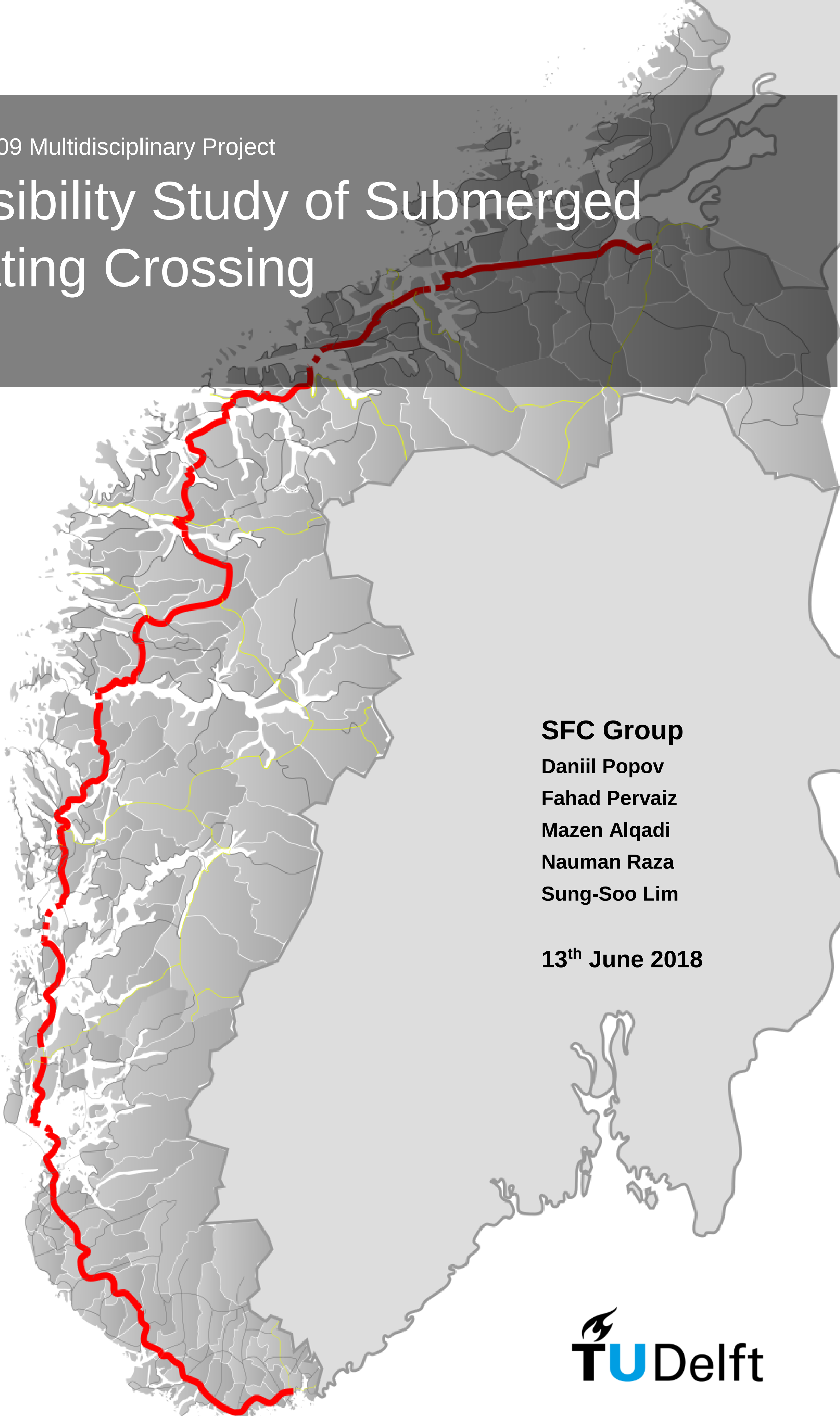
CIE4061-09 Multidisciplinary Project

Feasibility Study of Submerged Floating Crossing



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TU Delft

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Abbreviation & Acronym

AADT	Annual Average Daily Traffic
CCTV	Closed Circuit Television
DAL	Design Accidental Load
DNV	Det Norge Veritas
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
HAZID	Hazard Identification
MCA	Multi Criteria Analysis
OGP	International Association of Oil & Gas Producers
PHA	Preliminary Hazard Analysis
SFC	Submerged Floating Crossing
SONAR	Sound Navigation and Ranging
TLP	Tension Leg Platform
VIV	Vortex Induced Vibration
VLSS	Very Large Crude oil Carrier
WCS	Worst Case Scenario

Executive Summary

The main scope of this study is to investigate the technical feasibility of the submerged floating crossing (SFC) design for the 6 km of waterway width at Bjørnafjord of Norway. To convince general publics that SFC type crossing is safe enough, a comprehensive risk assessment is introduced to identify what types of risk are mostly posed to the SFC. Through hazard identification major hazardous events were screened, which include fire, flooding, external damage due to marine accident, and loss of support structure induced by dynamic response, which became a basis of worst case scenarios. Relevant marine accident includes ship grounding and submarine collision.

Approximate construction cost estimations among possible options to cross this fjord, SFC, undersea tunnel and immersed tunnel, were conducted, showing why only SFC is the most achievable option minimizing construction cost calculated simply by construction length.

The alternatives of SFC design have been examined with respect to three key aspects - alignments, cross-sections and a type of support structure - in a systematic way e.g. multi-criteria analysis. The base SFC design has been chosen based on multi criteria analysis with respect to these afore-mentioned aspects. The SFC comprises a single circular “tube” and support structures called “tethers”. The “tube”, made of composite materials, has 17.9 m of diameter to accommodate the two traffic lanes and an escape route in three different levels. To support the tube, the SFC with tethers was selected due to safety reasons. The tether configuration and its design criteria has been identified and checked to ensure the acceptable stability of tether in terms of Vortex Induced Vibration (VIV). The detailed information of the base SFC design is given in Chapter 4.

Consequence modelling approach is introduced to investigate the specified worst-case scenarios. Amongst the identified major hazardous events, only three events are relevant to the worst-case scenarios. The frequencies of two identified hazardous events, ship grounding and fire accident, were merely quantified due to the reason that the former is hardly probable to happen and the latter is less relevant to the objective of this feasibility study. The following are worst case scenarios assumed to be credible to the SFC:

- Loss of support structure, e.g. tethers
- Submarine collision
- Flooding due to accumulation of drainage

Both 1-D model and 3-D structural model have been employed to perform the first and second worst case scenario analysis which have evaluated vertical/angular displacements and cross-sectional indentation, respectively. For third worst case scenario, the amounts of possible sources of drainage have been calculated and the drain system is suggested as a safeguard. Independently, Vortex Induced Vibration (VIV) analyses have also been carried out for both the tube and the tethers to anticipate the significance of VIV occurrence and to optimise the diameter of tethers.

The construction and maintenance of the SFC is one of the prime considerations. The construction in dry dock and floating of each 200 m component before coupling, would require exact weight and position control of the installed SFC. The SFC segments, prefabricated in a construction site, are welded for ensuring water-tightness while floating on water surface.

In conclusion, the SFC has appeared to be a sheltered and sound idea appropriate to satisfy its expected capacities and to tackle given environmental conditions. The structure of the proposed SFC is intended to withstand all functional and environmental loads. The results of worst-case scenarios showed the base SFC design have a sufficient robustness to withstand the presumed significant loads. Due to the limitation in the recreation of physical phenomena of the hazardous events it is recommended to perform in-depth studies for some aspects in the followings:

- Safety e.g. Fire and explosion analysis, emergency preparedness
- Joint design e.g. configurations, welding analysis
- Environment e.g. Environmental impact including social effect
- Utilities e.g. Ballast system
- Installation and maintenance e.g. transportation, recoverability

1 Introduction

1.1 Background

Innovative development in bridge and tunnel technology has made it possible to cross a great number of fjords and straits during the last few decades. However, there are still many locations which are too wide and too deep to be crossed by the bridges, floating bridges and sub-sea tunnels. For such fjords, Submerged Floating Crossing (SFC) seems to be a good solution for waterway crossing. Such structure has never been built so far anywhere in the world. But countries like Norway are planning to construct SFCs in the near future because its flexibility with respect to length and water depth makes it a suitable option for road traffic crossing in fjords, rivers, lakes and island connections.

Concept of SFC was initially presented by United Kingdom in 1886, however in Norway it was introduced in 1923 for the very first time. Since then it is the subject of research, as it suits most at many fjords in Norway. Around 1960's some Norwegian researches concluded that the idea is worth pursuing and hence a tentative design of 1500m SFC was carried out. Since then there has been many developments in the design without any execution. But recently, E39 project was introduced by the Norwegian government, which is expected to include SFC on some major fjords' crossings.

1.2 E39 Ferry-Free Project

E39 is the part of Norwegian National Road System. The route runs along the western coast of Norway, from Kristiansand in the south to Trondheim in central Norway, a distance of almost 1100 km as shown in Figure 1-1. Along the route of the project there are eight major fjord crossings. One of the key components of the feasibility study of E39 route is to find alternatives for the fjord crossings. Most of these fjords are very wide and deep which makes the conventional water crossing options very expensive and less feasible. In this scenario many companies are considering the construction of SFC as a good innovative alternative to the conventional crossings. As shown in Figure 1-1, one of the eight fjord crossing is at the Bjørnafjorden.

Bjørnafjorden is a fjord in the county of Hordaland and E39 will connect Svarvhella and Røtinga through this fjord. It is around 30 km long and around 6 km wide fjord with maximum water deep reaching up to 500m. Following three different design concepts are being considered for this crossing;

1. Floating bridge with cable stayed main bridge
2. Three span tension leg platforms (TLPs) suspension bridge
3. Submerged Floating Crossings

The suitability of these options to fulfill the design requirements is under study. This feasibility report is a part of this study which is dedicated to the concept of submerged floating crossings.

1.3 Objective

The prime objective of this feasibility study is to carry out a preliminary design of submerged floating crossing, encompassing;

- Geometric Design i.e. cross section, longitudinal profile etc.
- Support Structure Analysis and Design

- Structural Behaviour Assessment
- Risk Analysis

The preliminary design should reflect that the structure is unsinkable and feasible to construct under the prevailing loading conditions.

Figure 1-1 Overview of E39 project (Ellevset 2014)

1.4 Main Definition

1.4.1 Submerged Floating Crossing (SFC)

Submerged Floating Crossing is a buoyant structure which floats under the water and is kept stable with the help of support structures. It may consist of the following elements:

- Tunnel tube which acts a carriageway for traffic, railway or pedestrians
- Support structure like tethers which can be vertical or inclined and fix the tube to the seabed
- Pontoons fixed on the top of the tunnel and anchor it to the sea surface
- Support of Tether at the sea bed in the form of anchors
- Connections to the shore at the end of the tunnel

1.4.2 Failure

If the buoyancy of SFC is overwhelmed due to any reason, the stresses on the support structure would increase which may result in the flooding of the tunnel. It will increase the downward loading on the tunnel and this unstable divergent condition may cause the collapse of entire structure. In this scenario SFC is considered as 'sunk'. To avoid the risk of such extreme failure of any structure, governing failure modes and allowable damage criterion are defined by different codes/standards.

For this study, the definition of 'unsinkable' SFC is that the structure placed at certain water depth does not exceed the allowable limits of governing failure modes. The failure modes for SFC are specified below:

- Structural deformation induced by loss of support structure elements, in terms of:
  - Vertical and horizontal displacement
  - Angular deformation
- Structural deformation induced by an external collision, in terms of:
  - Cross sectional local indentation
- Accumulation of drainage (Leakage), in terms of:
  - Excessive rate of drainage accumulation

Selection of the failure modes is based on the risk assessment analysis which is presented in Chapter of this report. Allowable criterion for each governing failure mode is defined in Table 1-1.

Table 1-1 Criteria for different failure modes

Failure modes	Criteria	Reference
Vertical displacement (deflection)	Span / 200	EN 1994-4
Cross sectional angular deformation	15 mrad	EN 1994-4
Cross sectional local denting	1.90 m	Zhang, 1999
Allowable rate of drainage accumulation	0.1 m^3/min	Reinertsen, 2016

Apart from these criteria, another criterion has been considered for the vertical displacement of the structure. This criterion is related to the elongation extent in the support structure with vertical displacement of SFC. Hook's law is utilized to relate the yield strength of the support structure with the vertical displacement.

1.5 Study Structure

With a comprehensive brainstorming, factors affecting the fact that SFC type of crossings have never been built before even though its concept and idea had broadly published, has been observed which became the basis of this study. The feasibility study contains seven chapters. Different aspects of the studies have been produced in these chapters.

Chapter 1, is related to the introduction of the study. A brief description of E39 project is presented along with the details of Bjørnafjorden, (the location of this proposed project). Objectives of the study has been defined and a failure criterion is presented.

Chapter 2 contains the risk analysis for the proposed SFC. Different risk analysis tools are discussed and applied to find the worst-case scenarios.

In Chapter 0, a comparison of different waterway crossings is made through trade-off study and reasoning behind the selection of SFC over other options is presented. After the selected of waterway crossing, a design principle has been established for the preliminary feasibility level design. This chapter also contains the loading conditions and operational requirements of SFC.

Chapter 4 is related to the preliminary design calculations. SFC profile, cross section and loadings have been defined in this chapter.

To check the design of SFC, the effect of identified hazardous events have been assessed through consequence modelling in Chapter 5. Three different models namely; 1D, 3D and Vortex Induced Vibration (VIV) Model has been produced and their results have been discussed.

Chapter 6 contains a brief detail about the construction and maintenance aspects of SFC. It discusses the installation and maintenance.

Chapter 7, is related to the outcomes of the study. A detailed discussion of results is presented, and a conclusion is drawn based on the results.

Figure 1-2 presents the tasks and their interconnectivity.

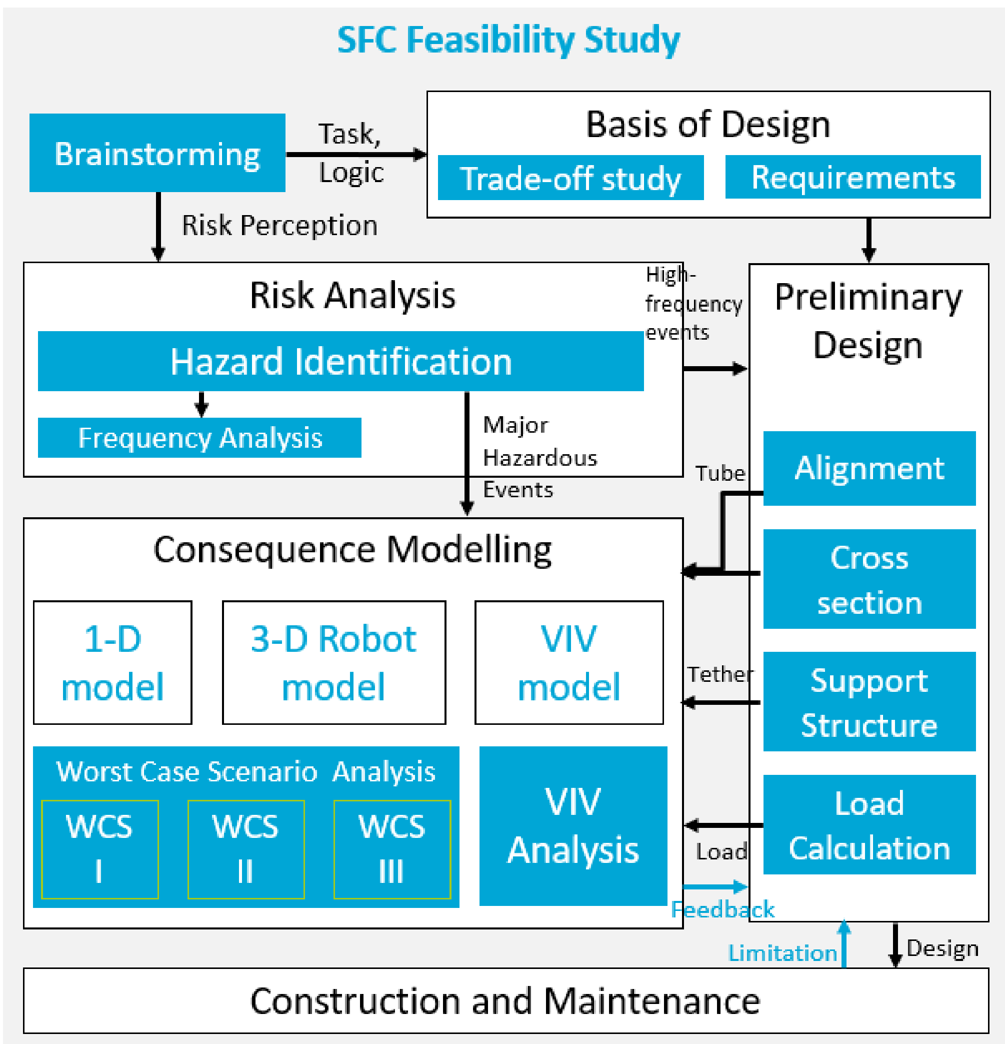

Figure 1-2 Explanatory charts for task structure

2 Risk Analysis

Risk is always related to what possibly can happen in the future. The word risk is the combined answer to three questions: (1) what can happen? (2) How likely is it? and if it does happen, (3) what are the consequences? In this regard, risk can be defined in terms of probability as well as consequences (CT4130 TU Delft), which means the probability of an undesired event in a proceed or for an object and the consequence of an undesired event.

It is a crucial requirement to the submerged floating crossing that the safety is at least of the same level as other fjord crossings like bridge and ground tunnel. This is especially important because the overall structural concept has never been used before. The dimensions, the complexity, the slenderness, the joints, and the marine operations surpassing previous experience. Even if each individual element and operation is found to have adequate safety, in principle a hazardous chain of events may be released unless the interaction of elements is adequately understood.

2.1 Risk Perception

Public perception and operational safety are important factors that increase or decrease the chances of constructing a new project. On one hand, as it is always with new projects, the construction of SFC is uncertain and thus, the conception of its venture is considered the riskiest by investor and companies. On the other hand, convincing the public to use long road tunnels is a challenge, particularly those that are deep in the sea. According to Wallis (2010) a study conducted by the Norwegian Public Roads Authority stated that, out of the total respondents, some 20-30% were 'uncomfortable' driving through long undersea tunnels. Another 5-7% were 'afraid' and 1-2% could have a phobia of tunnels (Figure 2-1)

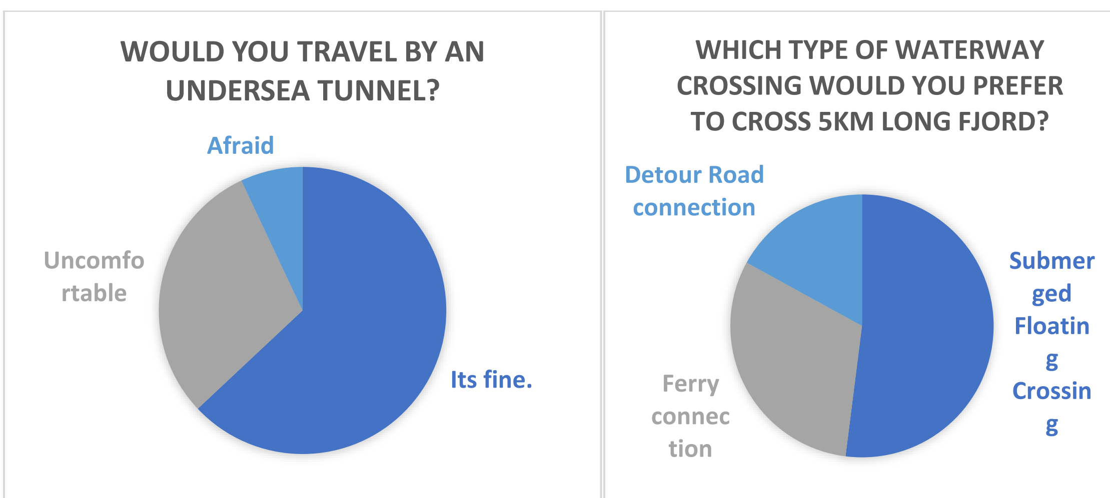

Figure 2-1 Two survey results conducted on risk perception over tunnels/crossings by Norwegian Public Road Authority (left), by SFC group (right)

In a similar approach, a survey was conducted to assess the public risk perception of SFC among 43 university students. (See Appendix A) The survey finds out that 52 % prefer to travel through SFC, compared to 31% and 17% using ferry and detour connection, respectively (Figure 2-1). The majority of those in favour of SFC chose it because it would reduce travel time (56% of those who in favour of SFC) whereas the remaining chose it for because they like adventure (22% of those who in favour of SFC). Others preferred ferry (30% of those who against SFC) because they might have a phobia of confined spaces (18% of those who against SFC). Moreover, most of the respondents who chose detour are likely to be scared of drowning (50% of those who against SFC).

