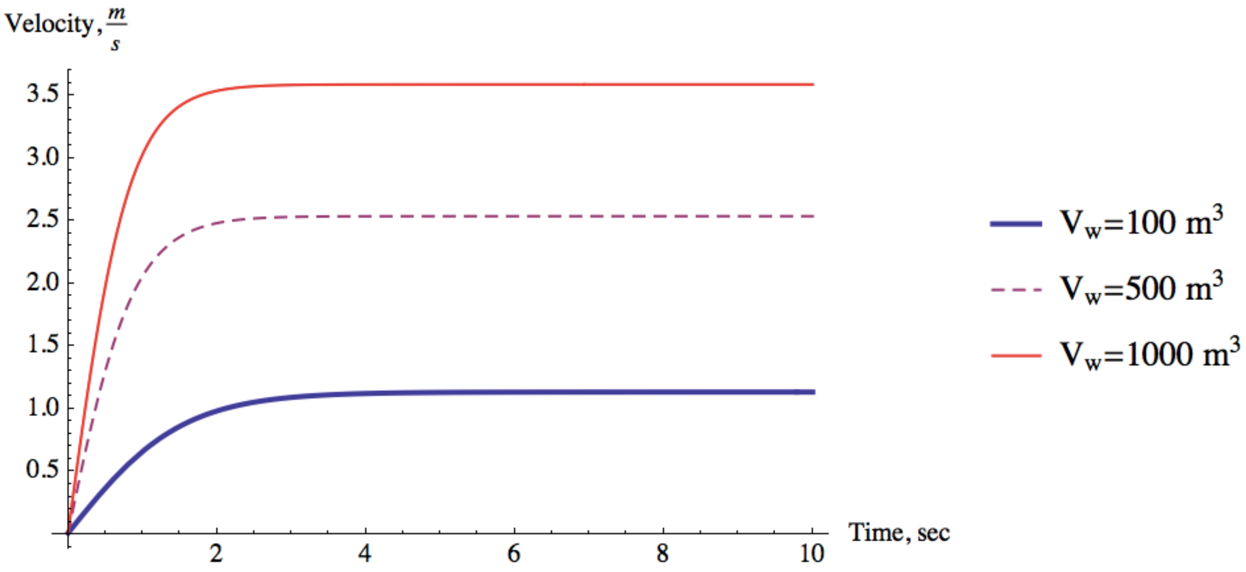


Figure 4.4. Sinking velocity in time domain

V_w *– amount of water in the BC*

The displacement of the system versus time:

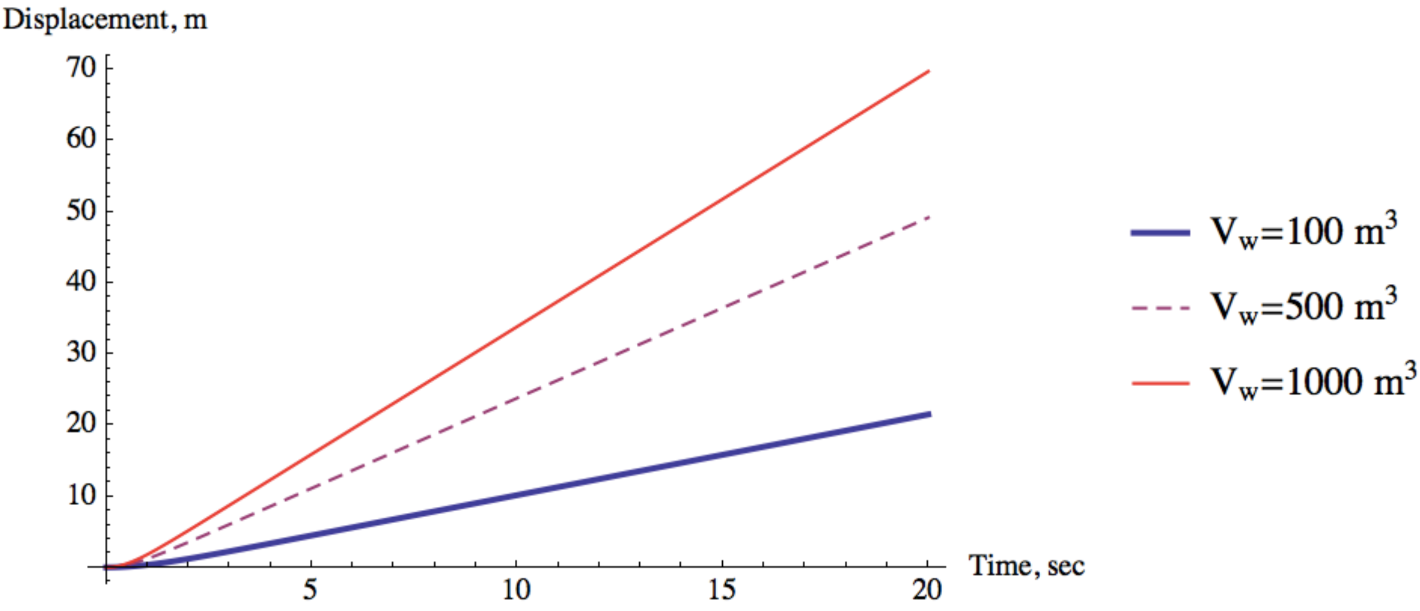


Figure 4.5. Displacement of the system versus time

V_w *– amount of water in the BC*

For our particular template and BC system the results are next:

- maximum velocity of sinking, which could be achieved with the BC (filled with 1000 m^3 of water) is 3.5 m/s;
- to achieve such speed, the system requires 3 sec (for filling the BC with water);

4.3.1.1. Sinking velocity with work of pumps

The previous section gives results of calculation of the velocity without taking into account work of pumps. It means that the water in the system is filled immediately, which is not realistic. In this section we will compare results obtained previously with new one, where the work of pumps is counted. For that purpose we will use systems of equations 2.43-2.44 from Chapter 2 “Technical description”.

New relations are presented in Figures 4.6 and 4.7.

In time domain the graph for sinking velocity will be:

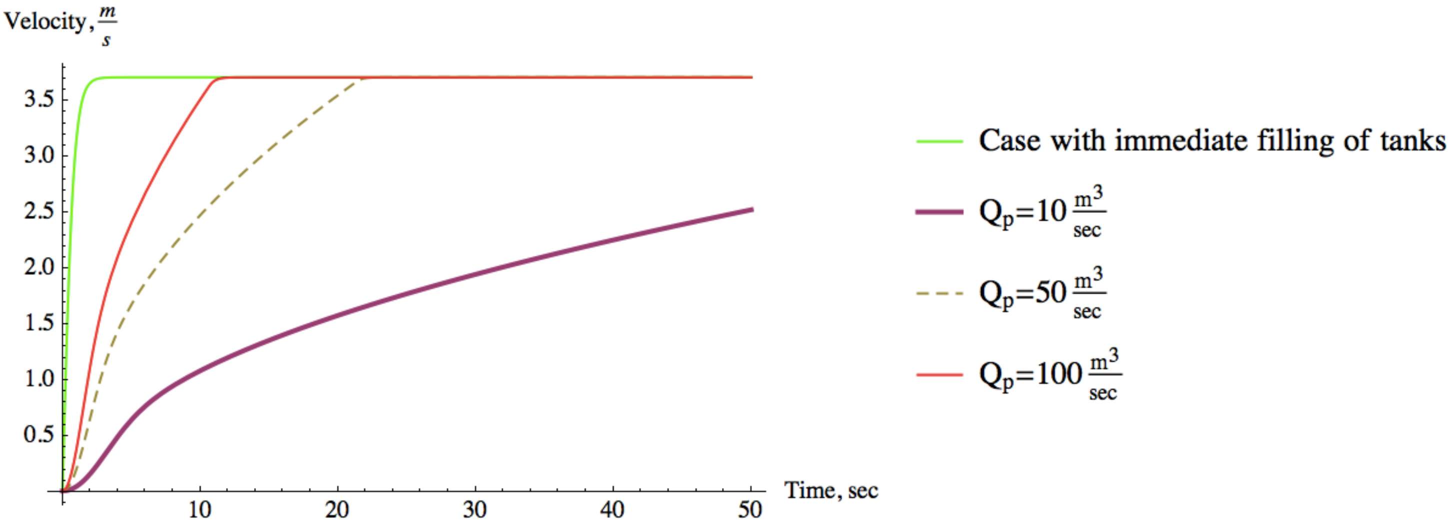


Figure 4.6. Comparison of sinking velocities in time domain (full BC case)

Q_p – pumps capacity

Next graph describes displacement of the system.