It is a crucial step to gain the confidence of the public and assure the safety of the infrastructure to clients and the insurance industry. To tackle this issue, it was referred by Wallis (2010) that the concept be built first at a theme park like Disneyland to provide a 'soft' introduction to the public. In this study, it is believed that clients and insurance companies would be convened with a comprehensive risk assessment of the study that:

- Investigate all possible hazards;
- Screen most-relevant worst-case scenarios and identify their consequences;
- Identify the measures to mitigate and prevent their happening

The following section discusses the method used for risk assessment to cover tasks mentioned above.

2.2 Risk assessment tools

This section discusses risk evaluation method adopted for the SFC. Each technique has several tools to perform it. Among which three tools were chosen which are Preliminary Hazard Analysis (PHA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA).

These tools were chosen because they complement each other and are suitable for preliminary design used in feasibility studies. Moreover, the use of these tools will;

(i) Provide insight in the cause and effect of failure of individual system components: and
(ii) Provide a good starting point for quantitative analysis methods that can be applied at a later stage.

Preliminary Hazard Analysis and Fault Tree Analysis are mainly employed for the identification of hazards. Event Tree Analysis is used in the frequency calculation in Chapter

2.2.1 Preliminary Hazard Analysis (PHA)

Rausand (2013) defined hazard identification as “the process of identifying and describing all the significant hazards, threats, and hazardous events associated with a system”. PHA method is commonly employed in the identification of hazards and potential accidents in the design phase of a system. The method is basically a review of where energy or hazardous material can be released in an uncontrolled manner.

The objective of PHA can be summarized as identifying the assets that need protection, identifying the hazardous events that might occur, determining the main cause of each hazardous event. PHA also determines how often each hazardous event may occur and its severity, and suggesting mitigation processes. The whole assessment tables of PHA are found in Appendix B.

2.2.2 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is used for Identification of any hazardous events and the root causes of the hazards. This technique involves breaking down an accident into its component causes. The Fault Tree Analysis illustrated here has been figured out based on literature (DNV Technica,

1999) and lecture materials (CIE4130 TUDelft, 2017) and drawn by a web-version software. The respective frequencies of occurrence for all root cause events were not quantified in this analysis. An example of FTAs is shown in Figure 2-2. The details of all FTA are found in.Appendix C.

In this project, hazards were determined by reviewing similar project risk register, through discussion with expert professional – the project supervisor –, and continual reviews from project team members throughout the project progress. Example of similar and somehow comparable projects are crossing bridge and immersed tunnel. The main hazards to the bridge, their possible consequences and their possible mitigating actions have been identified and complemented with hazards associated with the structure being submerged and floating. During hazard identification, attention where set to list most probable events that would endanger the integral safety which include structural safety, fire safety, security, traffic safety, tunnel safety, nautical safety, and dangerous goods. In the following section, risk is categorized based on the phase of the project, construction/ installation, and operating phases.

2.2.3 Event Tree Analysis (ETA)

Event Tree Analysis is a popular technique to be used in frequency calculation. This is a means of showing the way an accident may develop from an initiating event through several branches to one of several possible outcomes. The technique is usually used to extend the initiating event frequency estimated by one of the above means into a failure case frequency suitable for combining with the consequence models. (DNV Technica, 1999)

The comparisons between PHA and either FTA or ETA has been summarized in Table 2-1.

Table 2-1 Comparison table for a variety of risk analysis tools

	PHA	FTA or ETA
Features	• Stand-alone analysis, • Comprehensive risk assessment	• Performed on a major hazard accident selected from the list of PHA results
Results	• Used to screen events for further study • Comprehensive list of discrete risks and uncertainties together with their causes, consequences and suggested mitigation	ETA • The development of accident from the initiating event to possible outcomes FTA • Root causes of the specified hazards/hazardous events • The frequency estimated from the root causes to interested hazards.

2.3 Hazard Identification

The first essential step in risk evaluation is to identify all discrete hazards and uncertainties that would possibly jeopardize the integral safety of the SFC project during construction, installation, and operation phases. This is achieved by performing the qualitative techniques known as Preliminary Hazard Analysis (PHA) which encompasses causal and consequential assessment for identification and evaluation of significant hazards in terms of possible escalation, risk-reducing measures and a rating of probability and consequence.

2.3.1 Hazardous event from PHA

Construction phase

Based on PHA tabulated in Appendix **B** several hazards were identified. Some of the hazards that could occur during the construction phase are related either to the transportation method, assembling stages, or the existing environmental conditions:

- Grounding of structure element - tube, tether or joint section;
- Failure/mal-operation of bilge and ballast system; winch and cable system; and tugs;
- Free floating element will be exposed to a hydrostatic motions VIV and galloping during transportation;
- Human error such as inaccurate alignment and dimension deviations of tube and landfall joint or due to motions of joint after grouting and before proper pre-stressing : As for possible hazard during assembling stage, some of the possible ones are failure during connecting elements; and
- Surrounding environment and environmental data play a role as well : Operating during bad weather season and lack of environmental data negatively impact the efficiency and safety of the project.

These upper mentioned hazards can generally be prevented / eliminated by applying appropriate corresponding measures for each expected hazard and by applying only well proven and recognized technical solutions, conservative design assumptions and generous design acceptance criteria and putting an emphasize to redundancy and element reliability. For example:

- Hazards related to transportation of elements can be prevented by performing a comprehensive bathymetric survey of the entire route swept by elements or assembly of elements and credible obstacles to be removed before towing. The area to include tolerances for deviation from planned routing.
- Other hazards can be prevented by using highly skilled workers, new equipment, regular force movement monitoring, and accounting for flexible tubes for VIV.
- Adequate and redundant system of winches and tugs should be available to place the tube in the accurate position. Overall, transportation and assembling shall follow stringent operation procedures.

Operation phase

A demonstrable high level of operational safety of the crossing is paramount to its acceptance and long-term success. According to Fjeld (2012), the following hazard might occur during the operation phase of the SFC project:

- **Traffic tube ramming by ship** could be a hazard. However, such occurrence is avoided in the design by ensuring adequate keel clearance.
- **Traffic tunnel ramming by submarine** as the SFC is in an area known for its heavy ship and submarine traffic. This risk could be reduced by providing transponders for acoustic warning
- **Dropped objects / ship grounding, dragging chain or wire** is a hazard with low probability of occurrence due to that either anchoring or dragging operation might take place in shallower

water. For example, a grounding accident induced by mal-operation of anchoring occurred at the location where the water depth is around 30m (aibn, 2013). It implies that the possibility would be remoted to anchor or to drag the anchor to the SFC structure directly.

- **Fire** during the operation phase can be triggered by several causes such as traffic accident, explosion by car crash/terrorism. Considering this, the traffic tubes will be made of concrete and steel of adequate durability during a design fire. Escape ways and safe havens will be provided. Ventilation system designed for accidental fire. Firefighting systems to be provided. Possibly restrictions on cargo.
- **Explosion** could lead to a total failure of the SFC. The traffic tubes will be hoop reinforced to take the internal overpressure from a deflagration. Transportation of explosives which might release a detonation should be considered being forbidden.
- **Warfare, sabotage, and terrorism** also could result in damaging the SFC structure. The tunnel is provided with more reliable escape and evacuation means than those of other long bridges. It is also provided with pumps to counteract a reasonable influx of water. In general, the risk is not higher than for other bridges i.e. accepted by society.
- **Loss of oxygen supply** hazard can be mitigated by ensuring regular provision of ventilation systems and sensors and signals for automatic refusal of cars entering a toxic area. Transportation of toxic gases to be limited.
- **Leakage into the traffic tube** might occur during the operation phase and its risk can be reduce by the following measures. Providing monitoring instrument for possible water influx and redundant bilge and ballast systems of adequate capacity to dewater the tunnel and to stop influx of water from outside. Moreover, the tunnel is designed to withstand an allowable level of drainage pile-up.
- **Fatigue and unstable failure** like cracking of concrete could be reduced by the use of prestressed concrete sections.
- Corrosion occurrence is prevented by applying steel coating, and providing corrosion allowance during design stage.
- **Earthquakes** probability of occurrence is low as Norway is on a stable tectonic plate and has a moderate seismic activity with a return period of 10 000 years on the western coast i.e. about 3 m/sec^2 (Fjeld, 2012) or 0.9 m/s^2 for a return period of 475 years (Søreide, 2016). This can be taken into consideration during design stages.
- **Landslide generated wave** is one of the hazard that can be avoided by considering it during designing.
- **Inner subsea waves** are not considered to pose a significant risk on the SFC structure.
- **Unwanted Hydroelastic behavior:** vortex shedding, galloping etc are important parameter to consider during design and analysis. Based on the analysis in Section 0 (VIV) to VIV was found to pose/ not pose threat to the structural and operational safety of the SFC.
- **Uncertain soil or bedrock conditions and landfall degradation** is a risk that is avoided by performing comprehensive geological and geotechnical investigation prior to construction stage. Seabed layer should be strengthened.

2.3.2 Results of FTA

Major structural component failure, e.g. tube and tethers failures, and their failure mechanism have been identified by Fault Tree Analysis along with PHA. One of main results of fault trees analysis is shown in Figure 2-2. All other fault trees are found in Appendix C.

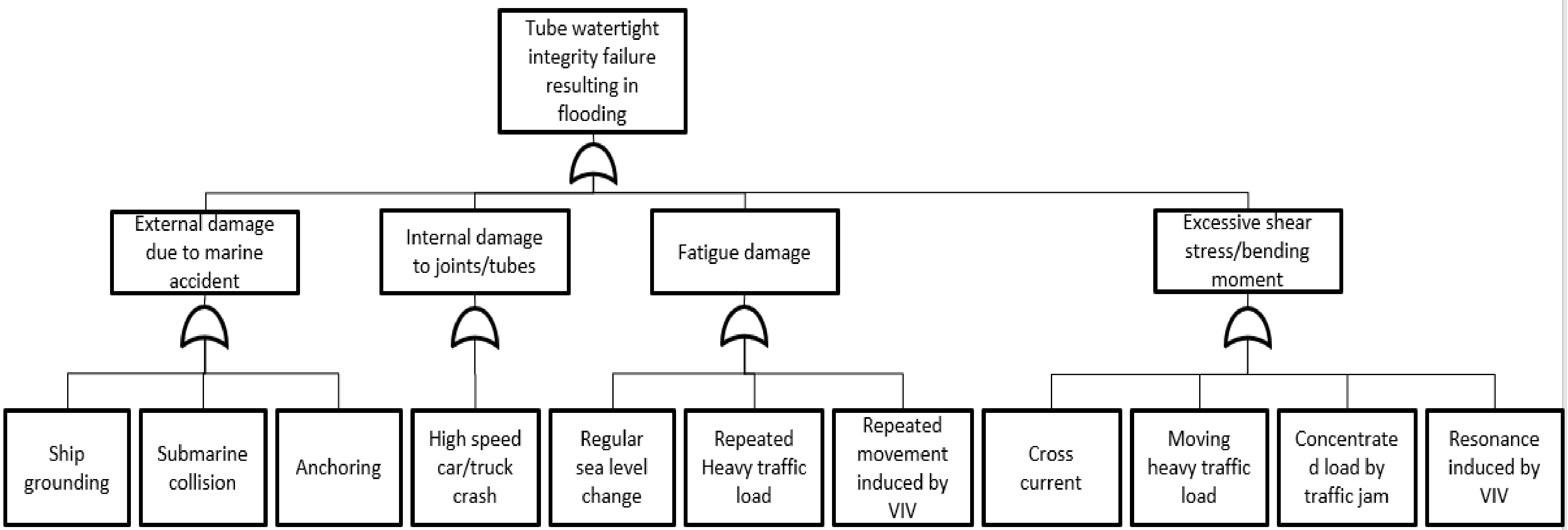

Figure 2-2 FTA for Structural component failure (up to the third hierarchial class)

2.3.3 Major Hazardous Events

All the above-mentioned hazards can be managed by some recognised measures, and proper investigation and analysis. A similar study by Hokstad et al, (2012), performed HAZID analysis on SFC. This study rated each hazard, hazardous event based on the expected frequency of occurrence and the expected consequence. A summary of the study finding is illustrated in Appendix B.

Based on the information in Table B1, a risk matrix structured in the following utilized a method as used by Hokstad et al, (2012). The risk matrix groups hazardous events based on their frequency and consequences. The major critical hazardous event in the risk matrix is present in Table 2-2.

Table 2-2 Identified Major Hazardous Events

Hazardous Event	Causes	Consequence
Fire and explosion	Traffic accident, explosion by car crash/Terrorism	Severe damage to the structure, Injuries and fatalities
Traffic accident	Steep incline and etc.	Injuries and fatalities, Major and minor damage to the structures
A loss of support structure	Fatigue, repeated movements e.g. VIV	Major and minor damage to the structures
External collision	Ship grounding or submarine collisions	Injuries and fatalities, Partial to total collapse of the structure
Flooding	Accidental leakage, accumulation of seepage or drainage	Damages to tunnel tube

2.4 Frequency Analysis

This Section deals with answers to the second question and some parts of the third question in the beginning of Chapter 2. The left side of the bowtie diagram illustrates the identification of hazards and threats which is aligned with the Section in this study. The barriers in the left side prevent the accident from breaking out, for example, monitoring the objects to collide with can reduce the probability of collision accident with the SFC.

Worst case scenario analysis as performed in Chapter 5 can be a representative of the consequences as depicted in the bowtie diagram (Figure 2-3), where the barriers, which can mitigate the escalation of risk consequence. Without these barriers the worst-case scenario could commonly occur.

Not always worst-case scenario analysis should be a way to assess consequences. Instead, event tree analysis can also assess its consequence in a probabilistic way. For ship grounding, probabilistic approach has been introduced to examine its frequency of occurrence in this feasibility study along with worst case analysis by using consequence modelling approach.

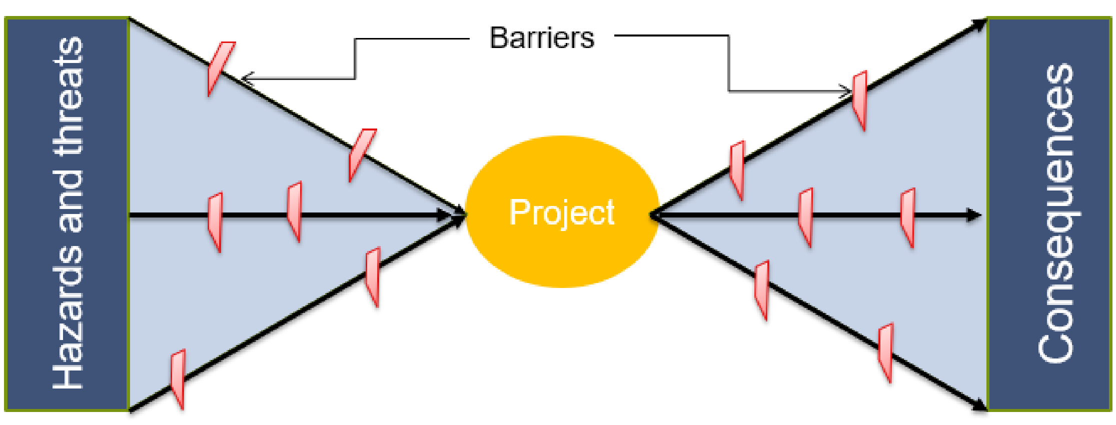

Figure 2-3 The bowtie diagram (Johansen, 2010)

2.4.1 Ship Grounding

Without floating structures of supporting structures for the SFC, a ship collision or grounding is less likely to happen to be a risk to the SFC tube or its support structures. Nevertheless, the quantification of the risk for ship grounding will be an indication whether to care general concern about it. The vessel traffic data have been provided by Kystverket in Norway (Kystverket, 2018) and also found in Appendix D.

The probability of ship grounding has been reviewed by Event Tree Analysis (ETA) based on the frequency of passing vessel nearby and their failure rates of maneuverability. In this analysis, the root causes of this accident are categorized into several groups of accidents in a systematic way. Successively, the respective consequence of the marine accident has been examined with respect to the frequency of respective accidents. The significant collision energy, e.g. exceeding the frequency of 10E-04 per year, should be presented in cumulative frequency which gives us understanding about the comparison between the consequence of marine accident and the assumed structural capacity against to the marine accident.

It is assumed that no reduction of ferry connection after the construction of the SFC has been taken into account for the following analysis.

Design accidental load (DAL)

The inherent uncertainty of the frequency and magnitude of the accidental loads, as well as the approximate nature of the methods for determination of accidental load effects, shall be recognized. It is therefore essential to apply sound engineering judgment and pragmatic evaluations in the design. (DNV, 2010)

In order to determine DAL as mentioned above, structural capacity needs to be elaborately assessed for the SFC, where the structural capacity is the allowable energy that the structure can withstand without a loss of load-bearing functionality, which is given by a designer from the design principle. In this preliminary design stage, however, the DAL values have been adopted based on a simplified estimation due to the lack of information.

DNV (2013) specified the minimum structural capacity against collision energies for offshore units, which is 35 MJ. This number, however, is aimed for offshore steel structures which would withstand less collision energy than what is expected for the SFC. Therefore, one passing vessel in this region has been chosen to estimate design accidental load (See). Since MS Color Magic has 75 100 GT (Gross tonnage), it would approximately correspond to 45 000 displacement tons. (Vasudevan, 2010). By engineering judgments, it is assumed that grounding speed will not be higher than 3 m/s since the vessel should have lost its propulsion. (Friis-Hansen, 2008) The collision energy by ship grounding will be calculated as below:

$$E_{grounding} = \frac{1}{2}\,(m+a)v^2 = 0.5\ \cdot 49500\ (tons) \cdot (3\,\frac{m}{s^2}) =\ 223\ [\mathrm{MJ}] \qquad (2.1)$$

Where the added mass of the ship, a, is 10% of the ship’s displacement(weight).

	MS Color Magic
Tonnage	75,100 GT
Lenght	224 m
Beam	35 m
Draught	6.8 m
Max speed	22 knots(∼11.32 m/s)

Figure 2-4 The passing vessel for Design accidental load

Thus, the followings are considered to be a DAL for the SFC:

- Design Accidental Load for ship grounding: 223 MJ

<u>Generic grounding frequency</u>

Unlike general grounding accident, the SFC could be damaged only if the accident of grounding escalates to sinking.

Following Pedersen(1995), the grounding scenarios may broadly be divided into four main categories:

I. Ships following the ordinary direct route at normal speed. Accidents in this category are mainly due to human error but may include ships subject to unexpected problems with the propulsion/steering system that occur in the vicinity of the fixed marine structure or the ground.

II. Ships that failed to change course at a given turning point near the obstacle.

III. Ships taking evasive actions near the obstacle and consequently run aground or collide with the object.

IV. All other track patterns than Cat. I, which means drifting ship.

Ship grounding by drift is only considered in this study since no floating structure could block the course of powered grounding ship as depicted in I through III. Thus, the generic grounding frequency for the SFC is derived in case a failure of steering/propulsion due to black out happens while transiting near SFC. The blackout frequency is 8.45 x 10^{-5} (per hour) and transit time is assumed to be 30 minutes. (Friis-Hansen, 2008)

Accordingly, the generic grounding frequency near the SFC is:

$$P_{g,passenger} = 25474\ (vessels\ per\ year) \cdot 1.15 \cdot 10^{-5} \cdot 0.5 = 1.46 \cdot 10^{-1}\ (per\ year) \tag{2.2}$$

$$P_{g,others} = 7603\ (vessels\ per\ year) \cdot 8.45 \cdot 10^{-5} \cdot 0.5 = 3.21 \cdot 10^{-1}\ (per\ year) \tag{2.3}$$

Frequency quantification

Generic grounding frequency includes all types of vessels grounding and assumes the situation prior to any measures not being taken. The following frequency quantification specifies the grounding accident mechanism.

- Sinking due to fjord striking : 9.0E-06 (DNV, 2010b)
- Significant collision damage: 40% (OGP, 2010b)

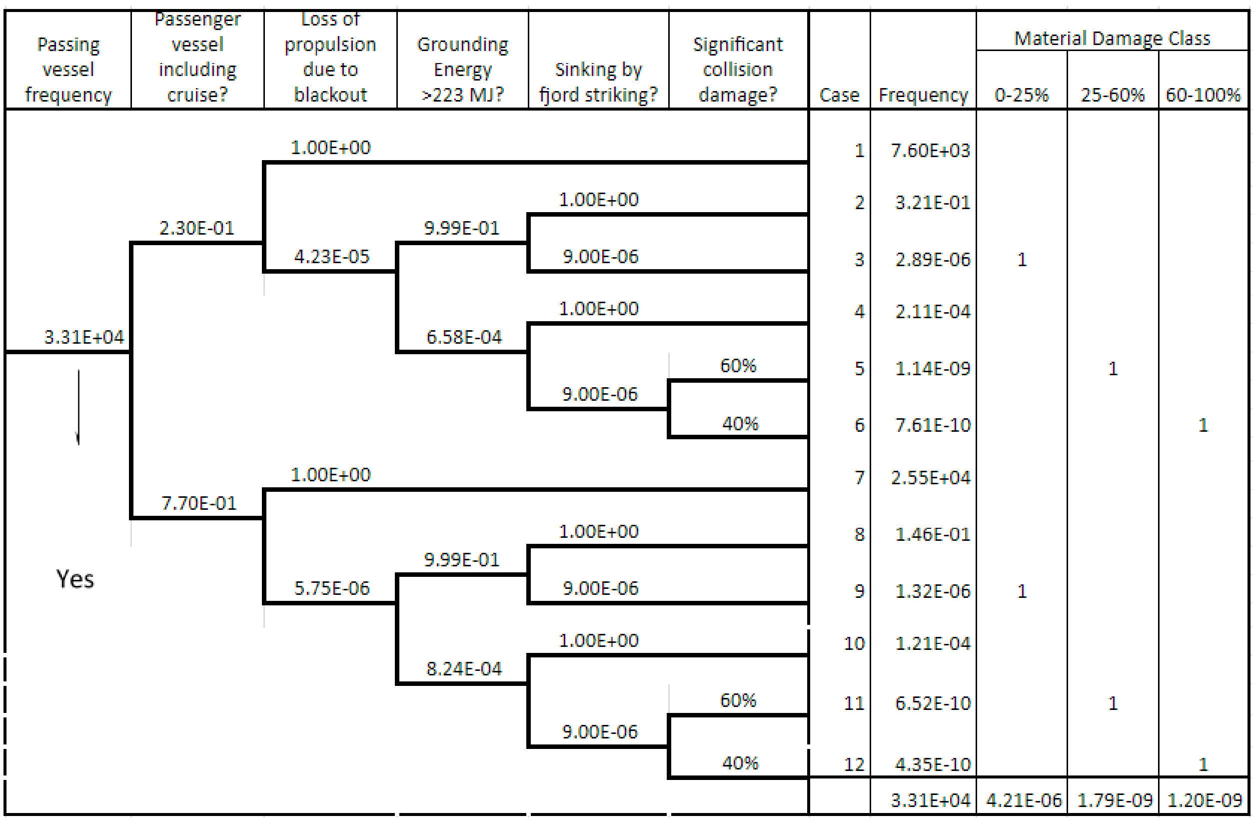

Figure 2-5 Event Tree Analysis for Ship grounding

Acceptable level

This project follows the level of safety considered acceptable by DNV GL (DNV GL, 2017). The main idea used here is that main safety functions, in this case, crossing structure itself, should not be impaired by a failure in the structure, where an individual frequency of occurrence for the impairment would be in the order of 10E-04 per year.

According to the vessel traffic data provided, any grounding accident is found to be very remote since the cumulative frequency corresponding to less than 10 MJ is even below 1E-04 per year.

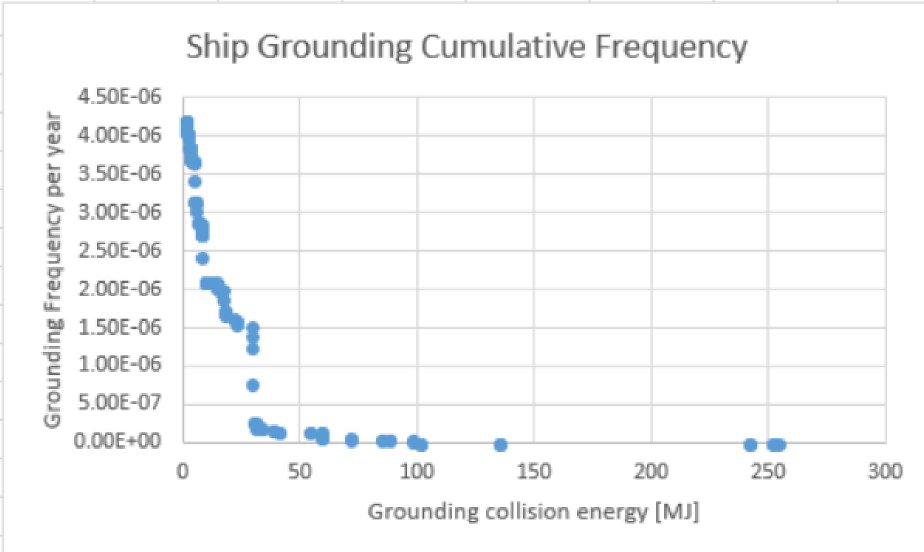

Figure 2-6 Cumulative frequency curves for grounding collision

2.4.2 Fire accident

For the fire accident, the SFC follows reliable road tunnel guideline, e.g. PIARC, ITA (2004) since at least SFC has its own operational requirement as a road as defined above. Accordingly, in this report, the DAL for fire and explosion accident has not been specified.

The data (TØI, 2012) presents that the average number of fires in Norwegian road tunnels is 21.25 per year per 1000 tunnels in the period 2008 - 2011. In the same period, fires at road tunnels in Norway with high gradient, defined as over 5%, accounted for 44% of total number of fires. These road tunnel represents merely 4% of the road tunnels in Norway, which is 41 tunnels. Since the SFC has 0.2% of gradient in tube parts, there should be a frequency reduction due to lower gradient. Thus, generic frequency of occurrence for fire accident at this SFC could be derived from:

$$\mathrm{P}_{Fire} = 1.24\ \times 10^{-2}\ (per\ year\ per\ tunnel)$$

However, this probability based on historical accidents does not include any classification of severity or significance of the consequences. Thus, this number can only be utilized for awareness of fire accidental events at road tunnels in Norway. In addition, as landfall connection parts of the SFC would be constructed with higher grade such that steeper than 5%, utmost care should be taken to prevent and mitigate fire accidents and its consequences.

3 Basis of Design

Preliminary Design of submerged floating tunnel is a complicated process, involving characteristics of tunneling engineering and ocean engineering along with many other disciplinary fields. The main elements of the design include alignment design, section design, structural analysis and waterproofing among many others. Concepts being utilized in immersed tunnels, highway tunnels and ship design technology can be borrowed to guide SFC design.

This chapter mainly focuses on the guidelines for the preliminary design, requirements of design and a comparison of waterway crossing alternatives. It will also provide an economic comparison of SFC with immersed and subsea tunnels.

3.1 Trade-off study for type of crossing

At Bjørnafjorden, which is very deep and the connecting points of E39 route are approximately 6km apart (see Figure 4-1), innovative waterway crossing concepts like suspension bridge, floating bridge, SFC or combination of these can be considered a good alternative to the traditional crossing concepts. Table 3-1 shows the possibility of construction of different crossings in deep fjords as defined in literature.

Table 3-1 Trade-off study for the type of SFC

Crossing types	For Highway Speed of 80km/h	For Water Depth upto 500m	For a Span of 5km
Conventional Bridge	Yes	Depends on span	Yes
Multi-span Suspension Bridge	Yes	Yes	No
Immersed Tunnel	Yes	Yes*	Yes
Undersea Tunnel	Yes	Yes*	Yes
Submerged Floating Crossing	Yes	Yes	Yes
Cable Car (Transporter bridge)	No	Yes	No
Submarine shuttle	No	Yes	Yes

*Immersed Tunnel and Undersea Tunnel Concepts may also be utilized but at the depth of 500m, water pressure and economic constraints may make these options unfeasible.

SFC, Immersed and Undersea Tunnels satisfy the speed, water depth and crossing length criterion. To further dig into these three shortlisted crossing options a comparison in terms of estimated length of crossing and construction cost is made in the following sections.

3.1.1 Estimated length of various crossing types

A typical initial representation of three shortlisted crossing options at Bjørnafjorden is shown in the Figure 3-1 and Table 3-2. The calculations have been carried out considering 8% road gradient on the land and 2% gradient for the tunnel portion.

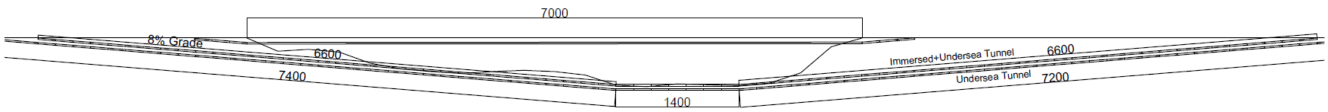

Figure 3-1 Construction concepts for various crossing types

Table 3-2 Construction length estimation for different crossing types

Crossing types	Estimated lengths [m]
Submerged floating crossing (8% grade for land connection part + 2% grade for tubes)	7 800
Immersed tunnel (8% grade)	14 600
Undersea tunnel (8% grade)	16 000

The length of submerged floating type is initially estimated based on the gently curved alignment between Os and Reksteren, the length of which is approximately 7000 meters. The length of the land connection is around 400m. Both immersed tunnel and undersea tunnel are assumed to have a relatively milder grade of 8% even though some Norwegian undersea tunnels (Hitra, Nordkapp, and Frøya) had been constructed with maximum 10% of grade. On the bases of these criterion, a grade of 8% has been selected for immersed and subsea tunnel options for Bjørnafjorden crossing. The lengths are basically linked to the economic ability of the structure. In the next section, a crude economic comparison of all three option will be made on the basis of the length mention in Table 3-2.

3.1.2 Construction Cost

Construction cost estimation is a critical and complex process, especially for the pilot projects like SFC. Due to non-availability of factual figures, there can be high level of uncertainty in the estimate. On the other hand, construction cost of a project, especially as diverse as undersea or immersed tunnels, is very much linked to the specific conditions of the project. So, to find an appropriate construction cost estimate for Bjørnafjorden crossing options is a very complex issue. However, for this feasibility study different costs of the similar projects from literature has been taken to draw a comparison. The cost data used in this section is found in Appendix E.

The difference in labor cost has not been considered in the investigation among the countries where the tunnels were built. The construction costs in past time were converted to current price considering the annual constant inflation of 1.5% and the currency to USD at the time the construction costs were reported. A comparison of existing immersed and undersea tunnels is presented in Figure 3-2. (cost data sources : Faber Maunsell Aecom, 2007 and Kartaltepe, 2008)

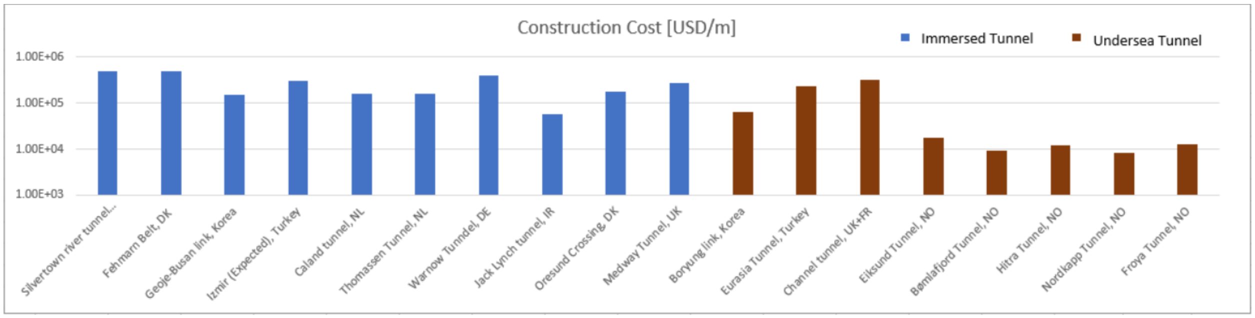

Figure 3-2 Construction cost for various tunnels

Some parts of Aksdal-Os section of E39 around Bjørnafjorden, also require either a replacement of current infrastructure or an entirely new construction of crossings. Therefore, approximately 20 billion Norwegian kroner is assumed to be allocated for Bjørnafjorden crossing as the whole budget for Aksdal-Os section is reported as 52 billion Kroner. (Statens vegvesen, 2016a)

Per unit length cost of construction for undersea tunnel type crossing, of 5 Norwegian undersea road tunnel is 12 100 USD (See Appendix E) while that of 2 non-Norwegian undersea road tunnel have 146 000 USD. Even though this tunnel is assumed to be built in Norway, a more conservative unit cost has been applied due to the uncertainties where the reported budgets might contain different level of costing, for instance, whether operational and maintenance cost is included or not, costing for turn-key based project or individual crossing contract based project.

Table 3-3 Comparison table of construction costs

Parameters	**Immersed Tunnel**	**Undersea Tunnel**	**Submerged Floating Crossing**
Budget [USD]	Approximately 2.04 Billion (20 billion NOK with 15 years of inflation and 1.5% annual inflation rate)		
Length [m]	14 600	16 000	7 800
Construction cost [USD/m]	2.77×10^5	1.46×10^5	2.77×10^5
Estimated cost by unit length cost [USD]	4.04 Billion	2.34 Billion	2.16 Billion
Remarks	1) Explosives noise impact to habitats during longer periods 2) Subsea works required along with the entire crossing (Immersed tunnel only) 3) Additional land purchase required 4) No construction records to such a deeper depth		No track records

A unit construction cost for SFC type has adopted as 277 000 USD on the basis of the unit construction cost of 8 European immersed tunnels. Cost impact is assumed from the difficulties in construction of SFC type crossing, however, the advantages will compensate the impact in some aspects, for example, shorter construction lengths, less subsea works, smaller land purchase and etc. Figure 3-2 shows the cost per unit length for immersed and undersea tunnels over the world. In Table 3-3 a tentative comparison for Bjørnafjorden has been shown based on the literature review.

As it is clearly shown that the total construction cost of SFC is lesser than immersed and undersea tunnels so SFC has been chosen as most viable option. However, it is very crude estimate which generally does not count for any special requirements for specific crossing. For example, the cost of immersed tunnel includes dredging cost among which is will not occur in case of SFC. There are still many uncertainties and extant estimate is difficult. But this tentative estimate is sufficient enough to support the idea of SFC instead of immersed and undersea tunnels.

3.2 Design Principle

SFC floats in water under the action of loading and buoyancy, hence relation between buoyancy and self-weight plays a very important role in controlling the static and dynamic behavior of the structure. Geometric configuration of the SFC are also the key factors for in deciding the stability. Minimum required dimensions can often result in an optimal design. Generally, there are ways to in which buoyancy can act on the structure; positive buoyancy and negative buoyancy. Former present an idea of constructing SFC which is fixed to bed with the help of tethers or pontoons on the surface. Positive buoyancy tries to move the structure upwards and support structures try to keep it at desired location by balancing the upward force. In case of negatively buoyant structure, SFC is constructed on the piers which are the structure rests. This option is only suitable in water depths up to 100m.

In this study, the maximum water depth in the fjord is 483m. Therefore, a positively buoyant structure is planned to be designed. Some major principles for the design are as follow;

1. Crossing must provide sufficient space for traffic and evacuation along with some additional space for maintenance and repair.
2. SFC should be able to withstand all environmental loadings with sufficient strength and stiffness considering that the structural response is within the limits defined in Table 1-1. If the limits exceed, then structural failure may occur.
3. Structure should be positively buoyant
4. The variation of surface curvature should be gentle to resist the hydrodynamic forcing
5. The alignment and position in water should not hinder the ship traffic passing above
6. SFC should perform satisfactorily with regards to deformations, settlements and vibrations
7. Overall, it should be a safe structure in terms of various hazards and risks

In addition, the design should comply with design codes and standards. No specific standards exist for SFC till now. So, different design codes have been consulted to find the appropriate limitations for the design in this study.

3.3 Loading Conditions

Apart from self-weight and buoyancy, SFC will encounter traffic loading and environmental loading such as wave and currents load, hydrostatic pressure and marine growth. Environmental loading forms the major part of the loading on the structure. For the design considerations, life of the structure has been considered as 100 year while the support structure life is considered as 20 years. Representative wave and current conditions has been provided through the report "Bjørnafjorden Suspension Bridge TLP-Design Basis" for 1, 10 and 100 year return periods. Therefore, instead of performing analysis with Met-ocean data to get the representative wave and current conditions, the provided values are used for the design. Section 4.4 of this report will mainly deal with the load calculations and load combinations.

3.4 Operational Requirement

SFC is assumed to be operating safely when all equipment is functioning as per design and within acceptable tolerances. Following requirements should be incorporated in the design of SFC;

- Road Class should meet the requirements for design class H8 in N400
  - Design traffic volume: 12000 - 20000 AADT (2040)
  - Speed limit: 110 km/h
- Drainage system should conform to the criteria of at least 0.1m^3/min
- Appropriate ventilation system to avoid the suffocation in the tunnel
- Ballasting system should be able to pump in and pump out the designed water ballast load efficiently

4 Preliminary Design

Analysis and Design of submerged floating crossings is one of the most demanding/complex tasks faced by engineering professionals. Unlike the case of ground tunnels, SFC has the added complication of being placed in ocean environment. In such scenario, hydrodynamic interaction and its response becomes major consideration. In addition to this, the range of possible design solutions such as tethers (TLPs), pontoons, geometric shapes etc. pose their own impact on the structure. Multidisciplinary Criteria is often used as an engineered approach to shortlist the available solutions. Non-linearities in the loading conditions with the multiple design solution need to be addressed and to do so modelling software are generally used. But before modelling, certain basic parameters need to be defined on technical grounds. Geometric configuration, alignment and loading conditions are the basic phases of the initial/preliminary design.

A design basis has been set in Chapter 3 which will act as the guideline the design of SFC. This chapter will mainly deal with the following parameters;

- The configuration of the SFC alignments (option 1, 2, and 3, See Figure 4-1)
- The configuration of the SFC section
- Supporting systems (e.g. Pontoon and crossing with mooring, Only crossing with mooring tendons)
- Load Calculations.

Defining SFC configuration (alignment, profile and cross section) is the starting point that sets up key features of the project.

- **Alignment.** Tunnels and bridges are aimed to avoid obstacles on the routes of transport infrastructure, such as rivers, ravines, mountains, city zones, etc. In turn, they are designed in a way that keeps construction and maintenance costs at a lowest level (without any damage to safety and comfort of future users), which implies guaranteed absence of known existing dangers within the ways of tunnels and bridges. This is mainly reached by adjusting the alignment.
- **Profile.** Another core characteristic of the tunnels and bridges is their profile, which also keeps reasonable balance between safety, comfort and costs by going smoothly over (or under) the obstacles.
- **Cross section.** Design of the cross section defines traffic capacity and affects structural behaviour of bridges and tunnels, therefore constituting third main parameter of safety and cost efficiency.