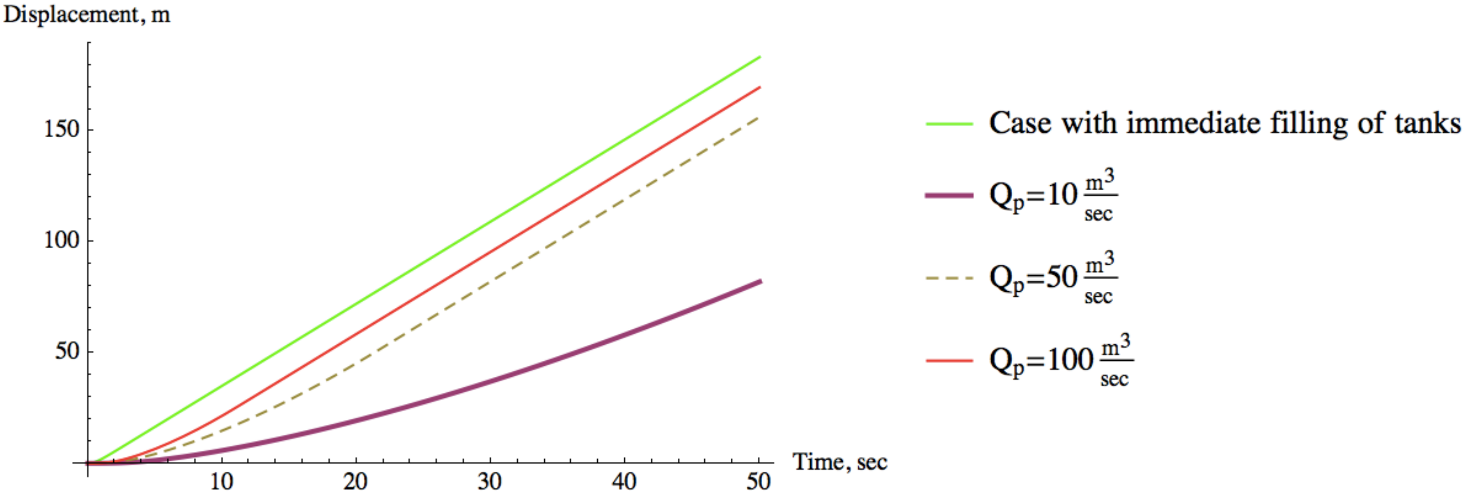


Figure 4.7. Comparison of displacements of the system in time domain (full BC case)

Q_p *– pumps capacity*

Results:

- maximum velocity of sinking, which could be achieved with the BC (filled with 1000 m^3 of water) is 3.5 m/s;
- to achieve such speed, the system requires at least 10 seconds, if the capacity of the pump is 100 cubic meter per second;
- implementation of pumps with capacity lower than 50 m^3/sec is not reasonable due to long response time.

Chapter 5. Economic performance

One of the aims of this thesis is to analyze the economic performance of wet methods in general, and the suggested innovation in particular in comparison with ordinary installation methods, such as installation from a barge and the use of subsea construction vessels (SSCV). The economic analysis will be based on statistical approach for the data from northern part of the North Sea (Statoil statistics, 2013).

5.1. Operational time

For all methods, we will divide the overall installation process into following stages:

1. Transportation to the location of installation
2. Installation of the equipment
3. Return to a harbor

As the first stage is transportation of equipment to the location of installation we will calculate the time needed to transport the equipment to the location.

There are three possible options to carry out the transportation:

- wet tow;
- barge;
- SSCV.

All these options have different transportation velocities, thus the time needed to transport the equipment to the location of installation will be a function of the distance from the shore. For our calculations we will assume next velocities of transportation:

- wet tow – 5 knots;
- barge – 10 knots;
- SSCV – 15 knots.

Time needed to install the equipment is hard to predict. This time is dependant on particular weather conditions on the location of installation and the water depth. However, we will assume a time of 17 hours is needed. For instance, installation of Ormen Lange template took 23 hours to transmit the equipment from the deck of the barge to the seabed.

Return to harbor period is assumed to be equal to the transportation time.

You can see the time of overall installation process on the Figure 5.1 below.

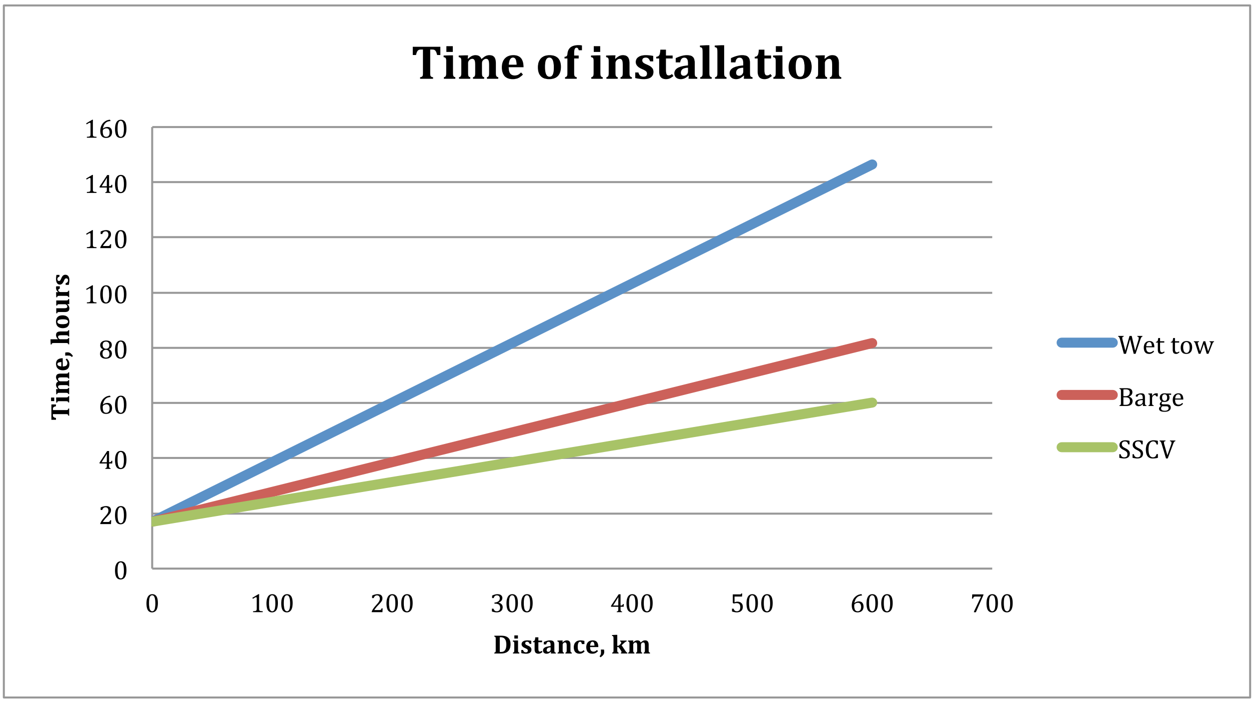


Figure 5.1. Time of installation for different concepts

5.2. Weather conditions

All methods of installation have their own weather limitations. As the seastate conditions are not constant, but changing in time from month to month, the time of installation will also vary, due to time "waiting for a necessary weather window". To estimate these time we will use statistics for 50 years from the Norwegian hindcast database.