4.1 Alignment

4.1.1 Considered types

Three different types of the alignment were considered. The main parameter varying from type to type is the number of turns and their characteristics. The alignment (as well as other characteristics) of the underground tunnels connecting the SFC with the main road is not designed in details within the project, however, it is assumed that the number of turns of the entire crossing (and thus of the underground parts) should be minimal (see Figure 4-1).

1) First option comprises straight floating part and turning floating part, which are connected with the southern road by straight underground tunnel. The number of turns on the northern part is the same for all three options due to lack of space for developing turn-free solutions.
2) Second option consists of straight floating tube and turning underground tunnel on the southern part of the crossing. Disadvantage of the latter is that its price is higher than price of the straight tunnel in previous (and following) option. The main advantage is the smooth character of turning, which allows higher speed on the given road section.
3) Third option comprises one smoothly turning floating tube connected with relatively short straight tunnel on the southern part. As it was said before, underground tunnels are excluded from the scope of the project, which means that only floating tubes will be considered further. All three options are placed between the same starting points.

Figure 4-1 Configurations of alternative alignments

4.1.2 Multi Criteria Analysis

Each option is considered in terms of three parameters: driving safety, construction cost and structural behavior.

- Driving safety comes down to the check if direct visibility is hampered from driver's perspective. Scheme (See Figure 4-2) depicts how far driver can see while going through the SFC.

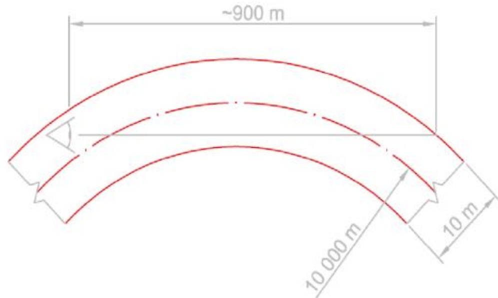

Figure 4-2 Schematic drawing for driving eyesight

In the figure the length of the line of unhampered visibility (minimum eyesight distance) for option 3 is shown. It is approximately 900 m: this is less than that for the straight crossing (option 2), but more than that for option 1.

- Construction cost is based on the length of the crossing: as can be seen from the Figure 4-1, *alignment type 1* is the shortest, *type 3* is slightly longer, *type 2* is the longest.
- Structural behaviour parameter is related to estimated difficulty of design solutions tackling negative effects incurred by loads. For instance, vortex induced vibrations for tethers are more severe in deeper water. Alignment *type 3* goes through the points with the smallest depth (compared to other types), apart from that it can better withstand wave loads coming from the ocean side due to its circular-arc shape.

Table 4-1 Multi Criteria Analysis for alignments

	Driving safety	Construction cost	Structural behavior
Option 1 (Straight)	Orange	Green	Orange
Option 2 (Straight + turning)	Green	Orange	Red
Option 3 (Smoothly turning)	Green	Orange	Green

Green represents the best match of a certain option with the requirements of considered parameter;
Orange represents the fact that certain option fulfills requirements of considered parameter to acceptable extent;
Red represents that certain option hardly complies with the requirements of considered parameter.

To conclude, the *alignment type 3* is chosen as preferable one based on criteria analysis (See Table 4-1) and will be considered further in the project.

4.2 Cross Section

4.2.1 Considered Types

Cross-section of the Submerged Floating Tube should comply with the following requirements:

- Car flows in opposite directions are separated and placed in independent (to a certain extent) parts of the cross-section;
- Area of the cross-section is sufficient for containing all the necessary equipment (air venting system; fire alarm system, etc.);
- Cross-sectional configuration provides safe zones for people in case of accidents (this in general implies fire accidents);
- Cross-sectional sizes (height, width) are adequate for given road carriageway configuration:
    - "The road is to be constructed with 4 lanes 3.5 m wide each, with 1.5 m wide shoulders on both sides. Carriageway width 2 x 10 m, with pedestrian/cycle lane of width 3.0 m" (Statens vegvesen, 2016b).
    - Original 20 m carriageway configuration, designed for the bridge, is divided into two parts 10 m each.
    - Annual Average Daily Traffic (AADT) and speed limit, which were initially used to design the road, are not affected by the implementation of the tunnel with such cross-section.

In the following Figure 4-3 and Figure 4-4 options of cross-sectional configuration are provided.

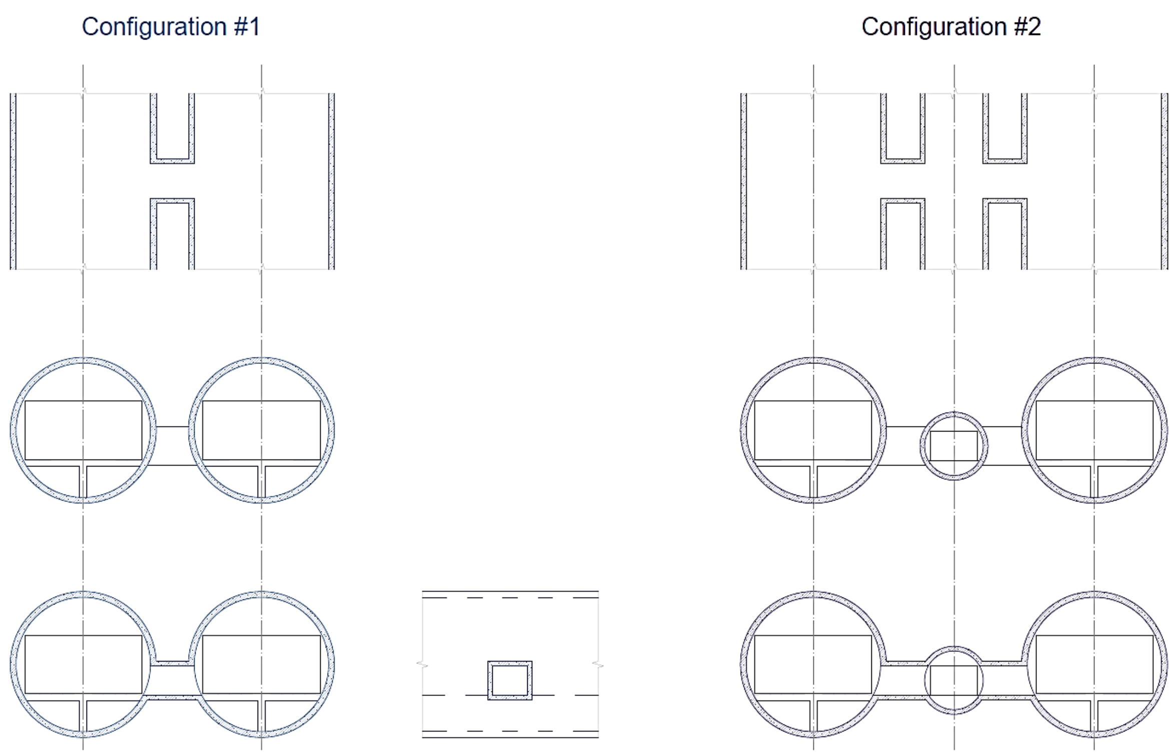

Figure 4-3 Cross section option #1 and #2

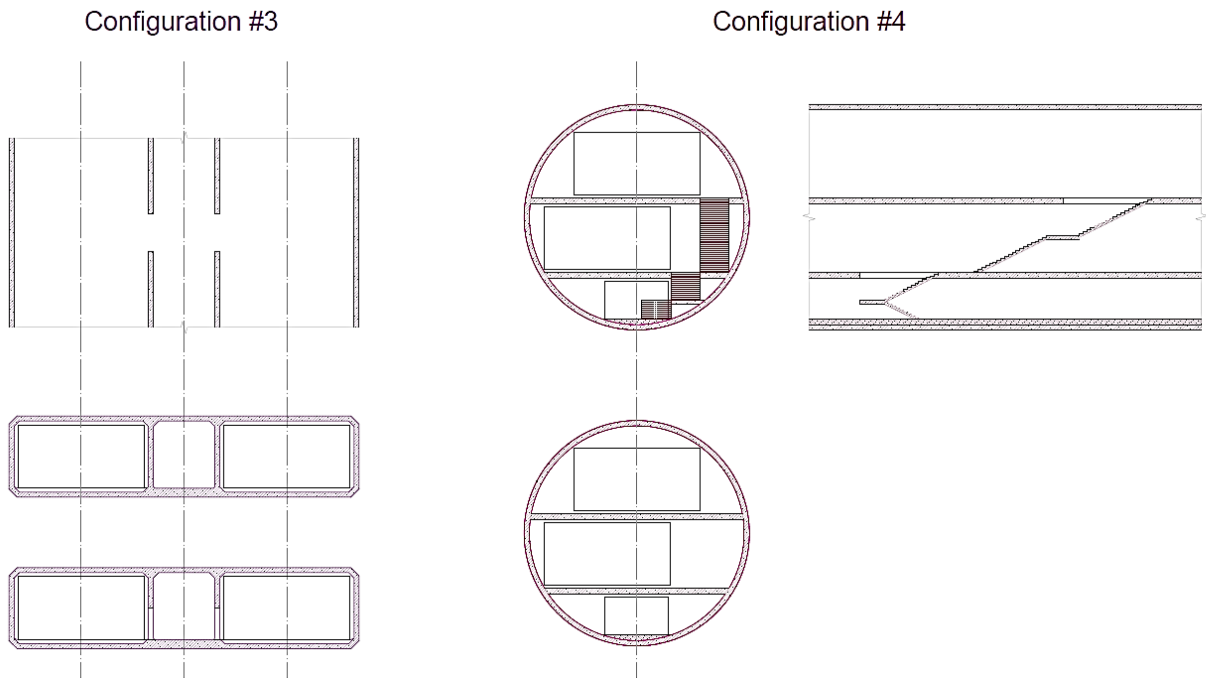

Figure 4-4 Cross section option #3 and #4

4.2.2 Multi Criteria Analysis

There are three parameters evaluated for each cross-sectional configuration: structural behavior, construction cost and space utilization.

- Structural behaviour parameter represents the response of a certain configuration to loads. Stress distribution in three considered circular cross-sections is similar and its pattern is more appropriate for the SFC than that of the rectangular cross-section. Besides this, two and three circles cross-section also include connection corridors that are spread across the length, which brings about additional unpredictability to the structural behaviour of those configurations (compared to one circle configuration) but can improve lateral stability.
- Construction cost: general estimation based on the size of the cross-section and its complexity.
- Space utilization parameter reflects the ratio of used area to the total area.

Table 4-2 Multi criteria analysis for cross section

	Structural behavior	Construction cost	Space utilization
One circle			
Two circles			
Three circles			
Rectangular			

Based on performed analysis it is concluded that the one-circle configuration will be considered further.

4.3 Support Structure

Two basic arrangements are proposed for the submerged floating tunnel, pontoons and base moored structure (tethers).

4.3.1 Pontoons

It is autonomous of water profundity, the framework is delicate to wind, waves, streams and conceivable ship impact. Configuration ought to be with the end goal that on the off chance that one pontoon is lost, at that point likewise the structure will survive.

The vigor of pontoon stabilized submerged floating tunnel is guaranteed by the accompanying:

1) Adequate freeboard for all load combinations
2) Change in the draft of the pontoon because of unforeseen occasions or loads
3) Design of ship impact.

The minimum pontoon size measure is administered by the variable loads on the framework, for example, movement of traffic, marine development, variety in ocean water density and so on. Deciding the pontoon size can subsequently be made by setting a necessity to settlement of the pontoon when completely stacked by traffic, being the overseeing variable activity.

4.3.2 Tethers

The reasons for the tethers are to balance out the buoyant submerged floating tunnel vertically and to give vertical firmness. The main thing is then to have adequate tether tension when introduced with the goal that time-differing loads and operational loads don't prompt tether slack. So, there are two major criteria for the tether design:

1) Keep away from tether slack amid the lifetime
2) No overstressing of the tethers

Tethers are considered in this study because of the safety reasons such that in case of pontoon, ships and ice sheet may collide with it.

In this SFC, taut leg mooring system is preferably used in terms of utilization in deep water. Compared to catenary system, pre-tension by weight is relatively smaller in taut leg system. In addition, a smaller footprint can also be an extra benefit to use taut leg mooring system.

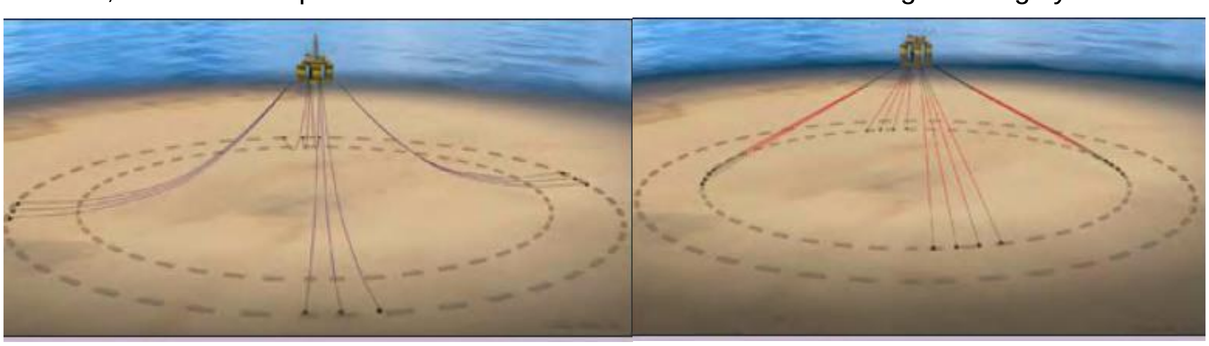

Figure 4-5 Catenary system(left) and taut leg system(right) (OE44100 TU Delft, 2018)

4.3.3 Multi Criteria Analysis

Table 4-3 MCE summary table for Support structures

Criteria	Pontoon + crossing with mooring tethers	Only crossing with mooring tethers
Seaworthiness		
Transverse stability for tube		
Space Utilisation		
Visual pollution		
Mooring difficulty		

As a result, only crossing tube with tether was evaluated as the better option for supporting structure by examining with a variety of criteria. The final decision has been made based on overall evaluation by the performers.

Main configuration of tethers:

Tether framework has an indistinguishable dynamic attribute in influence from the pontoon system. Their conduct in vertical way is however unique. Tether assembly consists of the following:

I. Top connector Assembly
II. Tether main body
III. Bottom connecter assembly
IV. Rock anchorage

The details of the top connector and bottom connector has been shown in Figure 4-6.

For the rock anchorage because of the variable profundity and soil conditions along the fjord crossing, a few elective establishment ideas were considered. Gravity-based foundation with a steel caisson stabilized by rock dump was found technically feasible along most of the submerge tunnel from the literature review of many submerge tunnels. The drilled and grouted rock anchors (piles) can be planned in the steep rock areas to avoid multifaceted and expensive underwater blasting and seabed measures.

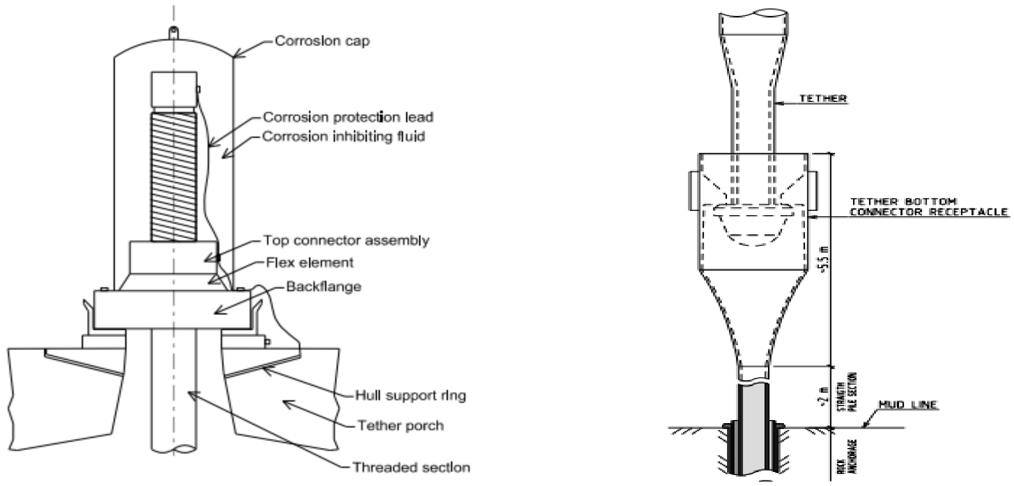

Figure 4-6 Tether top connector(left) and bottom connector(right)

Selection of Tether Material:

For this study 3 options for mooring material has been considered:

I. Chain:
   - Stud less or studded chain links
   - Heavy, high breaking strength, high elasticity
   - No bending effects
   - Most popular, all chain in shallow water (< 100M)
   - Chain segments are used near fairlead and bottom (in deep water)

II. Wires
   - Lighter than chain
   - Slight bending effect
   - Used as main mooring line segments in deep water (to reduce vertical loads)

III. High-Tech Fiber:
   - Light weight (almost neutrally buoyant)
   - Highly extensible
   - Potentially useful for very deep water

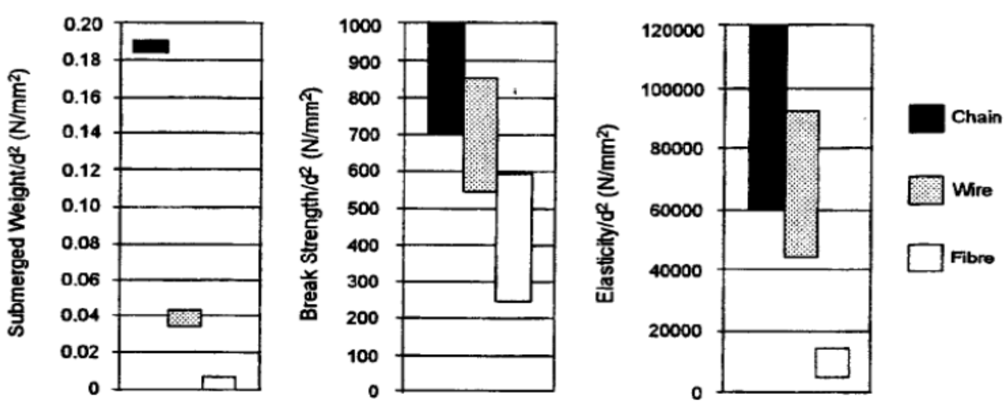

Figure 4-7 Flexibility in using varied materials

From these options, strand wires are selected on the consideration that it provides good elasticity and breaking strength. European standard EN 10025 is utilized for the design and the chosen the diameter and strength of the tether is finalized after Vortex Induced Vibration analysis, Section 0. Generally following three type of wire strands are used in offshore industry;

I. Spiral strand
II. Six strand ropes with a core
III. Multistrand

Figure 4-8 Various strands for tethers

4.4 Load calculation

The determination of the loads acting on the SFC is a complex problem. The nature of the loads varies with the architectural design, the materials, and the location of the structure. Loading conditions on SFC are also expected to change from time to time according to variation in traffic intensity and environmental conditions. In general terms, loads are classified as static and dynamic loads. Static load on an offshore structure like SFC may include gravitational load, hydrostatic load and current loads. The dynamic loads are generated from waves. According to EN-1990:2002, three major types of loading are considered for any design namely; Permanent Loads (G), Variable Loads (Q) and Accidental Loads (A).

4.4.1 Permanent Loads

These loads account for the self-weight, weight of the permanent equipment, weight of structural elements, the weight of permanent ballast etc. It can be worked out precisely from the known weights of the materials and geometry of SFC. Although the permanent loads can be accurately determined, it is recommended to make a conservative estimate to allow for changes by considering the tolerance in the estimated loads.

Material densities of concrete and steel considered for calculation of self-weight of SFC are 26.5 kN/m^3 and 76 kN/m^3 respectively. Self-weight calculated for SFC section is shown in Table 4-4. Material densities of concrete and steel considered for calculation of self-weight of SFC are 26.5 kN/m^3 and 76 kN/m^3 respectively. Self-weight calculated for SFC section is shown in table below;

Table 4-4 Self Weight Calculation

Sr. No	Parameter	Values (kN/m)
1	Reinforced Concrete	1038.80
2	Steel Cover	205.96
3	Weight of Permanent Equipment	20.00
4	Weight of Structural Element	20.00
5	Weight of Asphalt Road 100mm	2.50
6	Permanent Ballast	25.00
Sub-Total		1314.78
7	Weight of Water Ballast	20.00
Total G1		1334.80
ΔG; Tolerances		
1	Self-Weight	37.34
2	Water Ballast	0.60
3	Pavement	1.25
4	Structural Component	0.60
5	Permanent Equipment	0.60
ΔG		40.40

4.4.2 Variable Loads

Considering the variation of loads in time and space, imposed load are classified as variable loads. If there is doubt about the permanency of a self-weight, then the load shall be treated as variable imposed load. In case of SFC, traffic loads, wave load, current load, external water pressure and marine growth are the main variable loads.

Table 4-5 Variable self weight Calculation

Sr. No	Parameter	Values (kN/m)
1	Weight of Water absorbed by concrete	0.00
2	Weight of Marine Growth	17.00
3	Weight of Water absorbed for ballast	0.20

Sr. No	Parameter	Values (kN/m)
Total G2		17.20

4.4.3 Traffic Loads

According to Eurocode traffic intensity for highway has been considered for two lanes, road along with pedestrian/bicycle lane. The calculated loads are as follow;

Table 4-6 Traffic Load Calculation

Sr. No	Parameters	Value (kN/m)
1	Two lanes with full traffic (Total 4 Lanes)	72
2	Pedestrian Loading (Total 2 Lanes)	4
3	Bicycle Lane (Total 2 Lanes)	16
T-max		92

4.4.4 Buoyancy

When SFC is submerged in water, a buoyant or upward force exerts on it because of the displaced water. If the buoyant force is greater than the weight of the SFC, flotation will occur. The buoyancy in this case mainly depends upon self-weight of SFC, weight of the volume of water displaced by SFC, traffic load and variable loads. Calculations for the buoyancy has been carried out considering the water density of 10.06 kN/m^3. The table below shows the maximum and minimum values for the buoyancy.

Table 4-7 Buoyancy Calculation

Sr. No	Parameter	Values (kN/m)
1	Maximum Buoyancy, B_{max}	1426.01
2	Minimum Buoyancy, B_{min}	1328.02

The calculation of the aforementioned loads results in a maximum and minimum load of 1392.38 kN/m and 1294.39 kN/m respectively. Maximum value incorporates self-weight, tolerance in self-weight and variable bounded self-weight. However, minimum load is calculated by deducting the tolerance from G1.

Considering these loads along with the upward external pressure of water at the bottom of the SFC and buoyancy, maximum upward directed and maximum downward directed forces are calculated which are 146.36kN/m and 141.61 kN/m respectively, as shown in Figure 4-9. For the vertical stability of the structure, these forces should balance each other. Permanent ballast and water ballast has been adjusted in such a way that the difference between these forces comes minimum.

4.4.5 Environmental loads

Loads caused by environmental phenomena such as wind, waves, current, tides, earthquakes, temperature and ice etc. are categorized as environmental loads. The environmental forcing can be steady or oscillating. Steady loadings are basically caused by steady currents while oscillating loads are because of wave motion and fluctuation in the motion of the structure. The steady currents can also generate fluctuating load in transverse direction, which may have serious consequences (e.g. VIV) on the structure.

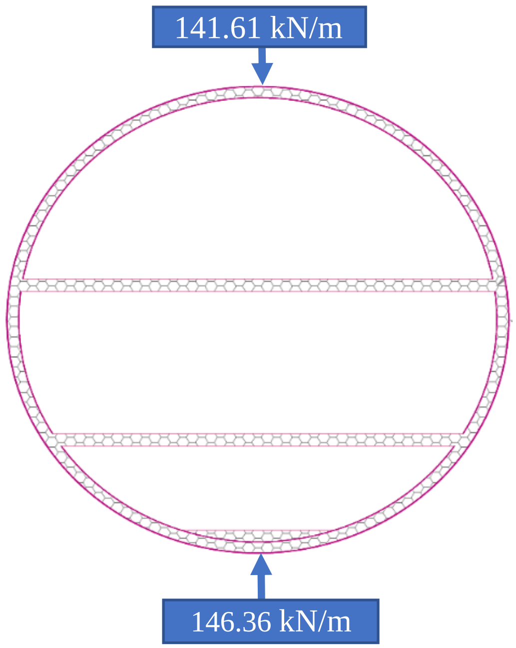

Figure 4-9 Cross section of SFC showing Net upward and downward forces

<u>Wave Forces:</u>

While designing a structure in sea, wave loading is usually considered the most important among all environmental loadings. This is the loading caused by the motion of water due to waves which are result of wind action on the sea surface. Wave forces are determined by solving two separate but interrelated problems namely sea state and wave action on structure. Sea state is computed by idealizing the wave surface profile and wave kinematics given by an appropriate wave theory. The second problem is the determination of the wave forces on structure.

There are two main approaches to calculate these wave forces; Design Wave Method and Spectral Method. In design wave method, a set of representative design waves and associated time periods are selected to generate loads on the structure which ultimately defines the response of the structure under wave forces. However, in Spectral Method an energy spectrum of irregular sea state is generated at the location of the structure. Then with the help of transfer function, response of the structure is computed. For the current study, Design Wave Method is utilized and a set of significant wave heights and period is chosen as shown in Table 4-8.

Table 4-8 Design wave condition

Sr. No	Heading	1 Year Condition (24.5m/sec wind)		10 Year Co-ndition (27 m/sec wind)		100 Year Condition (30 m /sec wind)	
		Hs (m)	Tp (sec)	Hs (m)	Tp (sec)	Hs (m)	Tp (sec)
1	N	1.2	4.1	1.3	5.2	2.0	5.2
2	NNE	1.2	3.1	1.3	4.9	2.0	4.9
3	ENE	1.2	3.1	1.3	5.9	2.0	5.9
4	E	1.2	3.9	1.3	6.3	2.0	6.3
5	ESE	1.2	4.8	1.3	6.2	2.0	6.2
6	SSE	1.6	4.7	1.7	5.4	1.8	5.4
7	S	0.9	3.3	1.0	4.0	1.5	4.0
8	SSW	1.3	4.3	1.4	5.2	2.3	5.2
9	WSW	1.5	4.4	1.9	5.4	3.0	5.4
10	W	1.5	4.6	1.9	5.6	3.0	5.6
11	WNW	1.5	4.7	1.9	6.0	3.0	6.0
12	NNW	1.5	.6	1.6	5.8	2.5	5.8

Firstly to calculate particle velocity, accelerations and dynamic pressure, wave theories are utilized. There are different wave theories available for specific wave conditions as shown in Figure 4-11. In this study case for the chosen significant wave height and wave period of 3 m and 6 seconds respectively, Linear wave theory can be utilized for calculations.

The wave particle motion and dynamic pressure results of wave theories are used to calculate the wave forces on structure. Depending on the structure size two different cases can be distinguished:

- Approach for Large volume bodies which are also termed as hydrodynamic compact structures. These structures influence the wave field by diffraction and reflection. The forces on these bodies have to be determined by costly numerical calculations based on diffraction theory.
- Approach for Slender, hydrodynamically transparent structures. These structures do not have much influence on the wave field. The forces can be calculated in a straight-forward manner with Morison's equation.

In computing wave forces on the SFC, it is considered being fixed in its equilibrium position. However, to check the applicability of appropriate theory for wind sea and swell scenarios, Figure 4-10 can be utilized which defines the different hydrodynamic regimes. For the calculations of wave forces, the wind sea with Hs=3m and Tp = 6 sec has been considered corresponding to 100 year return period. For swell, Hs=0.4m and Tp= 16 sec have been chosen against the 100 year return period condition. For swell case, inertia dominates and SFC acts as slender structure hence the forces can be found by using Morison Equation. However, for wind sea condition diffraction effects have to be taken into account and hence diffraction theory will prevail.

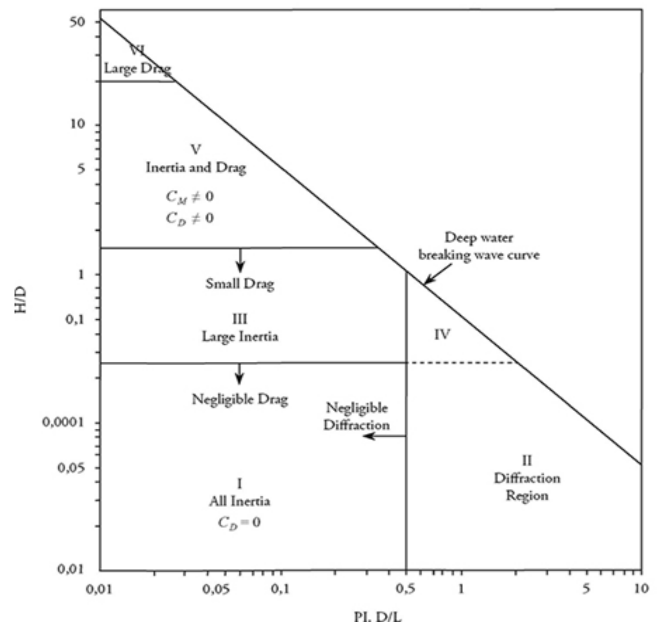

Figure 4-10 Regime for hydrodynamic characteristics

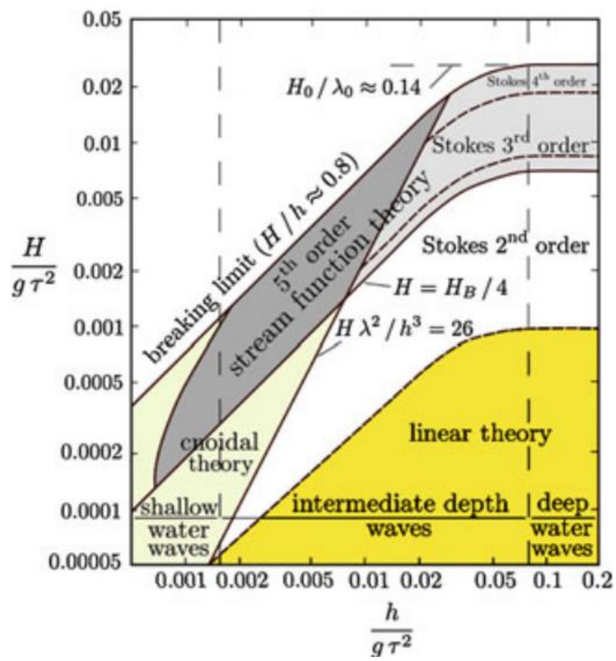

Figure 4-11 Wave theory selection

Morison superimposed the linear inertia force (from potential theory and oscillating flows) and the adapted quadratic drag force (from real flows and constant currents) to get the following resultant force (per unit length):

$$F(t) = \frac{\pi}{4}\rho C_m D^2 \cdot \dot{u}(t) + \frac{1}{2}\rho C_D D \cdot u(t)|u(t)| \quad (4.1)$$

Drag and added mass coefficients are the most researched parameters in this equation. Many formulations are available for these coefficients which are based on dimensionless numbers like Keulegan-Carpenter number, Reynolds Number and Froude Number etc. For this study Cd and Cm values of 0.6 and 2 respectively has been considered on the recommendation of Clause. (1992). The result of wind sea condition is plotted in Figure 4-13.

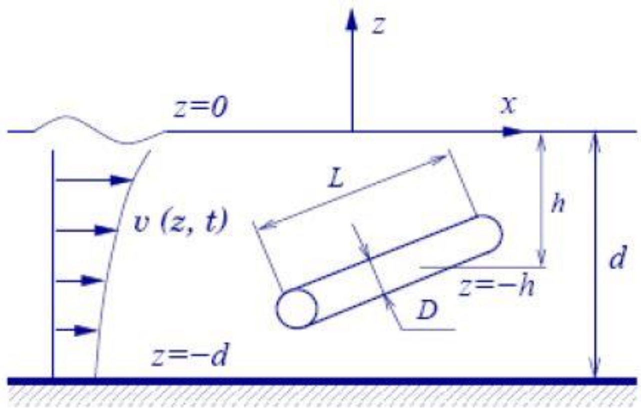

Figure 4-12 Representation of SFC with parameters in Morison Equation

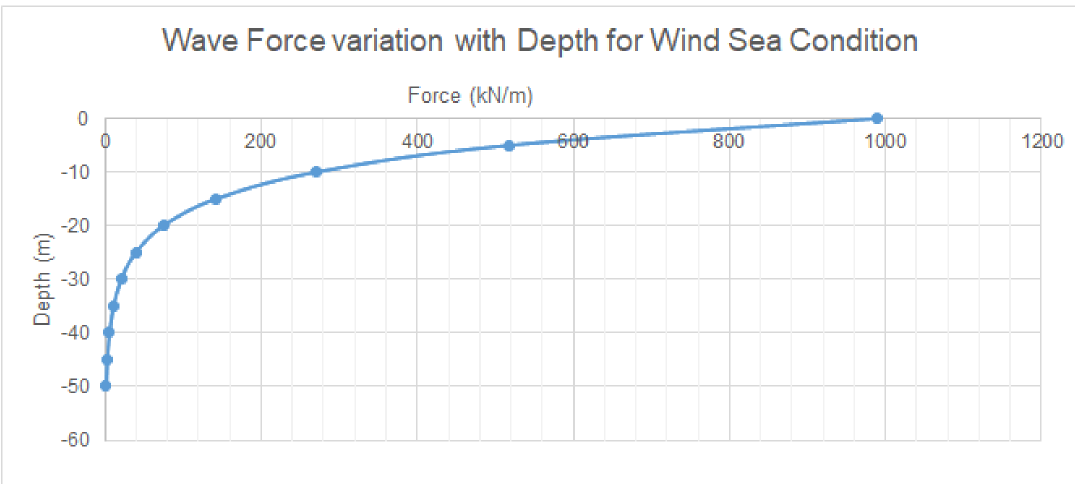

Figure 4-13 Wave force variation with depth for wind sea

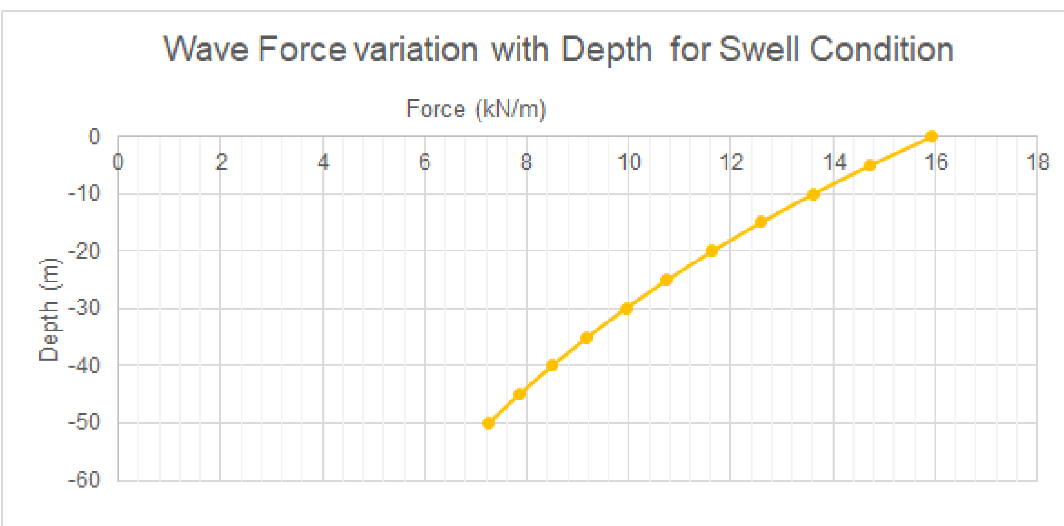

Figure 4-14 Wave Force with respect to depth for swell sea

For swell sea scenario, on the recommendation of Army Corps of Engineers a simplified Diffraction formula can be applied for the calculation of diffraction forces as the ratio of Diameter to wavelength is quite small (0.36). The simplified diffraction formulas providing the horizontal component of the force on the cylinder in the z-direction and at depth z, is;

$$F_z \cong \frac{\pi^2 \rho g D^2}{2} \left(\frac{H}{L}\right) \frac{\cosh k(d+z)}{\cosh kd} \cos \sigma t \qquad (4.2)$$

The superposition of the wind and swell sea conditions generate the wave forces of 10 kN/m and 7.3 kN/ on the top surface and bottom surface of the tunnel respectively.

<u>Current and Tidal Loads:</u>

The current introduces a varying pressure distribution around a member of the offshore structure generating a steady drag force on the structure in the direction of flow. Since the pressure distribution is not symmetric about the direction of flow, a transverse force is also generated on the structural member. For the calculation of current loads, following drag force formula has been used. The value of the drag coefficient has been taken as 0.6. Figure 4-15 indicates the variation of currents along the depth. For the calculation current velocity corresponding to 100 year return period has been utilized. The calculated current force by the currents are given in the following Table 4-9.

$$F(c) = \frac{1}{2}\rho C_D D \cdot Uc(z)$$

Table 4-9 Current Force with respect to depth

Sr. No	Depth (m)	Velocity (m/sec)	Force(kN)
1	0	0.7	48.28
2	10	0.4	15.76
3	20	0.27	7.18
4	30	0.27	7.18
5	40	0.25	6.16

Water level variations due to tide has been considered in the buoyancy directly. As instead of using actual bathymetry, a constant value of 482m water depth has been considered which can be assumed as the conservative estimate for the 200m length of the SFC. Thus, the additional rise in water level due to tide and sea level rise has been considered in the total water depth.