First step is to determine the expected durations of weather windows below a threshold and the expected percentage of time being below a threshold. For that purpose MATLAB software was used.

To calculate the expected duration of a weather window and the percentage of time below a threshold, the following methodology was used:

1. Sort the data by months.
2. Choose the data with significant wave height lower than a threshold.

3. Calculate the durations and number of weather windows.
4. Find the expected (average) duration of a weather window.
5. Find the expected percentage of time by dividing the time below a threshold by the total amount of time in the month.

The MATLAB procedure is presented in the Appendix 1. The results of the calculations you can see in Table 5.1 and Table 5.2.

Table 5.1. Expected duration of good weather windows for northern North Sea

Threshold, m	Mean durations of windows below threshold, hours											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0.5	9	16.50	28.5	6	17.22	19.31	15.46	18.44	11.18	0	0	0
1.0	13.66	18.58	19.91	19.93	27.57	27.84	29.73	33.48	23.47	15.44	19.10	16.50
1.5	23.63	27.15	28.05	32.58	42.08	50.44	54.97	52.11	31.95	24.99	23.09	23.11
2.0	25.76	32.88	30.47	43.94	63.21	85.50	96.48	81.06	47.51	32.28	26.04	28.59
2.5	30.38	38.26	37.04	57.96	91.92	126.82	156.61	131.97	63.07	39.97	31.74	32.78
3.0	36.72	44.01	47.78	76.58	137.94	195.36	259.29	210.77	83.92	50.26	39.48	36.85
3.5	46.22	53.27	59.77	100.59	191.26	289.89	392.91	287.84	108.11	64.00	51.25	43.99
4.0	52.85	64.41	71.99	135.63	282.78	422.84	460.26	392.18	133.75	84.07	65.96	54.59
4.5	65.04	77.53	94.49	182.53	382.01	527.01	550.62	515.05	190.53	109.29	81.39	67.99
5.0	81.27	95.54	117.27	231.72	485.51	599.69	681.15	618.55	275.03	149.92	104.21	87.03
5.5	99.04	122.09	149.60	325.64	567.70	639.10	717.47	692.95	359.07	198.83	143.38	109.80
6.0	120.08	153.49	195.64	405.64	629.50	707.11	717.58	717.47	418.83	261.27	189.28	133.33
6.5	146.89	194.40	248.98	493.59	660.29	707.11	717.63	717.58	459.59	329.13	233.87	167.99
7.0	185.87	240.95	313.02	557.04	705.61	707.16	730.66	730.55	520.95	442.84	307.43	218.11
7.5	227.93	288.14	394.93	590.96	718.03	707.16	744	730.61	550.44	537.43	364.38	283.66
8.0	267.18	360.37	453.66	618.92	730.84	707.21		730.61	600.67	584.07	399.45	330.07
8.5	330.44	433.00	524.89	671.30	730.84	707.26		730.66	649.69	629.05	495.26	396.55
9.0	384.90	490.75	611.29	683.08	744	720		730.66	682.98	649.17	574.63	498.90
9.5	459.7	540.77	660.62	695.02				730.66	694.91	660.00	629.16	561.20

10.0	531.85	592.22	694.10	720				730.66	694.91	693.40	671.65	620.78
10.5	585.25	622.03	744					744	694.97	693.85	683.19	660.52
11.0	611.82	643.27							707.21	718.14	707.32	693.85
11.5	682.52	654.41							720	730.90	720	693.90
12.0	705.97	666.05								744		693.95
12.5	718.24	666.05										705.86
13.0	718.24	678										705.92
13.5	730.89											706.02
14.0	730.89											730.89
14.5	744											730.89
15.0												730.89
15.5												744

Table 5.2. Percentage of time being lower than the threshold in the various months

Threshold, m	Expected percantage of time below threshold, %											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
0.5	0.02	0.09	0.14	0.03	0.95	0.77	0.98	1.22	0.31	0	0	0
1.0	0.95	1.52	2.25	6.23	14.69	21.20	25.21	23.81	7.86	2.30	1.42	1.19
1.5	5.05	8.58	10.17	25.13	43.03	52.92	58.83	54.25	27.34	12.18	7.73	6.38
2.0	14.47	20.27	23.19	44.68	65.24	74.43	79.46	76.07	47.96	27.58	19.25	16.74
2.5	26.55	33.66	37.96	61.38	79.64	86.50	90.32	88.04	64.62	44.13	34.00	29.03
3.0	39.92	47.06	52.64	74.26	88.40	93.52	95.68	94.26	76.60	59.35	49.93	42.01
3.5	51.48	58.64	64.26	83.57	93.19	97.07	97.94	97.07	84.75	71.12	63.05	54.49
4.0	62.29	68.54	73.96	89.48	96.38	98.59	98.98	98.72	90.57	80.11	73.29	65.91
4.5	71.81	76.98	81.42	93.26	98.11	99.35	99.57	99.44	94.52	86.56	80.74	74.74
5.0	79.00	83.29	86.97	95.98	99.05	99.66	99.88	99.77	96.87	91.40	87.10	81.88
5.5	84.63	88.43	91.20	97.72	99.47	99.87	99.94	99.91	97.98	91.49	91.39	86.97
6.0	88.77	92.17	94.38	98.59	99.72	99.97	99.96	99.94	98.70	96.57	94.36	90.56
6.5	92.01	94.72	96.21	99.16	99.84	99.97	99.96	99.96	99.18	97.96	96.29	93.54
7.0	94.58	96.46	97.67	99.47	99.92	99.98	99.99	99.98	99.50	98.85	97.60	95.80
7.5	96.28	97.90	98.58	99.66	99.96	99.98	100	99.99	99.67	99.32	98.50	97.36
8.0	97.47	98.71	99.09	99.78	99.99	99.99		99.99	99.83	99.53	99.07	98.24
8.5	98.34	99.22	99.52	99.90	99.99	99.99		99.99	99.92	99.65	99.49	98.98
9.0	98.85	99.53	99.77	99.96	100	100		99.99	99.96	99.72	99.76	99.39
9.5	99.30	99.70	99.89	99.97				99.99	99.98	99.80	99.87	99.68
10.0	99.57	99.83	99.96	100				99.99	99.98	99.86	99.95	99.83
10.5	99.73	99.94	100					100	99.99	99.92	99.97	99.88
11.0	99.86	99.96							99.99	99.97	99.99	99.92
11.5	99.93	99.97							100	99.99	100	99.93
12.0	99.97	99.99								100		99.94
12.5	99.99	99.99										99.95
13.0	99.99	100										99.96

13.5	99.99											99.98
14.0	99.99											99.99
14.5	100											99.99
15.0												99.99
15.5												100

As we can see from Table 5.1 and Table 5.2 the most severe conditions are in December with highest values of wave height 15.5 m. The easiest conditions are in July – highest values 7.5 m. The following calculations of the economic performance of different methods will be based on the statistics from December and July in order to give the answer regarding application of different methods from the economic point of view for different weather conditions.

5.3. Operational limit

As our operation is weather restricted, we must follow the regulations of DNV-OS-H101 (DNV-OS-H101, 2011). This standard introduces a safety margin – an alpha-factor for operations. Moreover, we should take into account a contingency time.

For our calculations we will assume that contingency time is equal to time of operation $T_{POP} = T_{CT}$.

The value of the alpha-factor depend on several factors:

- time of operation;
- significant wave height;
- level of weather forecast.

In our calculations we will use a base case forecast. The values of alpha-factor are presented in the Table 5.3 below (DNV-OS-H101, 2011).

Table 5.3. Alpha-factor, base case forecast

Operational period	Hs=1	Hs=1,5	Hs=2	Hs=2,5	Hs=3	Hs=3,5	Hs=4	Hs=4,5	Hs=5	Hs=5,5	Hs>=6
Tpop<12	0,65	0,705	0,76	0,767	0,775	0,7825	0,79	0,7925	0,795	0,7975	0,
Tpop<24	0,63	0,68	0,73	0,737	0,745	0,7525	0,76	0,765	0,77	0,775	0,7
Tpop<36	0,62	0,665	0,71	0,715	0,72	0,725	0,73	0,7375	0,745	0,7525	0,7
Tpop<48	0,6	0,64	0,68	0,687	0,695	0,7025	0,71	0,7175	0,725	0,7325	0,7
Tpop<72	0,55	0,59	0,63	0,642	0,655	0,6675	0,68	0,69	0,7	0,71	0,7

The Operational limit for the significant wave height can be calculated next:

$$OP_{WF} = OP_{LIM} * \alpha$$

Evaluations were conducted for each specific cases of H_s and T_{pop}.

To find the expected duration of weather window and the expected percentage of time below a threshold, interpolation in Table 5.1 and Table 5.2 was done.

5.4. Probability of successful operation and average "waiting time"

For our calculations we will assume that the distribution function of good weather windows follows an exponential distribution (Haver, S., 2014):

$$F_D(d) \ = 1 - exp\left\{- \frac{d}{\lambda}\right\}$$

where λ is the parameter of the distribution (expected duration of weather window), d – duration of an operation (including contingency time).

The probability for an unsuccessful operation, assuming that our events are independent, is $P(D \leq 72) = P_1 * P_2 * \dots * P_n$

For each event we have the same distribution function, thus $P_1 = P_2 = P_n$.

According to definition of probability $P_1(D \leq 72) = F_D(d) = \left(1 - exp\left\{- \frac{d}{\lambda}\right\}\right)$

As we have several weather windows in each month the final probability of unsuccessful operation will be: $P(D \leq 72) = \left(1 - exp\left\{- \frac{d}{\lambda}\right\}\right)^n$, where n – expected number of weather windows for each month.

To calculate expected number of weather windows (n) for each month we can use next formula:

$$n = \frac{Hours\ in\ the\ month * Expected\ percentage\ of\ time\ below\ threshold}{Mean\ duration\ of\ window}$$

But this is the probability of an unsuccessful operation. In order to obtain the probability of success, we should subtract this probability from 100%. Thus, probability of success is: $P(D \geq 72) = 1 - \left(1 - exp\left\{- \frac{d}{\lambda}\right\}\right)^n$.

Now we can find the probability of experiencing a window with sufficient duration for each month and for each specific case of significant wave height and operational time. Such calculations were done in MS Excel.

The next step is to determine the average operational time including time "waiting for necessary weather window". For that purpose we will use Monte-Carlo simulation (Berg, 2004).

Monte-Carlo method has the following methodology: We create a table with random probabilities and then compare it with real probabilities for each month. If our random probability is less than the real value, then the operation is finished. Otherwise, the operation continues. Then we calculate the average time of the operation.

For each specific case 10 000 simulations were done. Simulations were performed in MATLAB. Program's script you can see in Appendix 2.

Results for the July you can see in Figures 5.2 – 5.4.

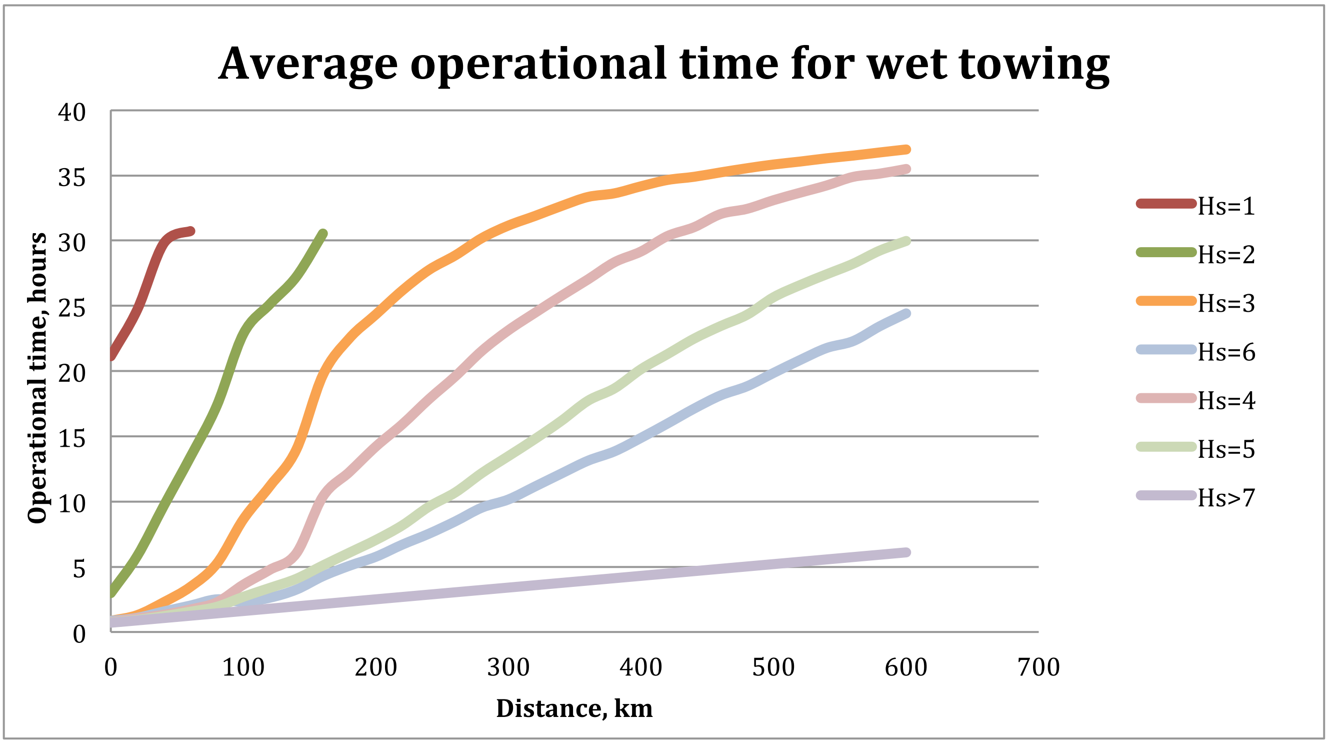


Figure 5.2. Average operational time for wet towing in July for different values of the allowable significant wave height during towing