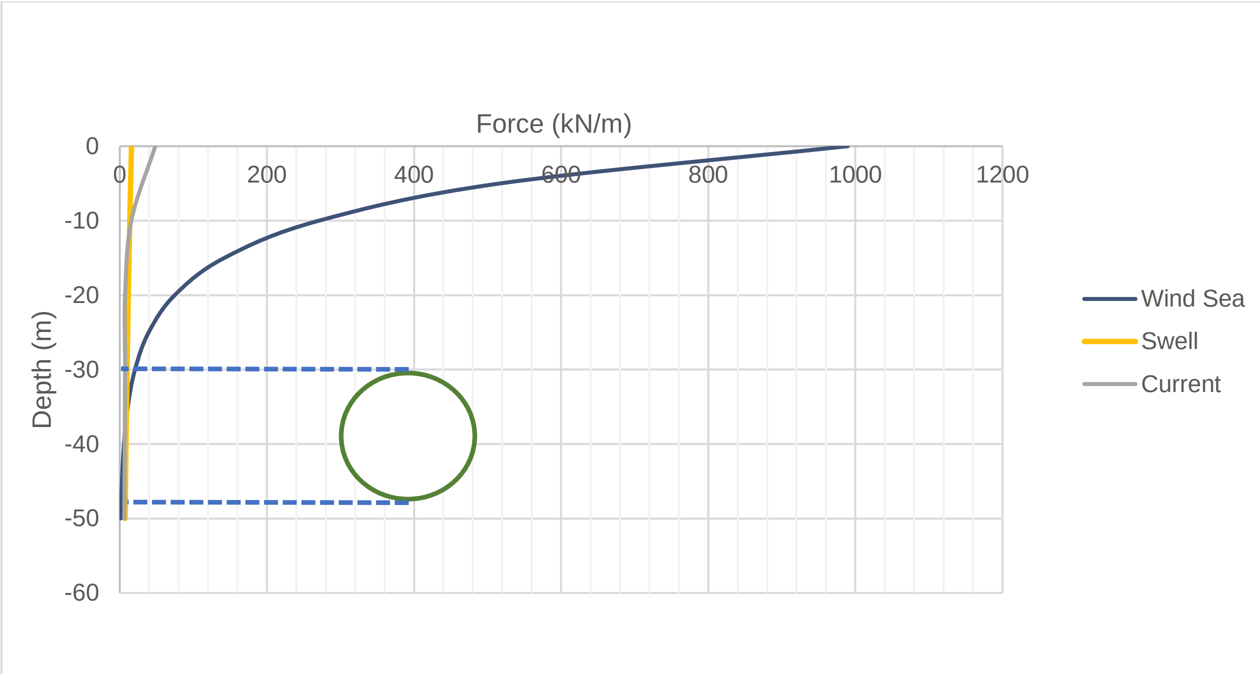

Figure 4-15 Wave force with respect to depth and proposed submersed location

Hydrostatic Pressure:

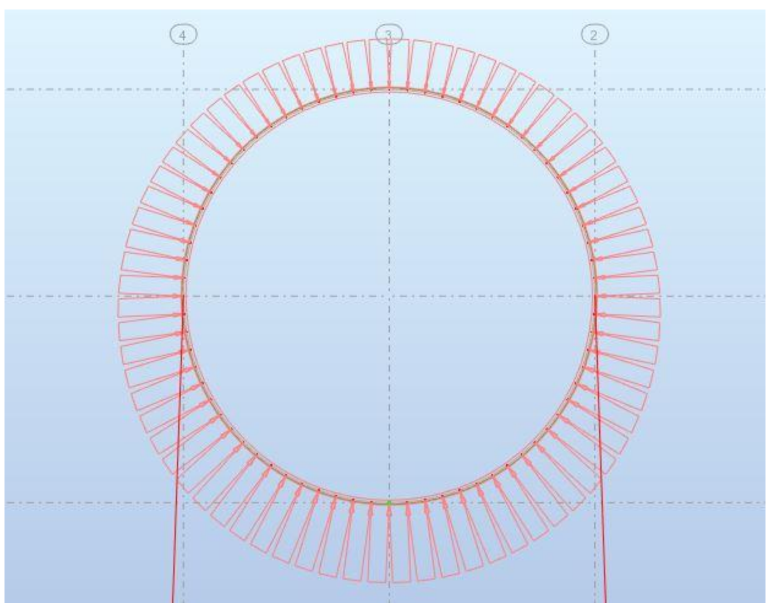

Figure 4-16 Hydrostatic Pressure Distribution from Structural Analysis Model of the SFC

The SFC in stable position will experience hydrostatic pressure acting normal to the surface of the structure. In force generated by this hydrostatic pressure is equal to the displacement weight of the structure in one direction and in other direction it would be zero. The hydrostatic pressure variation on the SFC can be visualized from the following figure:

Marine Growth

Marine growth is accumulated on submerged members. It results on the increase of volume along with the increase of drag coefficient due to higher roughness. The increase in mass of SFC will result in higher gravity loads and hence lower member frequencies. According to a Norwegian Standard marine growth of 17 kN/m has been considered in the design.

Accidental Loads

Accidental load on SFC are imposed due to marine accident e.g. submarine collision and ship grounding in the tunnel. The magnitude of the loads may cause the failure of the structure. Earthquakes are also considered in this category but due to the fact that Norway is not very prone to earthquakes, so this loading has not been considered in this study. The details of accidental load due to submarine collision and ship grounding are described in Section 5.4.1 and Section 2.4.1 of this study, respectively.

5

5 Consequence Modelling Approach

Complexity in the design and analysis of structures like SFC demands the critical evaluation of all constraints and loading conditions. The analysis can give an idea either the structure meets all requirements with safety and integrality during the design life. Simulating the working conditions and characteristics of SFC can improve the structural design to ensure the overall integrity of the structure.

Consequence modelling refers to the calculation or estimation of numerical values that describe the credible physical outcomes (OGP, 2010a). Following three models are introduced to represent the behavior of the SFC:

a) 1-D Beam model
b) 3-D model
c) VIV model

The consequence modelling is aimed for the analysis based on worst case scenarios. In this feasibility study, hazardous events of fire and traffic accidents have not been treated in a way of consequence modelling approach. Ship grounding case also has not been analyzed but reviewed from the perspective of its probability in Section 2.4.1. Accordingly, the following three types of worst case scenarios are mainly examined:

- A loss of support structure
  - To assess vertical displacement (A loss of a couple of both side tethers)
  - To assess cross-sectional angular deformation (A loss of either side one or two tethers on one side of SFC)
- External collision
  - To assess cross-sectional local indentation (in case the collision energy is absorbed to dent)
- Flooding due to accidental leakage

Besides worst case scenarios as identified above, VIV analysis has been performed both for the tube and tethers. The combined results of these 3 models will give the idea either the structure is in serviceability limit or not. The failure conditions are also described based on these results.

5.1 1-D Analysis

The first model of consequence modelling approach uses a one-dimensional conventional "Euler-Bernoulli Beam" for the SFC tube. Thus it is assumed that cross sections initially perpendicular to the axis of the beam remain plane and perpendicular to the neutral axis during bending. It is also assumed that longitudinal strains vary linearly across the beam. The length of the beam is 200 meters which is equivalent to the length of a segment. (CT5123 TU Delft, 2009)

$$m = -EI\kappa = -EI\frac{d^4 v}{dx^{4'}} \tag{5.1}$$

$$-EI\frac{d^4 v}{dx^4} + f_y = 0, \tag{5.2}$$

Where m is bending moment, v is displacement, EI means stiffness and f_y stands for axial forces.

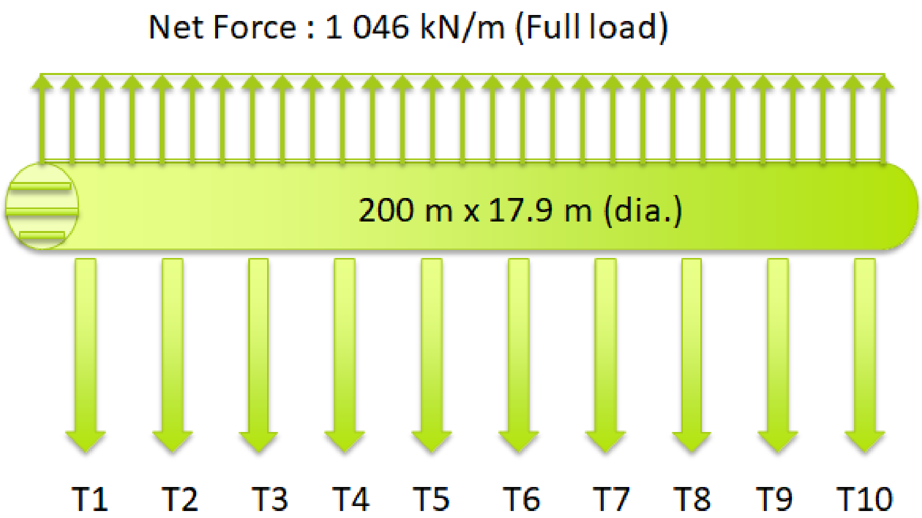

Figure 5-1 Schematic figure of 1-D beam model

5.1.1 Boundary condition

The 1-D beam model is used for pure bending case where pinned boundary condition is presumed at the both longitudinal ends of the beam. (CT4145 TU Delft, 2018). Thus vertical bending moments and displacements are assumed to be zero at the ends. The mathematical expression is in the following:

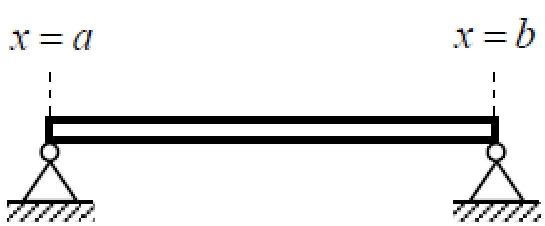

Figure 5-2 Pinned supports

$$x = a : w = \frac{\partial^2 w}{\partial x^2} = 0 \tag{5.3}$$

$$x = b : w = \frac{\partial^2 w}{\partial x^2} = 0 \tag{5.4}$$

5.1.2 Transformed section

In case of composite materials the moment of inertia, I, needs to be calculated by using "transformed section" due to the discrepancy of elastic modulus, E, for materials forming the section. The principle of transformation for one material is to adjust the area of one material to an equivalent amount of transformed section based on the ratio of elastic modulus of two materials. The ratio as defined below, n, is multiplied to the area of steel material in a typical cross section of the SFC. Total moment of inertia (Second moment of area) has been summated over inner and outer structural elements and calculated by using parallel axis theorem.

$$n = \frac{E_A}{E_B} \tag{5.5}$$

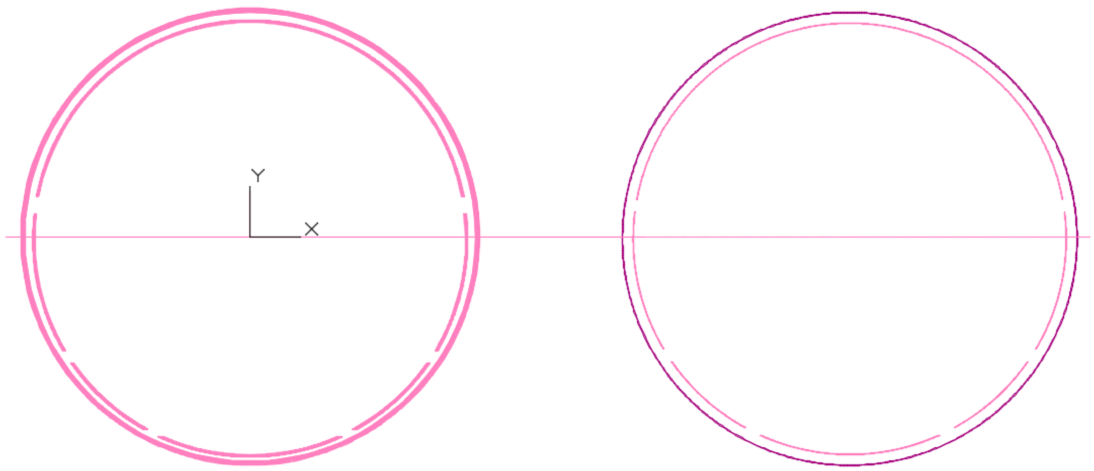

Figure 5-3 Transformed section(left) and original section (right) for steel material

5.1.3 Wave load

For tether loss case including pure bending, both swell and wind wave have been taken into consideration. It is presumed in the first worst case scenario that both waves could amplify the response of the modelled beam, which have different modes for respective waves. According to dispersion relation, a wind wave could have 50 meter of wavelength and a swell could have around 200 meter of wavelength as the swell has 12 second of peak period. Referring to linear wave theory, dynamic pressure by wave particle movements has been taken into account. The modes given by the waves are presented in Figure 5-9.

5.2 3-D Analysis

With the recent innovative ideas of analysis using software, it is now easier to do simplified and realistic evaluation of the serviceability limit state and ultimate limit state characteristics of structures like SFC, which are subjected to various environmental conditions. With the help of advanced finite element tools, analysis of such complex structures can be carried out with confidence to ensure compliance with industry design codes.

5.2.1 Modelling

As the environmental loads have already been calculated in the previous sections of this study, so a 3D structural model is constructed by Finite Element Method utilizing Robot Structural Analysis and materially nonlinear static analysis was carried out for SFC. It is modeled as moored floating structure with the assumption that it is fixed supported at each end of the structure. Tethers (moorings) are considered as pinned joints with the sea bed at water depth of 482m.

A SFC model is considered to be submerged at 30m below the water surface. Dimensions of structure with 200m length, 18m diameter and 500mm section thickness has been defined in the model. The material for the SFC has been considered as B65 concrete which is most commonly used for the offshore structures under extreme loadings. Tethers has been considered at two degree inclination with respect to the vertical. Tethers are modeled to be made of S235 steel. The initial configuration of the tunnel is as shown below;

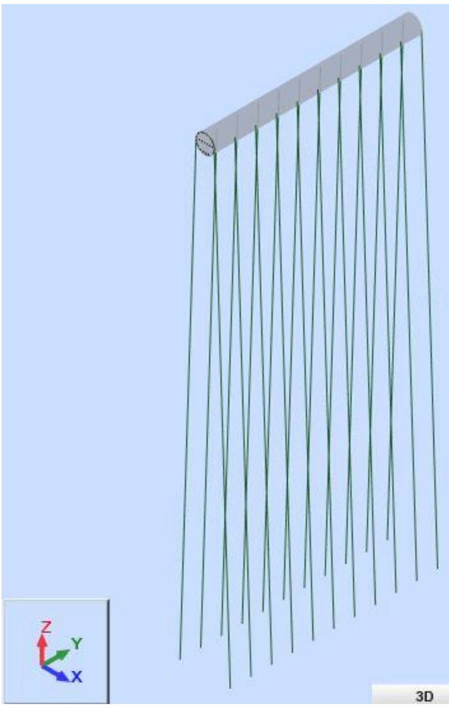

Figure 5-4 3D Model for SFC

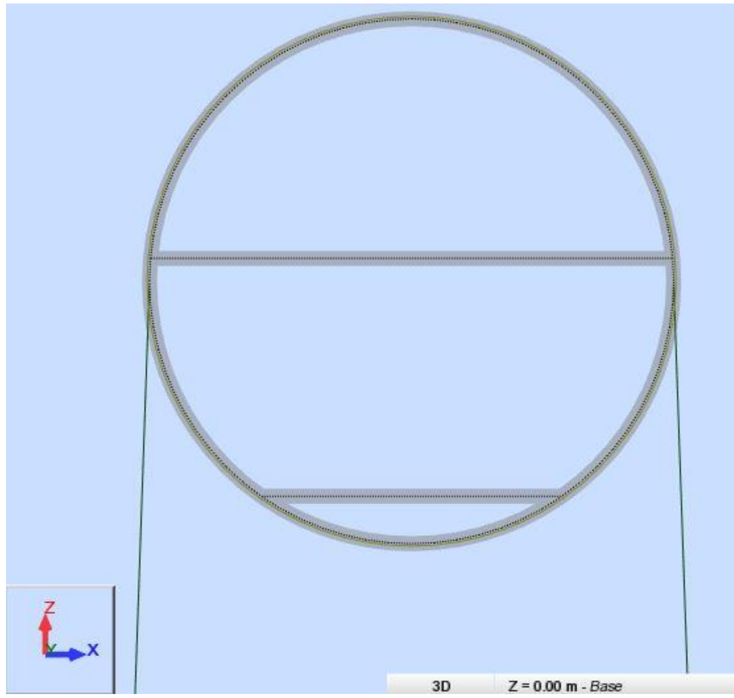

Figure 5-5 A Modelled cross-section of SFC

5.2.2 Load Definition

Four types of loadings have been defined for the model, namely dead load (DL1), hydrostatic pressure, wave and current load and traffic load. Dead load mainly includes the self-weight of the structure. Hydrostatic pressure has been applied for a depth of water of around 482m. A simplified approach has been considered for the application of waves and current load. As the direction of these loads change with time so instead of variable load with the depth, a resultant point load has been applied at the middle of the section in the direction of propagation of wave/tide. For the case of the moving loads, the inbuilt Eurocode in the model has been utilized and a traffic load of around 94kN/m has been defined throughout the length of the structure. A representative figure for wave load is shown in Figure 5-6.

5.2.3 Load Combinations

As SFC is a buoyant structure so when there is no traffic in the tunnel then the upward forces increase in the structure causing extra tension in the tethers. Considering this scenario as the critical situation, moving traffic loads has not been simulated in the model. A manual combination of all the remaining loads has been generated with a dead load factor of 1.35. This combination is referred to as Case4, in all the model results.

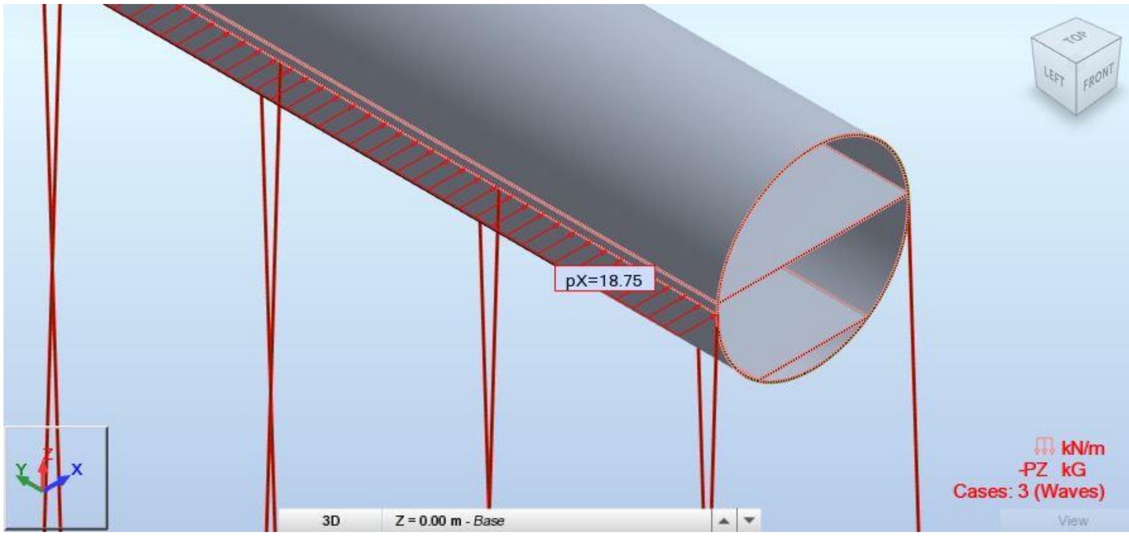

Figure 5-6 Definition of wave load

5.2.4 Tether Configuration

From the environmental load calculations an initial value for the tether spacing has been calculated which come out to be around 17.3m. On the basis of this calculation a tether spacing of 20m has been chosen initially to apply in the model. To optimize the design of tether two approaches will be applied:

- **First approach** for the model would be to keep the spacing of the tethers same (20m) and rerun the model considering different diameters of the tether.
- **Second approach** would be to assume a suitable diameter (i.e. 0.5m for the initial run) and rerun the model for different tether spacing.

In order to get the final optimized design of tether a comparison of tether tension with diameter and spacing is made. Based on this comparison a model is finalized which will be used in further investigation of behavior. The final results of these approaches are shown in the Figure 5-7 and Figure 5-8. Results of Robot Model for these scenarios are in Appendix F.

From Figure 5-7 one can see that tension in the tether decreases initially up to the size 200mm but after that it starts increasing. Considering this 500mm was chosen, as the tether diameter but when vortex induced vibration (VIV) analysis (shown in Section 0) was performed on this diameter, then it showed significant vibrations. To reduce the effect of VIV there is an option to increase the stiffness/mass of tether. So considering this situation, diameter of 1000mm is chosen for the tethers. Figure 5-8 indicates the maximum tension in tether and spacing of tethers considering the diameter as 1000mm. This graph is not very helpful in deciding the spacing so another comparison of vertical displacement and tether spacing is made which can be seen from Table 5-1.

This analysis eliminates the spacing option of 10m and 40m. The spacing of 33.3m with 6 tethers in 200m span offers a quite high vertical displacement, even though it is still in allowable limit, but it can be eliminated on this basis. Considering the complexity of the structure and uncertainty in loading, 20m spacing has been chosen for this study. Therefore, the finalized design of tether is with 1000mm diameter and 20m spacing.