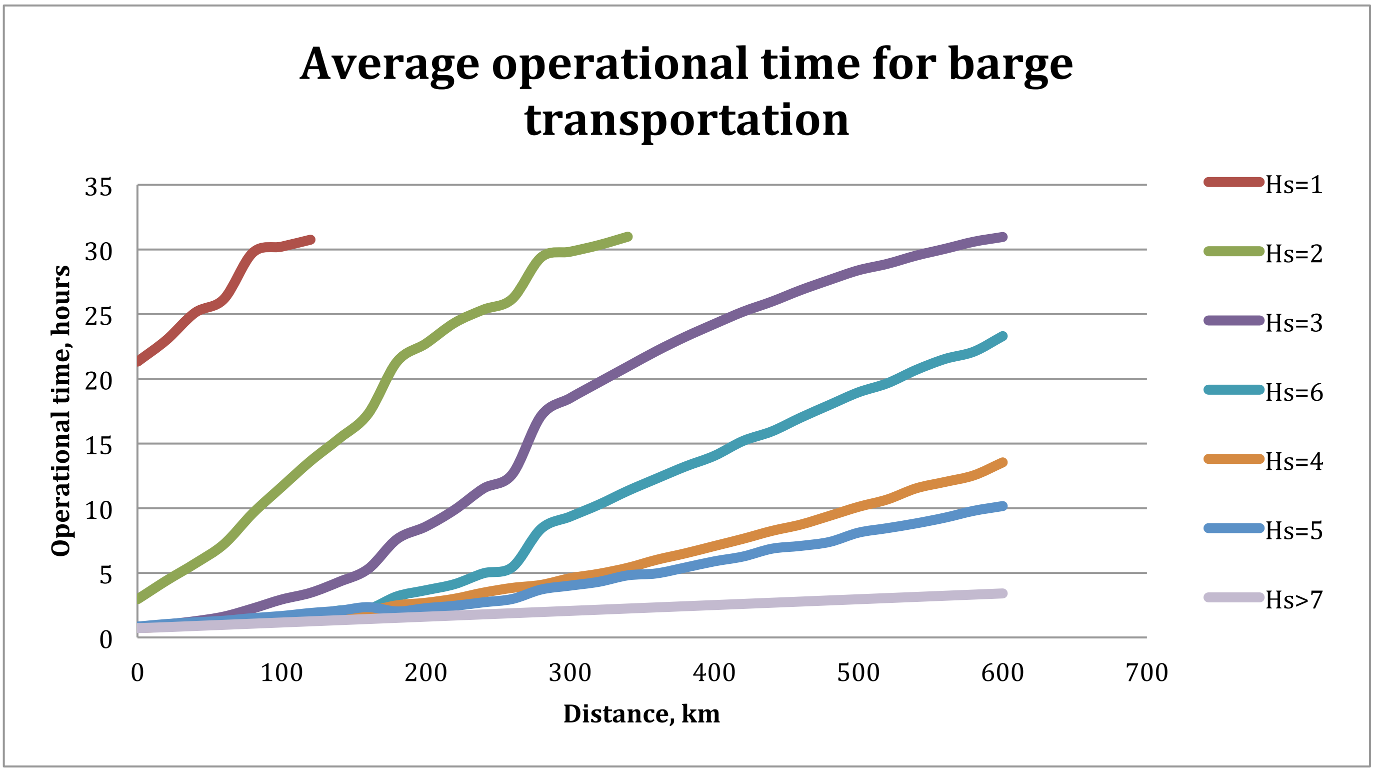


Figure 5.3. Average operational time for barge transportation in July for different values of the allowable significant wave height during towing

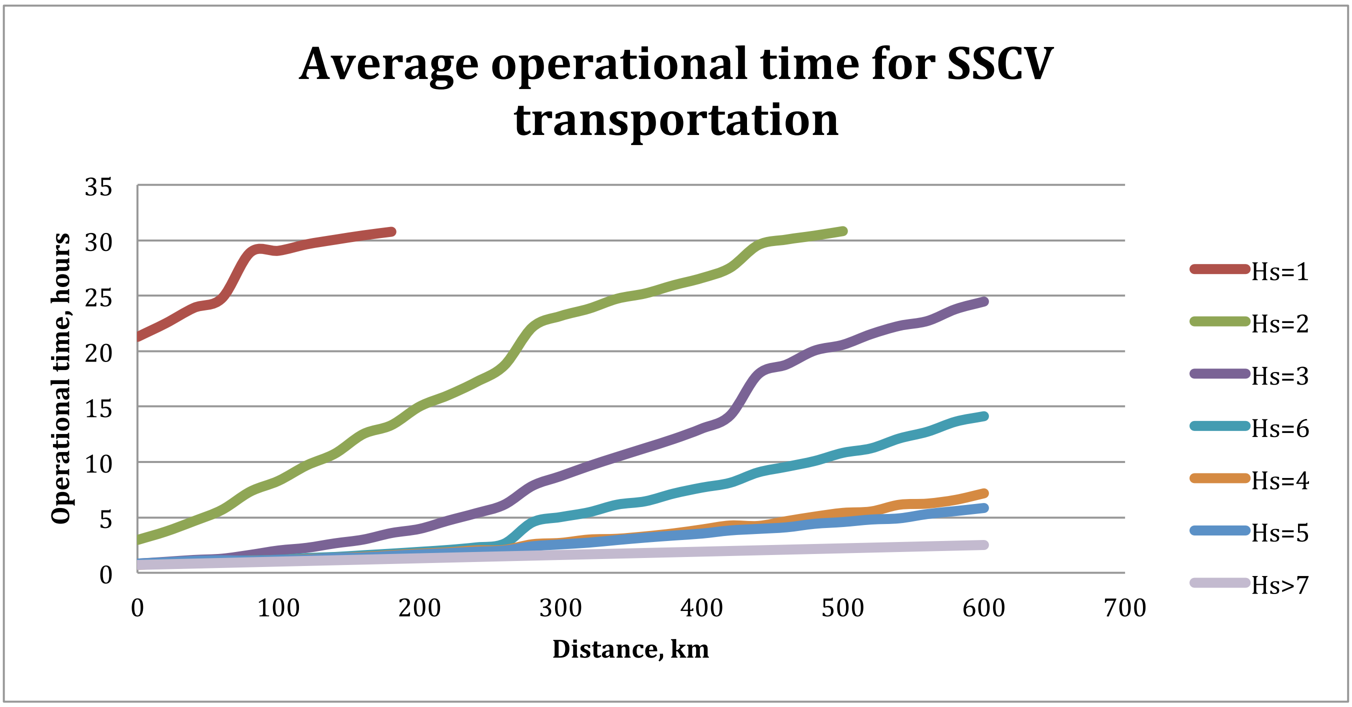


Figure 5.4. Average operational time for SSCV transportation in July for different values of the allowable significant wave height during towing

Results for the December you can see on the Figures 5.5 – 5.7.

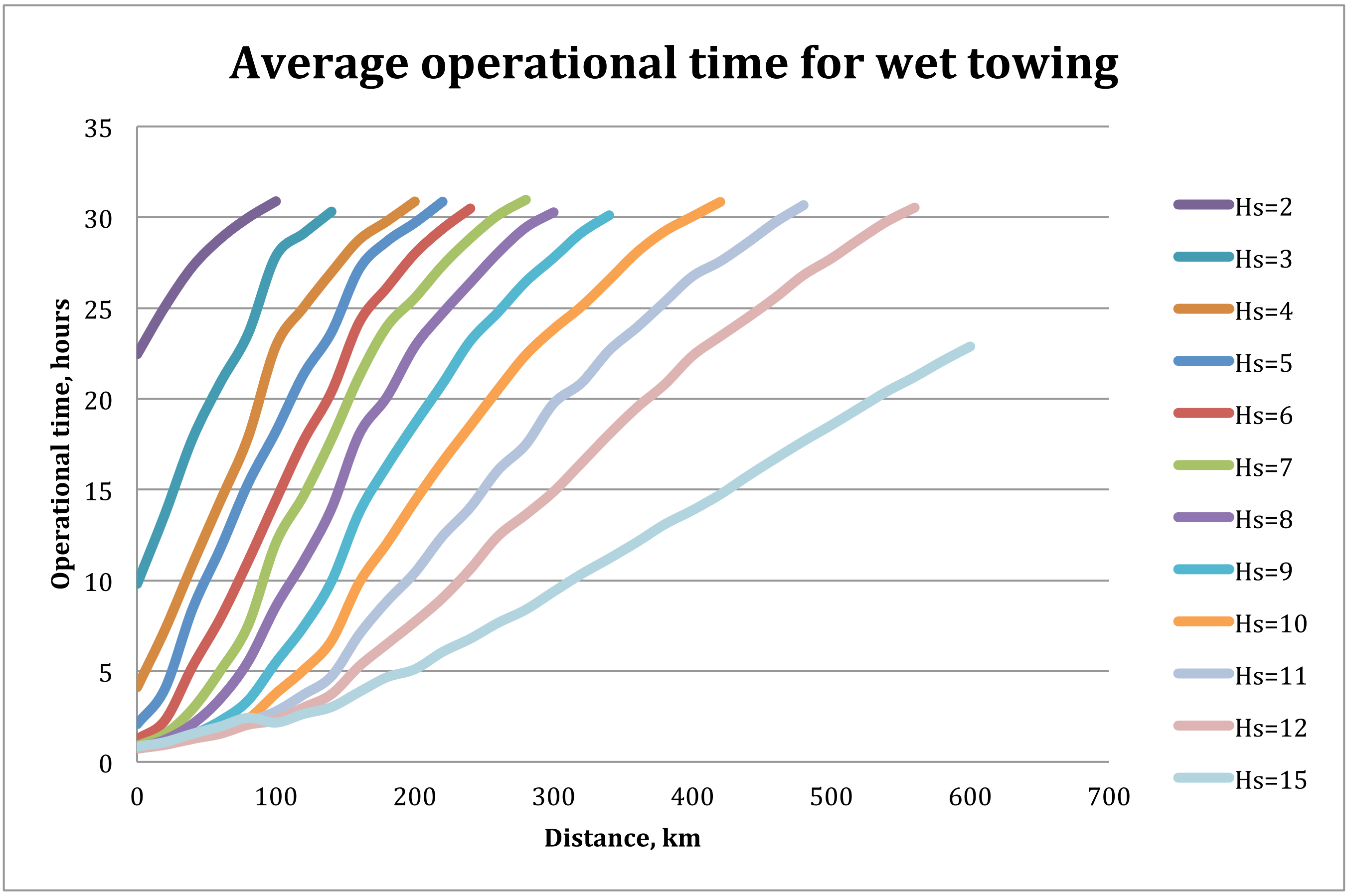


Figure 5.5. Average operational time for wet towing transportation in December for different values of the allowable significant wave height during towing

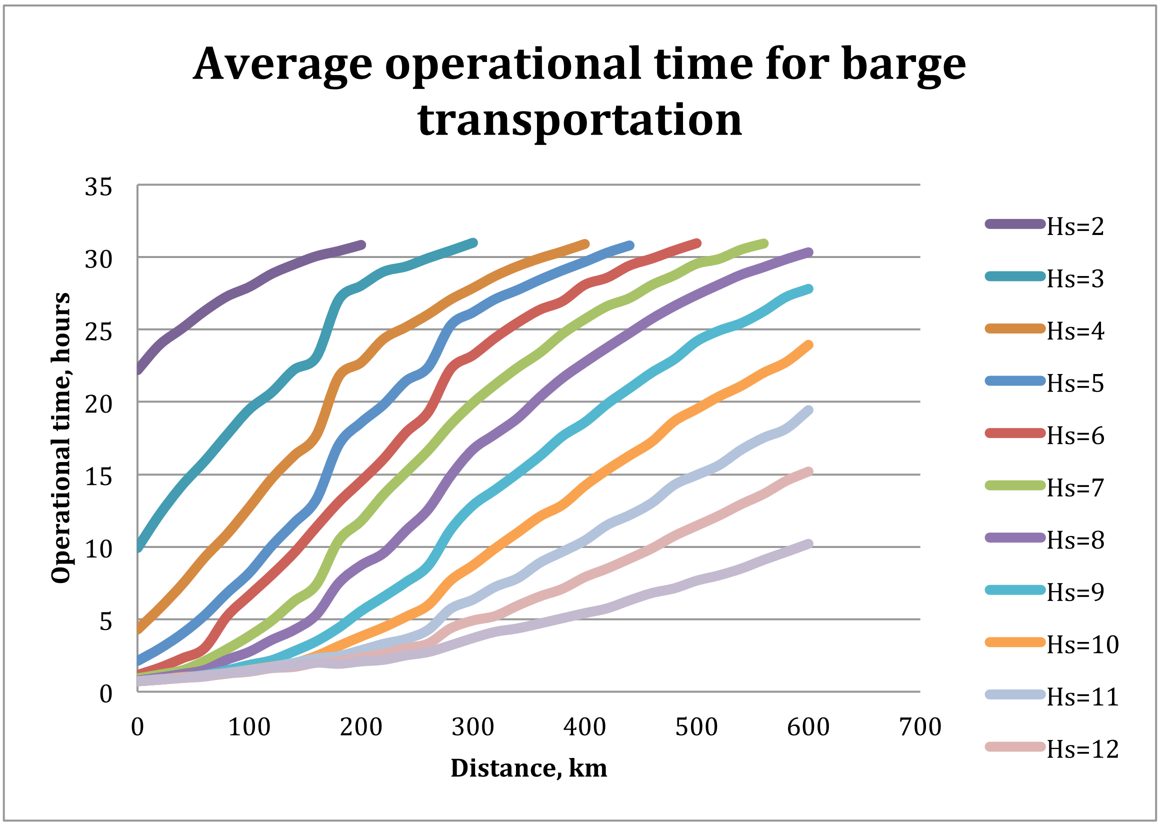


Figure 5.6. Average operational time for barge transportation in December for different values of the allowable significant wave height during towing

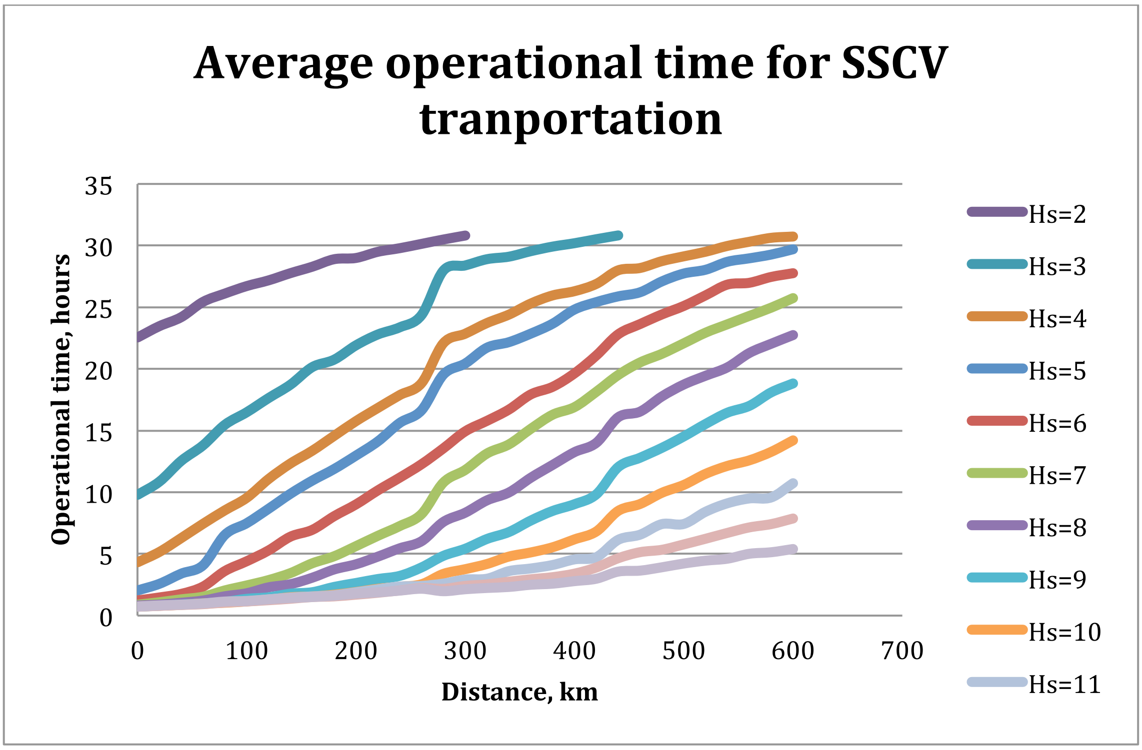


Figure 5.7. Average operational time for SSCV transportation in December for different values of the allowable significant wave height during towing

Result analysis:

Figures 5.2 – 5.7. show that if our design criteria (wave height) will be higher, it will result in less average time for the operation, thus the cost of installation will be lower.