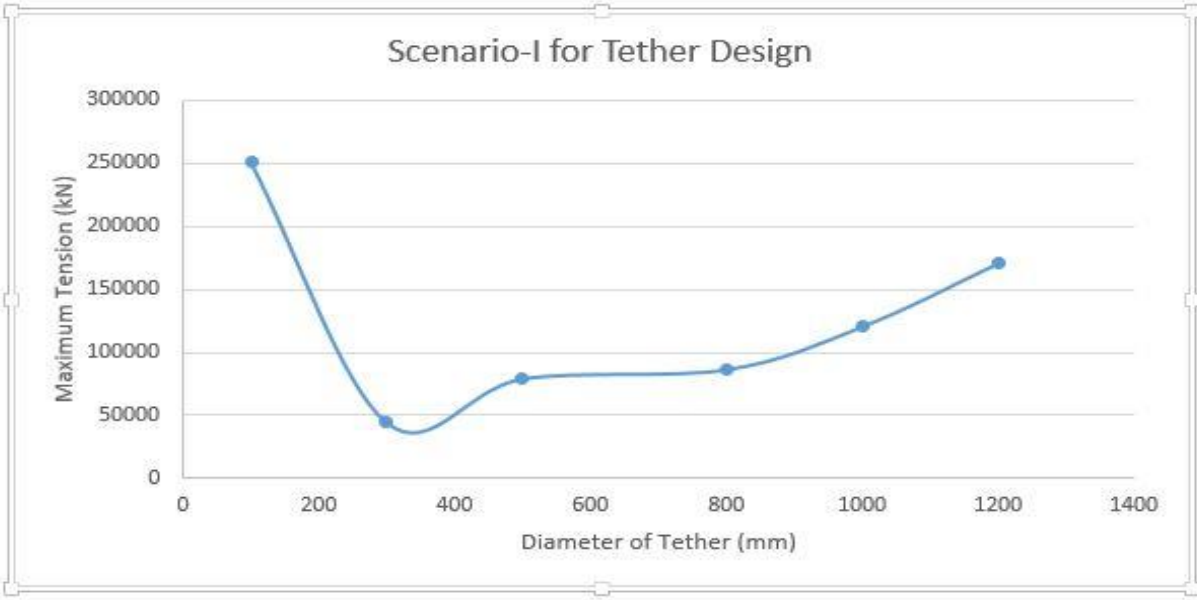

Figure 5-7 Tension and its dependency on tether diameter

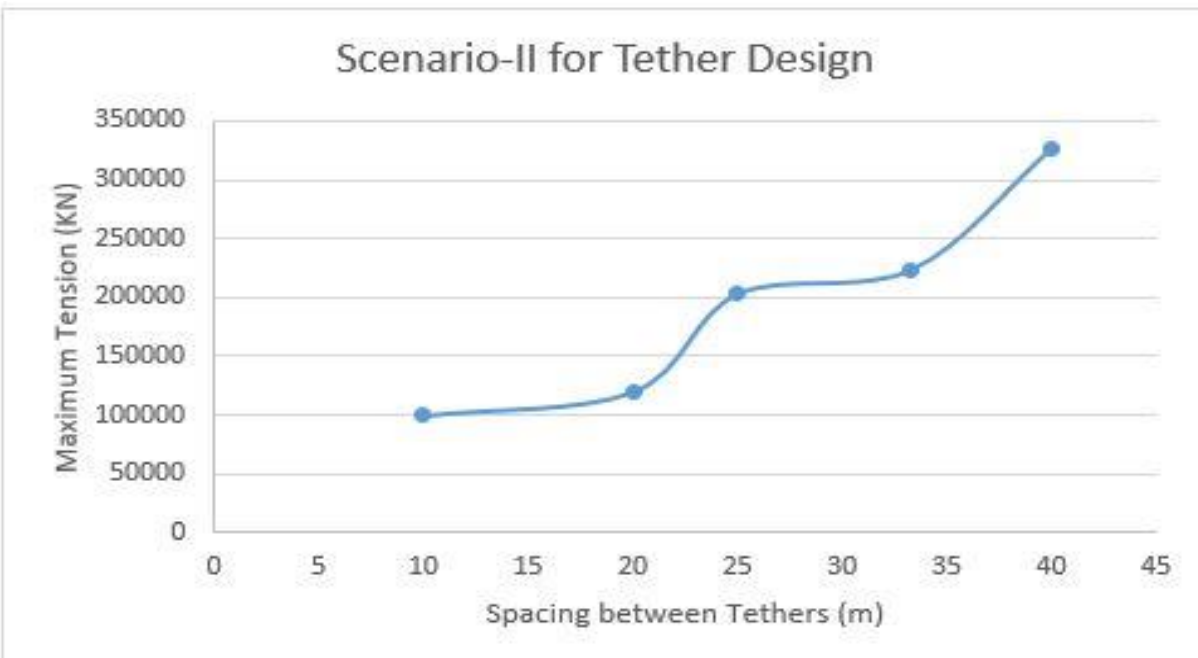

Figure 5-8 Tension and its dependency on tether spacing

Table 5-1 Vertical displacement with respect to tether spacing (WCS-I)

Sr. No	Spacing	Vertical Displacement	Allowable Limit	Ramarks
		mm	mm	
1	10	62	50	Vt. displacement higher than Allowable limit
2	20	70	100	Vt. displacement is within Allowable limit
3	25	88	125	Vt. displacement is within Allowable limit
4	33.3	154	166.5	Vt. displacement is within Allowable limit
5	40	234	200	Vt. displacement higher than Allowable limit

5.3 Scenario 1: A loss of support structure

The tethers of SFC are generally designed to have sufficiently high pre-tension in order to avoid slacking in extreme environmental conditions. Considering the extreme scenario, the underlying concern here is weather the stability of structure would be endangered if there is a loss of a few tethers. The main purpose of scenario-I is to check either the design is robust enough to guard against total failure of the structure in the event of a few tendon failure due to some reason. The dynamic survivability after the loss of tethers under prevailing environmental conditions is simulated using 1D and 3D models.

There are mainly two sub-scenarios:

- A loss of a couple of tether at both side (starboard and portside)
- A loss of two adjacent tethers at one side

5.3.1 1-D Beam Results

Based on the 1-D Beam model as defined above, the results of the first scenario have been derived.

Statically indeterminate

In the 1-D Beam model, the stiffness of tether tensions were not calculated due to the complexity of calculations. Due to statically indeterminate e.g. a larger number of unknowns than the number of boundary conditions, the tether tensions T1 through T10 have to be simplified to less than three unknowns. As assuming zero displacements at mid points 2 through 9 are not realistic at all, vertical deflections are allowed at these points.

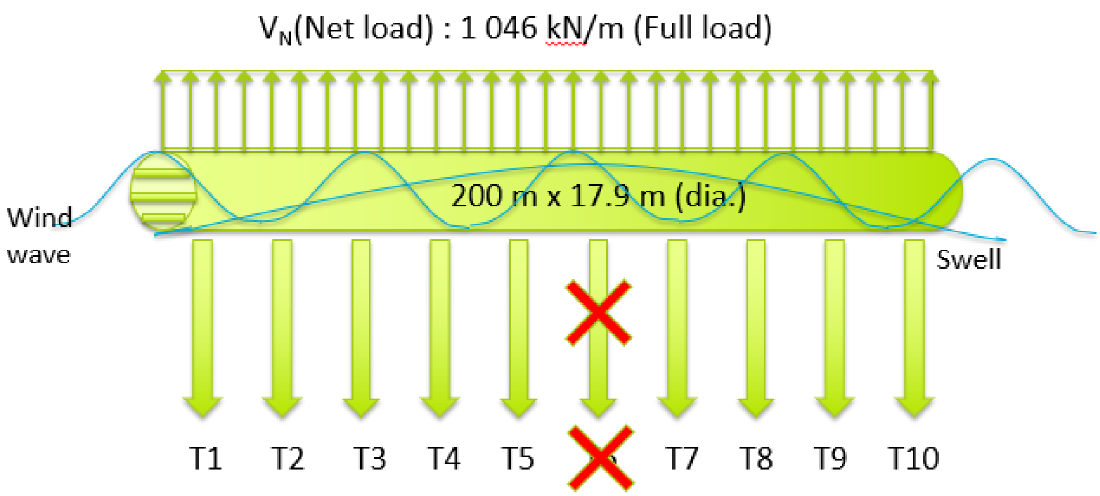

Figure 5-9 Schematic figure of worst case scenario No.1 in 1-D beam model

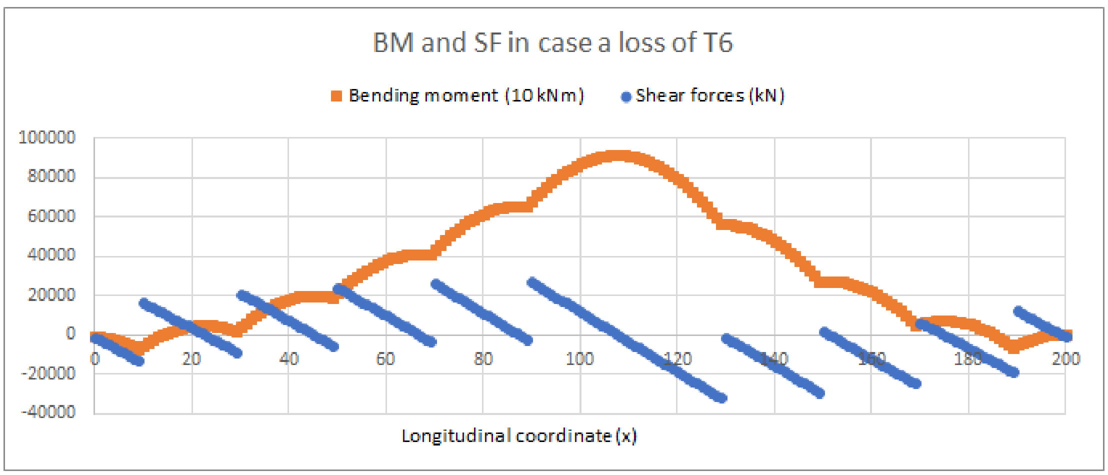

Figure 5-10 Bending moments and shear forces in case of loss of T6

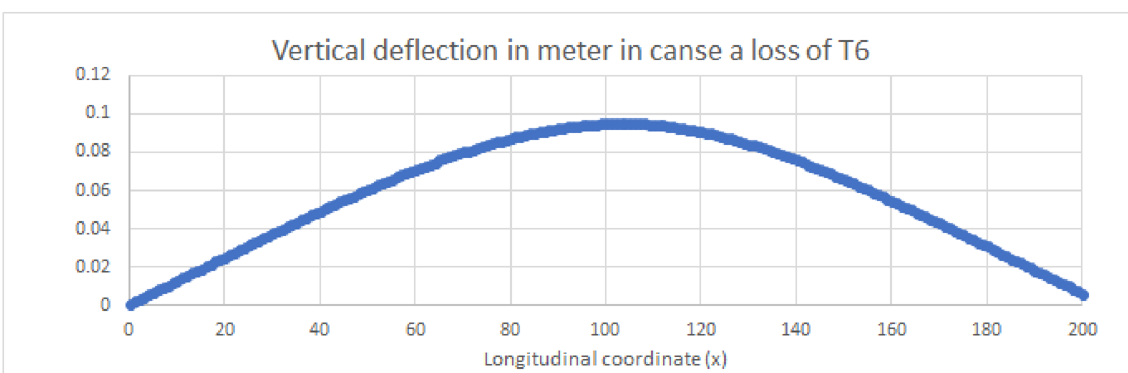

Figure 5-11 Vertical deflection in case of loss of T6

As results, the maximum vertical deflection is estimated to be 0.095 meter and the maximum moment is found to be 919 MNm, which is 25.6% of allowable moment as defined in Figure 5-19.

5.3.2 3-D Analysis Results

Following four scenarios are simulated in ROBOT to check the stability of the structure under tether loss conditions;

1. Case 1: Loss of one tether on starboard size and port side (total two tethers loss)
2. Case 2: Loss of two tethers on starboard size and port size (total four tethers loss)
3. Case 3: Loss of one tether on one side (total one tether loss)
4. Case 4: Loss of two tethers on one side (total two tethers loss)

The consequences of the loss and structural conditions for all these cases are explained in the following sections.

Case 1: Loss of one tether on starboard size and port side (total two tethers loss)

The main approach for comparison would be the vertical deflections and rotation in the structure after the loss of tethers. The results of these simulations are shown in Figure 5-12 and Figure 5-13.

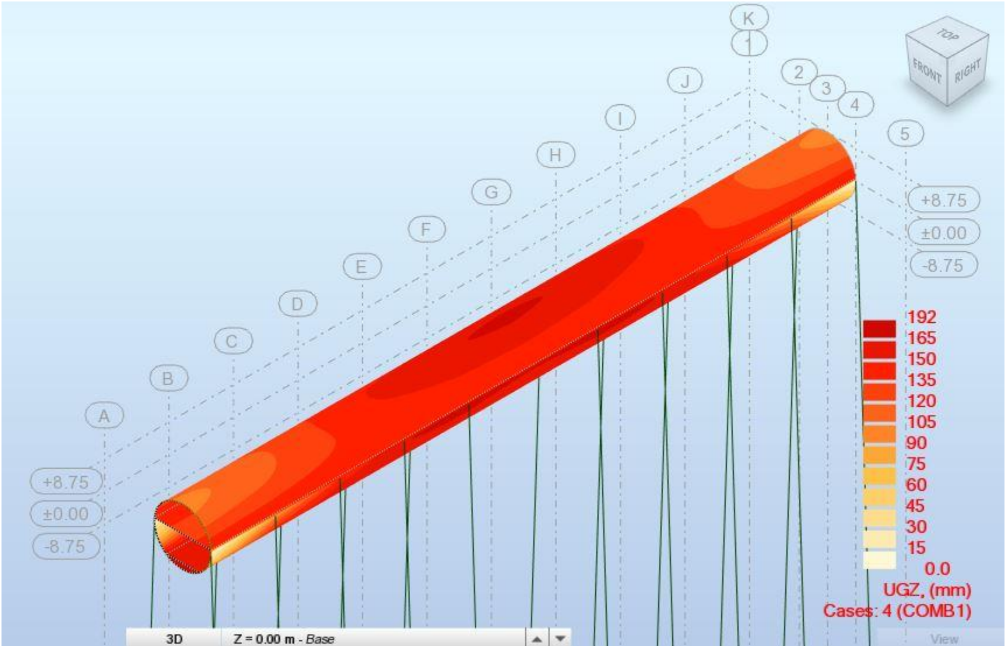

Figure 5-12 Vertical Displacement in SFC with one tether removed on both sides

The maximum deflection in this case goes up to 192mm at the location of the removed tether because of the increase spacing between the tethers which causes additional stresses on the adjacent tethers. This deflection is within the allowable limits considering the allowable vertical displacement value as 200mm (Span/200). Considering the second criteria for maximum allowable deflection in SFC, related to yield strength in tethers, a vertical displacement of around 400mm is allowed with yield strength of tether as 235 MPa and a factor of safety of 20%. The rotation of the section in this case is around 0.008 radians which is within the allowable limit of 0.015 radians. Thus it is concluded from case 1 that even after the removal of the tethers the deflections and rotation do not exceed to endanger the serviceability of the SFC. The details of model results are presented in Appendix G.

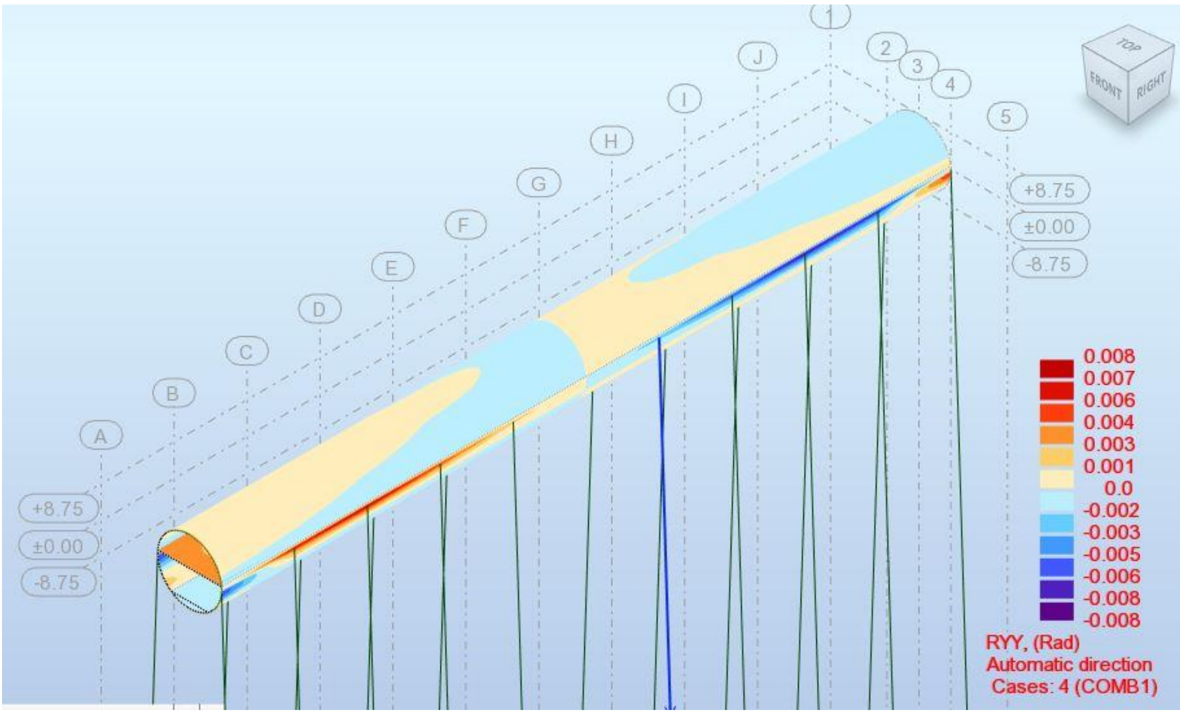

Figure 5-13 Angular Deformation of SFC after loss of one Tether

Case 2: Loss of two tethers on starboard size and port size (total four tethers loss)

This can be considered the worst case scenario. The probability of this case occurring is quite low. Simulation results for vertical displacement and angular deformation are shown in Figure 5-14 and Figure 5-15.