Wet transportation –in July: if our design limit for the transportation will be less than 1 m it will be impossible to transport the equipment, as there are no sufficient weather windows in this month. If the limiting wave heights are 1 to 2 m, installation is available only for the distance 80 and 120 km. For other values of the limiting wave height there is no distance limitations. In December the highest transportation distance is 250 km, as the value of wave height more than 7 m is assumed to be impossible for the operation.

Barge – the same as for wet methods, for limiting wave heights 1 to 2 m, distances are 120 and 320 km correspondingly. In December the maximum distance is 300 km (wave height 3 m).

SSCV – limiting distances are 180 and 500 km. In December there are no limitations to perform an installation operation. However, the average time of the operation will be high.

5.4. Day rates and design limitations

For calculation of cost we will use the following day rates for the vessels (Pribytkov et al., 2013):

- wet towing (traditional) – 400.000 $/day
- wet towing (innovative solution) – 500.000 $/day
- barge (including cost of a crane for heavy lifts) – 600.000 $/day
- SSCV – 500.000 $/day

The limiting criteria for the installation operations is the significant wave height. As was described in the previous chapters the main advantage of the wet tow method is the increased value of the limiting significant wave height, thus the operations can be designed for higher values of H_s. We will assume the next values of H_s for further calculations:

- wet towing (traditional) – 6 m.
- wet towing (innovative solution) – 7 m.
- barge (including cost of a crane for heavy lifts) – 3 m.
- SSCV – 4 m.

5.4. Cost of installation operation

Now we can compare different installation techniques with respect to the cost. The comparison will be done for two months – December and July.

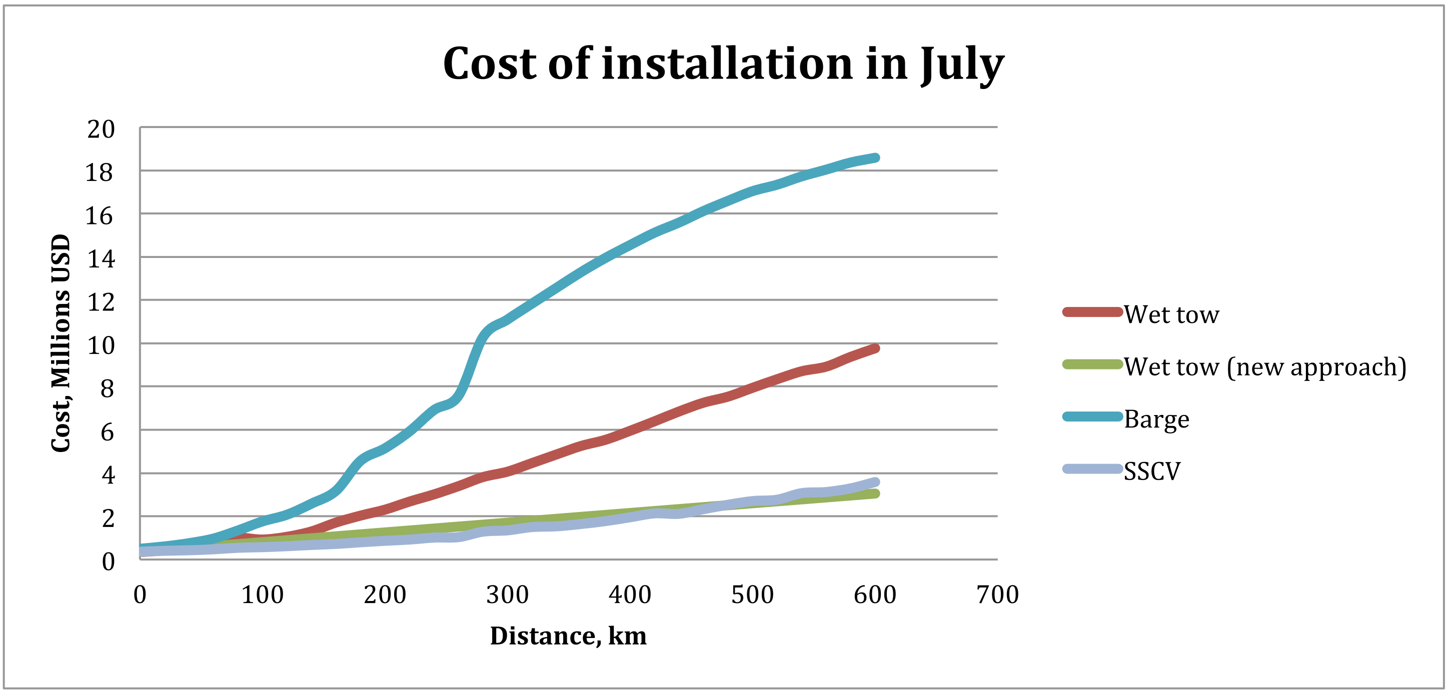


Figure 5.8. Cost of installation in July

Figure 5.8 shows that the most cost effective way to transport and install the equipment are use of SSCV or innovative wet towing. However, for the distances up to 500 kilometers, SSCV is the cheaper option. For the distances more than 500 km, the preferred option will be the innovative wet towing.

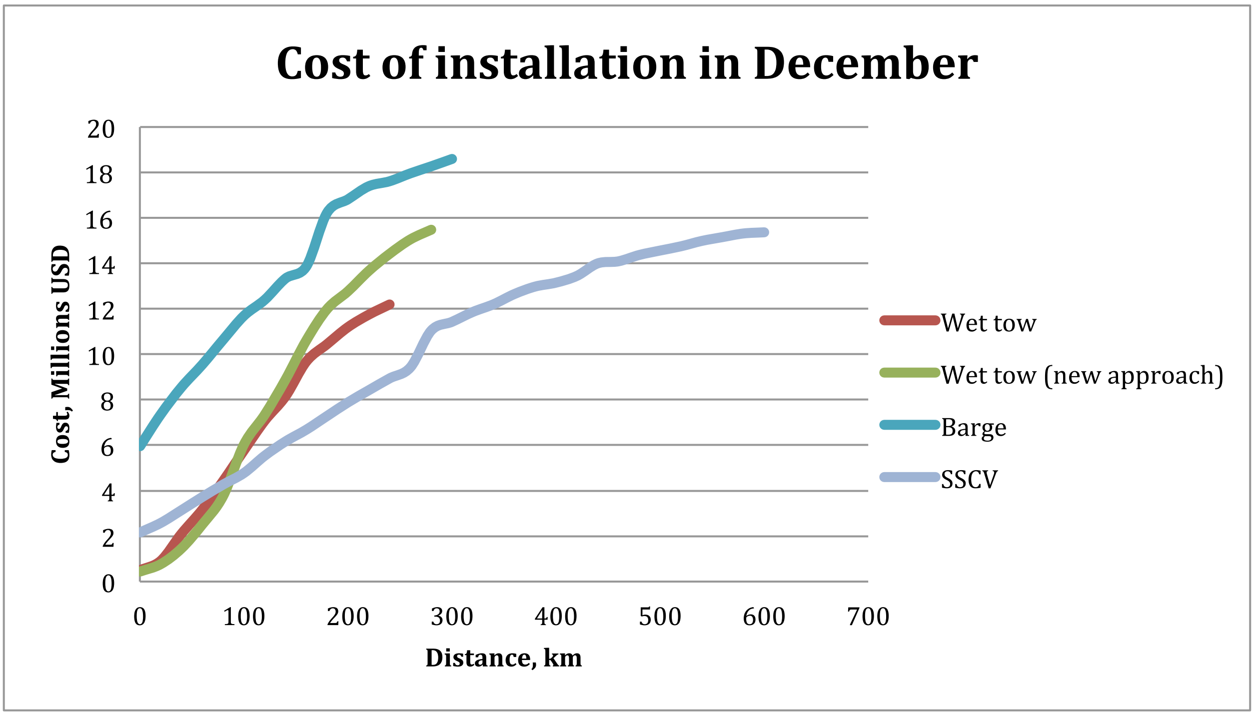


Figure 5.9. Cost of installation in December

Figure 5.9 represents the results for December. In December, if the distance of the location of installation is not far away from the shore (<80 km), the preferred option will be the wet towing. For greater distances the only way to carry out the operation is to use SSCV to install the equipment.

Nevertheless, the only up to date way to install heavy equipment with the weight more than 500 tons is to use offshore barges to transport the equipment to the location of installation and then use offshore heavy lift cranes to install it onto a seabed. As we can see from the comparison (Figures 5.8 – 5.9), regardless of the season of installation, such approach has the worst economic performance. The implementation of a new concept could be a cheaper alternative.

Conclusion

The present research states some basic theoretical proposals for a new transportation and installation concept. Based on the obtained results, following conclusions are made:

- the dimensions of the BC system to transport Ormen Lange template should be not less than 44x33x2 meters. Tug boat should be able to create a draft force app. 3 MN to obtain the speed of transportation to the location of installation 5 knots. The speed of installation could be up to 3.5 m/sec. To achieve such speed in reasonable amount of time (within 10 seconds), water injection pump, installed on the BC, should have capacity not less than 50 m^3/sec;
- a water depth within a harbor should be not less than 20 meters to accommodate the equipment with installed BC;
- to mitigate the risk, several measures should be implemented: double hull of the BC system, doubled amount of computers to control immersion depth, ROV monitoring, accumulators with compressed air on the BC for emergency ascending and accumulators of electric power for emergency positioning;
- application of innovation is expediency for installation of heavy weighted equipment (weight more than 500 tons) regardless of season. During the summer months analysis shows that the price of installation with a new method will be approximately the same as with the most used method – SSCV. During the winter season new approach has the window of applicability for transportation on the field’s distance less than 80 km from the shore;

However, a lot of things should be studied further to finally prove technical and economical feasibility of the project. The most important research areas are:

- precise calculation of transportation and installation process, including 3D modeling of process in wave conditions;
- determination of exact weight of the system;

- determination of availability of necessary equipment, e.g. compressors, pumps, horses, etc.;
- calculations of performance of the system under a high pressure (deep water conditions);
- consideration of transportation alternatives and combination with other methods, e.g. semi-submergible barges;
- examination of different world's areas in respect to economic performance in various weather conditions;

References

1. Olsen, T. A. (2011). *Subsurface towing of heavy module*. Retrieved from http://www.diva-portal.org/smash/get/diva2:506723/FULLTEXT01.pdf
2. Mork, H., Lunde, J. (2007). *A Cost-Effective and Safe Method for Transportation and Installation of Subsea Structures – The Pencil Buoy Method.* SPE 108608. Offshore Europe Conference held in Aberdeen, UK.
3. Risoey, T., Mork, H., Johnsgard, H., Gramnaes, J. (2007). *The Pencil Buou Method - A Subsurface Transportation and Installation Method.* OTC 19040. Offshore Technology Conference held in Houston, USA.
4. Wang, A., Yang, Y., Zhu, S., Li, H., Xu, J., He, M. (2012). *Latest Progress in Deepwater Installation Technologies.* ISOPE. Twenty-second International Offshore and Polar Engineering Conference held in Rhodes, Greece.
5. Wang, A., Zhu, S., Zhu, X., Xu, J., He, M., Zhang C. (2013). *Pendulous Installation Method and its Installation Analysis for a Deepwater Manifold in South China Sea.* ISOPE. Twenty-third International Offshore and Polar Engineering Conference held in Anchorage, USA.
6. Lima, J. M., Lima, M., Silveira, P. F., Stock, P. F. (2008). *Development of Subsea Facilities in the Roncador Field (P-52).* OTC 19274. Offshore Technology Conference held in Houston, USA.
7. Jacobsen, T., Næss T. (2014). *Installation of Subsea Structures Using Mid-Size Construction Vessels in Harsh Environments.* OTC 24899-MS. Offshore Technology Conference held in Kuala Lumpur, Malasia.
8. Aarset, K., Sarkar, A., Karunakaran, D. (2011). *Lessons Learnt from Lifting Operations and Towing of Heavy Structures in North Sea*. OTC 21680. Offshore Technology Conference held in Houston, USA.
9. Subsea 7 (2015). *Scandi Acergy.* Retrieved 01.06.2015, from: http://www.subsea7.com/content/dam/subsea7/documents/whatwedo/fleet/constructionvertical/Skandi_Acergy.pdf

10. Teras Offshore (2015). *Teras 002. Semi-submersible heavy lift barge.* Retrieved 01.06.2015, from: http://www.terasoffshore.com/?p=section&sub=article&articlegrppk=81&articlepk=127
11. DNV-RP-H101 (2003). *Risk management in marine and subsea operations*.
12. DNV-OS-H101 (2011). *Marine Operations, General.*
13. Norsok standard Z-013 (2010). *Risk and emergency preparedness assessment.*
14. Glomnes E., Skalle H., Taby J. (2006). *Ormen Lange Template Installation.* Project work. Glomnes E., Skalle H., Taby J, Trondheim.
15. Pribytkov, E. A., Zolotukhin, A. B., Gudmestad, O. T. (2013). Selection of Subsea Production Systems for the Field Development in Arctic Enviroment. *SPE 166879. Arctic and Extreme Environments Conference & Exibition held in Moscow.*
16. Statoil statistics. (2013). *Northern North Sea hindcast data*. Retrieved from prof. Haver S., University of Stavanger.
17. Haver S. (2014). Description of Metocean Characteristics for Planning of Marine Operations. Stavanger: University of Stavanger.
18. Berg, Bernd A. (2004). *Markov Chain Monte Carlo Simulations and Their Statistical Analysis.* NJ: World Scientific.
19. Thomas L. (2012). *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World.* Eddition 2001. Pittsburg: RWC Publications.
20. Gudmestad O. T. (2014). *Marine Technology and Operations compendium*. Stavanger: University of Stavanger.

APPENDIX 1. MATLAB script for calculation of weather windows

```
k=1;
for i = 1:length(HD)
    HD(i,6)=k;
    k=k+1;
end
HD_Mon=[];
k=1;
%Number of month
for i = 1:length(HD)
    if HD(i,2) == 12
        HD_Mon(k,:) = HD(i,:);
        k=k+1;
    end
end
HD_Mon_hs=[];
k=1;
%Value of Hs
for i = 1:length(HD_Mon)
    if HD_Mon(i,5)<=1
         HD_Mon_hs(k,:) = HD_Mon(i,:);
         k=k+1;
    end
end
for i=1:minus(length(HD_Mon_hs),1)
    if minus(HD_Mon_hs(i+1,6), HD_Mon_hs(i,6))>1
        HD_Mon_hs(i,7)=1;
    end
end
```

```
Num_Intervals=0;
for i = 1:length(HD_Mon_hs)
    if HD_Mon_hs(i,7)==1
        Num_Intervals=Num_Intervals+1;
    end
end
Num_Intervals=Num_Intervals+1
Mean_Duration=length(HD_Mon_hs)*3/Num_Intervals
Percantage_Time=(length(HD_Mon_hs)/length(HD_Mon))*100
```

APPENDIX 2. MATLAB Monte-Carlo script

```
%Initial parameters for simulation
NumberSim=10000; %Number of simulations
NumberWD=31; %Amount of days in the month
k=0;
Average=ones(31,31);%Resulting matrix
for i=1:31
   for j=1:31
      for s=1:NumberSim
         if Probabilityofsuc(i,j)<rand(1)%Generation of random probabilites
            k=k+NumberWD;
         end
      end
      Average(i,j)=k/NumberSim;
      k=0;
   end
end
```

APPENDIX 3. Numerical solution of equations in Wolfram Mathematica

Appendix 2 contains 2 program script from Wolfram Mathematica, enclosed to this thesis.