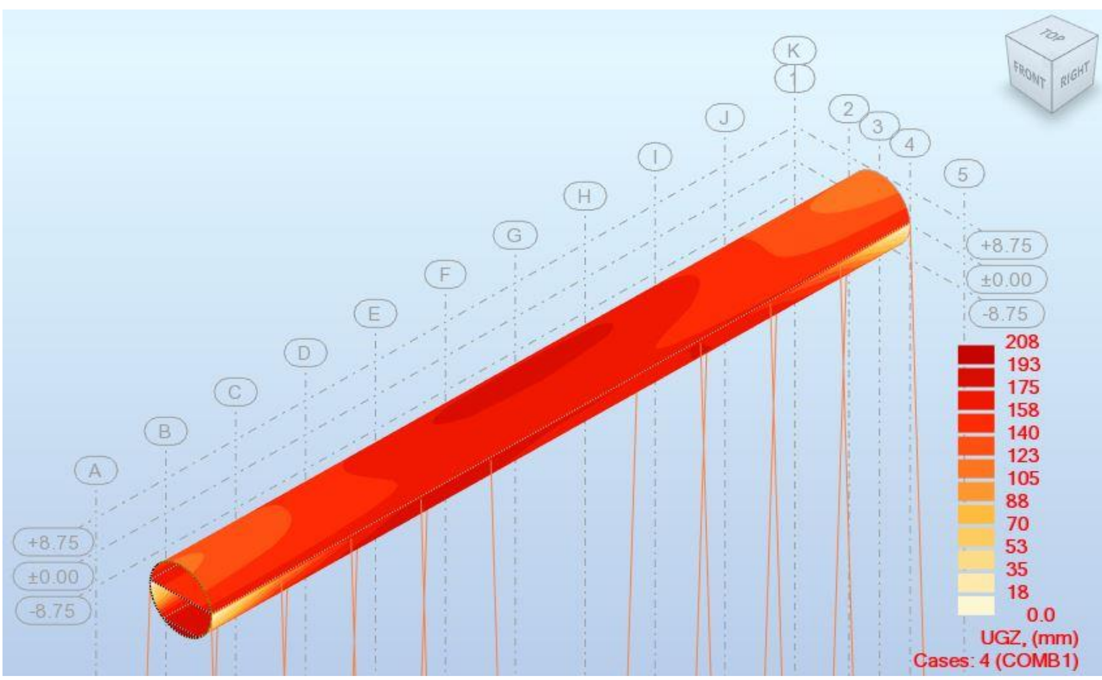

Figure 5-14 Vertical Displacement in SFC with two tether removed on both sides

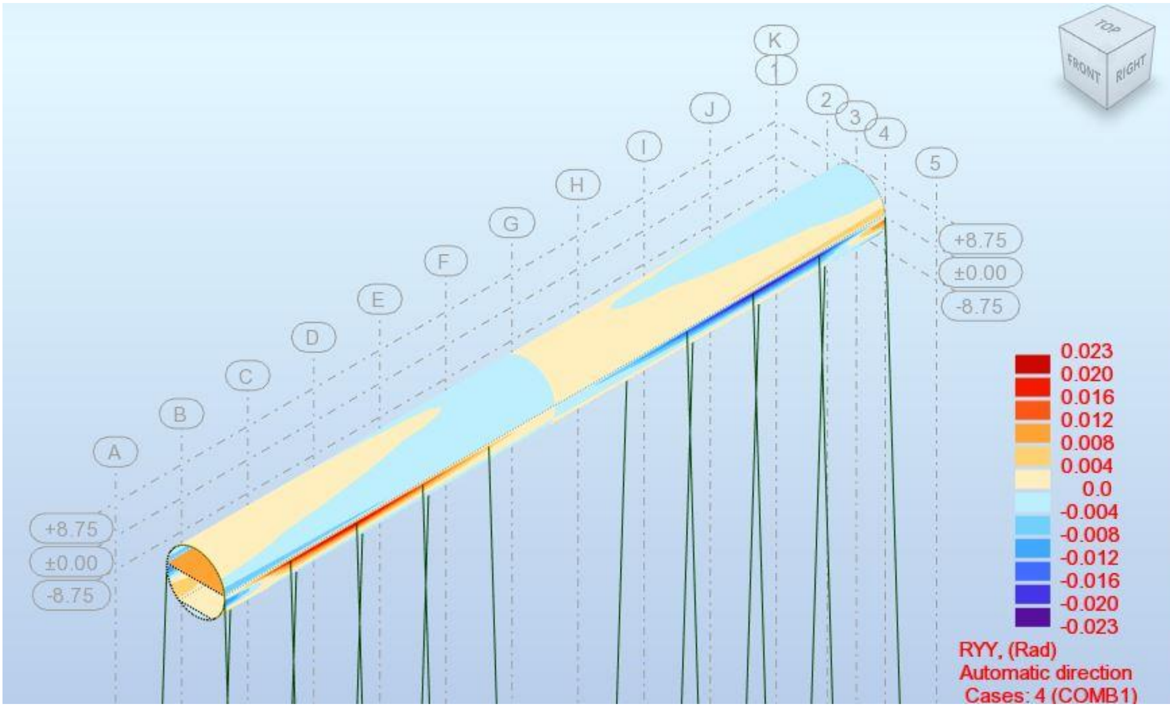

Figure 5-15 Angular Deformation in SFC after loss of two tethers on both sides

The vertical deflections in this are around 208mm in the section where tethers are removed. Deflection still does not exceed the allowable criterion for yield strength of tether (i.e. 400mm) and unsupported span (i.e. 300mm). The governing scenario in this case is related to the angular deformation of the structure, which goes up to 0.023 radians exceeding the allowable limit of 0.015 radian. Hence this scenario can be considered as the failure of the SFC.

<u>Case 3: Loss of one tether on one side (total one tether loss)</u>

If due to some reason tether on one side of the SFC fails, then because of the applied environmental loads there is a possibility that structure exceeds the permissible rotation limit.

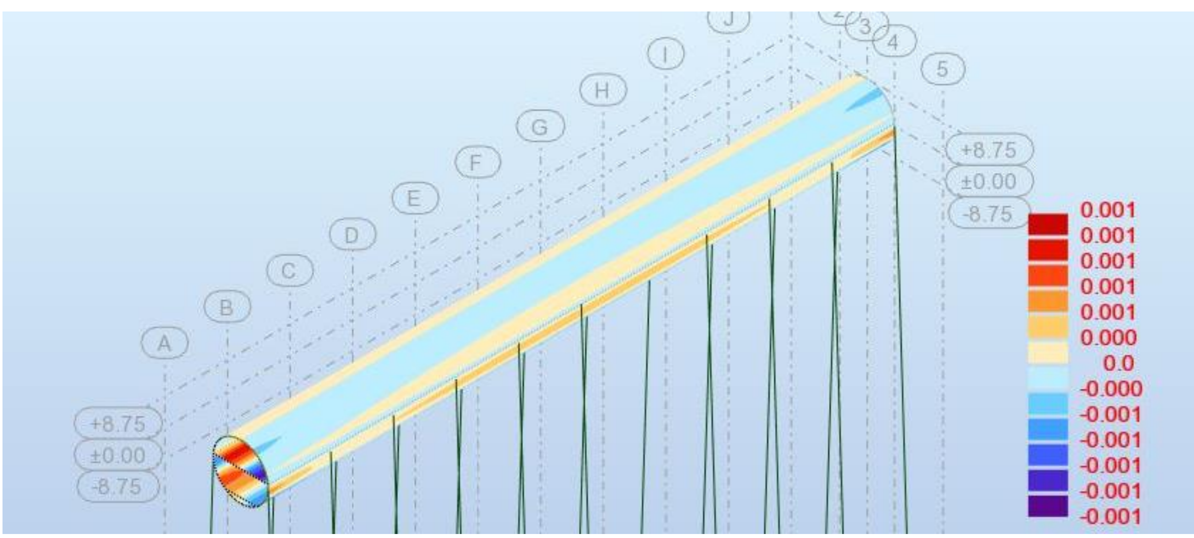

Figure 5-16 Rotation in SFC in case of one tether loss on one side

The rotations around the connection of enact tethers with SFC in this case goes up to 0.10 radians. This rotation is within the acceptable rotation limit of 0.015 rad.

<u>Case 4: Loss of two tethers on one side (total two tethers loss)</u>

In this scenario, simulation is shown in Figure 5-17. The rotation in this case goes up to 0.006 radians which is within the acceptable limits.

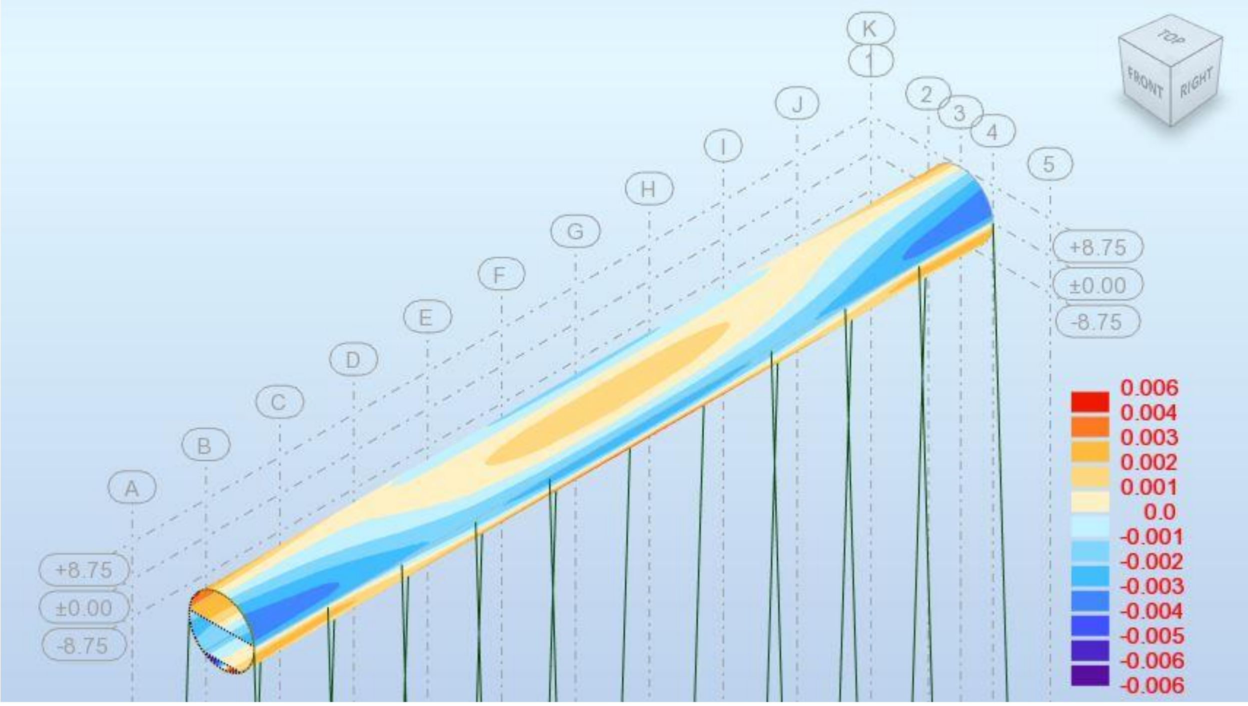

Figure 5-17 Rotation in SFC for loss of two tethers on one side

From the 3D modelling of these scenarios it can be concluded that the SFC is within the acceptable limits of deflection and rotation till the failure of one tether on both sides of the structure but if two consecutive tethers in the SFC breaks on both sides (total loss of four tethers) then it can be considered as the failure of the structure.

5.3.3 Findings of Analysis

Cross section rotation

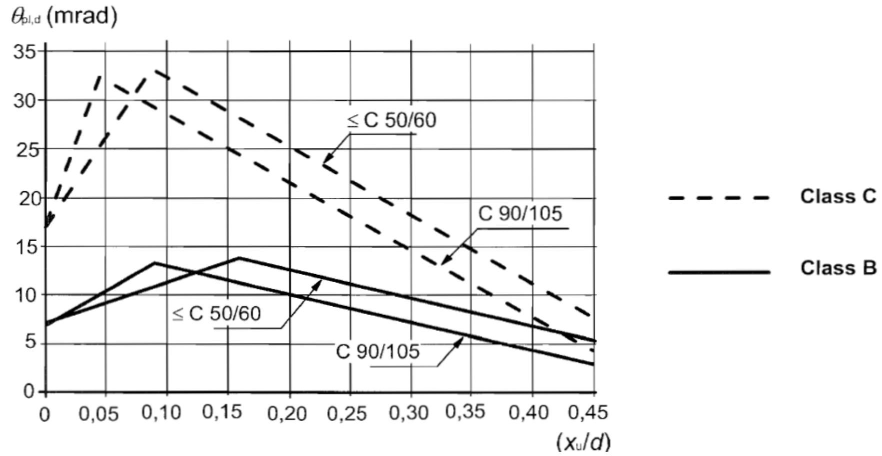

Figure 5-18 Basic value of allowable rotation (the values apply for a shear slenderness = 3.0)

Concrete class B65 is employed to form the lining of the SFC. According to Figure 5-18 no more than 15 mrad of ration is allowed in any case for class B concrete. Thus, 15 mrad is the critical value of the angular displacement of the SFC.

Limiting condition and allowable bending moments

Since the strain gradient with respect to the profile is linear as Euler-Bernoulli beam is adopted in 1-D model, adjoining materials has the following strain profile in Figure 5-19. 0.125% and 0.28% of strain have been introduced for steel and concrete material, respectively. Accordingly, the strain value for steel parts would limit the case. Allowable bending moments and stress have been derived in accordance with the limiting case.

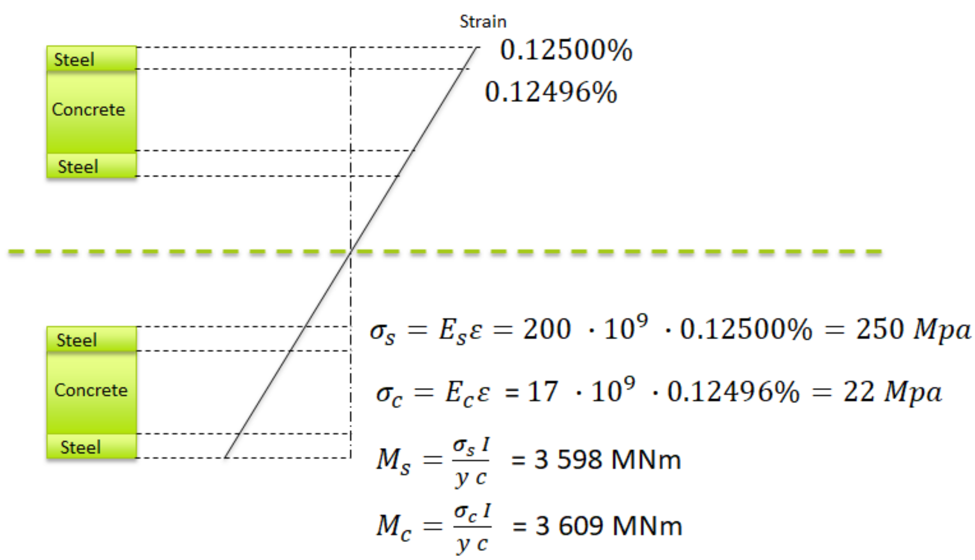

Figure 5-19 Strain profile and allowable bending moment

Table 5-2 Acceptable criteria for scenario 1

Criteria	Allowable value	Calculation (1D Beam)	Calculation (ROBOT)
Vertical displacement (deflections)	1) Span/200 2) 400mm (from the yield strength of tether)	95mm	• 192 mm for loss of two tethers • 208 mm for the loss of four tethers
Angular Deformations	15 mrad (EN 1992-1-1, 2004)	-	• 0.001 for loss of one tether • 0.006 for the two tethers • 0.008 for loss of one tether on both sides • 0.023 for loss of two tethers on both sides.

5.4 Scenario 2: External collision

5.4.1 Assumption

External collision for the tube is considered only as an extreme failure condition. In this regard, submarine collision is solely a possible scenario rather than surface ship collision since the SFC does not have any floating pontoons on surface and sufficient keel clearance is assumed in the decision of depth of structure.

Design accidental load

The submarine regarded as design load is called Ula class submarine for Royal Norwegian navy. The submarine has 1 150 tons of displacement and maximum speed is assumed to be 23 knots which could lead to 80.5 MJ of collision energy. 10% of added mass is applied with respect to the weight of the submarine since bow impact has been assumed.

$$E = \frac{1}{2}(m + a)v^2 = 80.5\ MJ \qquad (5.6)$$

Figure 5-20 Ula class submarine (https://www.naval-technology.com/projects/ula-class-submarines/)

Collision force

By analogy with the shape of bulbous bow of a VLCC, the collision force of the submarine can be presumed to be 65 MN corresponding to the deformation depth induced by 80.5 MJ of collision.

Ductility design principle

It is assumed that all the collision energy is absorbed to the SFC tube structure. DNV (2010a) defined that Ductility design implies an assumption where the installation undergoes large, plastic deformations and dissipates the major part of the collision energy.

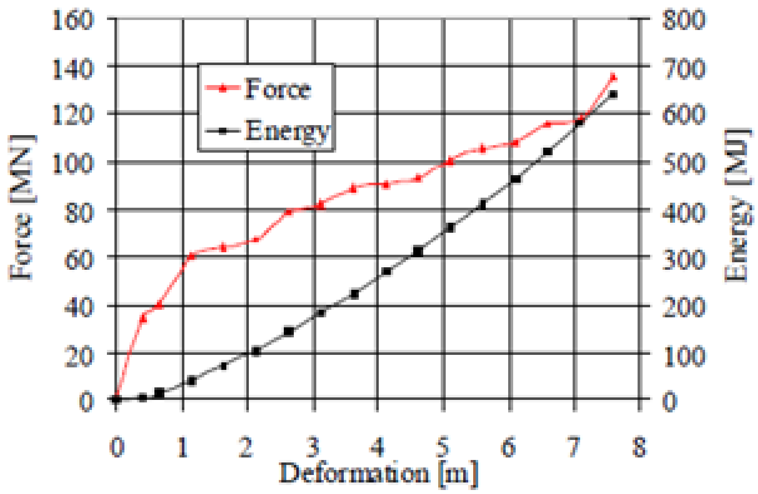

Figure 5-21 Force-deformation relationship for bulbous bow of a VLCC (DNV, 2010a)

Figure 5-22 An example of bulbous bow

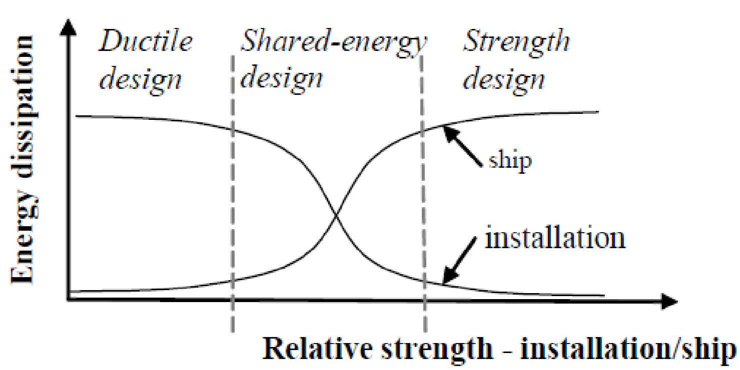

Figure 5-23 Energy dissipation for strength, ductile and shared energy design

In order to assess the behaviour of the SFC in the worst-case scenario 2, the following critical values were found and are introduced:

Critical rupture strain for mild steel

The outer shell of the SFC is assumed to be made of mild steel. Zhang, (1999) referred to McDermott's formula to represent critical rupture strain in collisions. Once the critical rupture strain is determined, the critical deflection or penetration can be derived where the collided structure is defined as a plate strip.

$$\varepsilon_c = 0.10 \cdot (\frac{\varepsilon_f}{0.32}) \quad (5.7)$$

Where ε_f is the tensile ductility and ε_c is critical rupture strain for mild steel material.

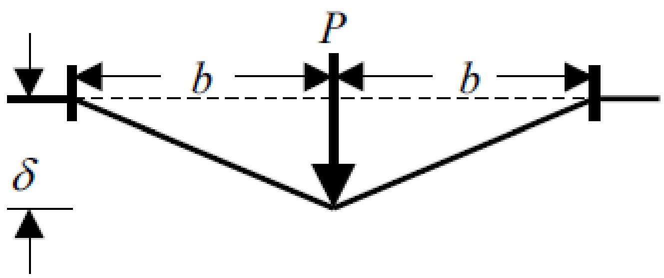

Figure 5-24 Transverse deflection of a plate strip (Zhang, 1999)

The strain due to transverse deflection can be calculated from:

$$\varepsilon = \sqrt{1 + (\frac{\delta}{b})^2} \quad (5.8)$$

Since the effective span of cross sectional structural member has not been specified yet, it is assumed to be 10 m of span, which is similar magnitude from the top of the SFC to the first road level. Therefore, critical rupture strain is calculated as 1.90 m.

5.4.2 1-D Beam results

With regards to indentation depth, δ, to tubes, Wierzbicki and Suh (1988) formulated the equation below:

$$\frac{P}{M_0} = 16\sqrt{\frac{\pi}{3}}\sqrt{\frac{D}{t}\frac{\delta}{R}}\sqrt{1 - \frac{1}{4}(1 - \frac{N}{N_p})^3} \quad (5.9)$$

Where, : Lateral concentrated load;

M_0: Fully plastic bending moment of the wall;

D : Diameter of undeformed tube;   t: thickness of circular tube;

R: Radius of undeformed tube;

N: External axial force;

N_p: Plastic force capacity of cross section

In this formula, $\frac{N}{N_p} = 0$ implies freely rotating or sliding boundary condition, whereas the tube with full end fixity applies to $\frac{N}{N_p} = 1$. In order to conduct more conservative estimation, the ratio is given as zero which leads to 0.56 m of indentation depth.

5.4.3 ROBOT 3D Modelling results

A model of SFC cross section of SFC, has been simulated in ROBOT with an indentation area of around 2.25 m^2. Collision load calculated for submarine is around 65MN which is distributed on the indentation area and applied on the model. Following Figure 5-25 show the applied loads on the model Including the submarine load.

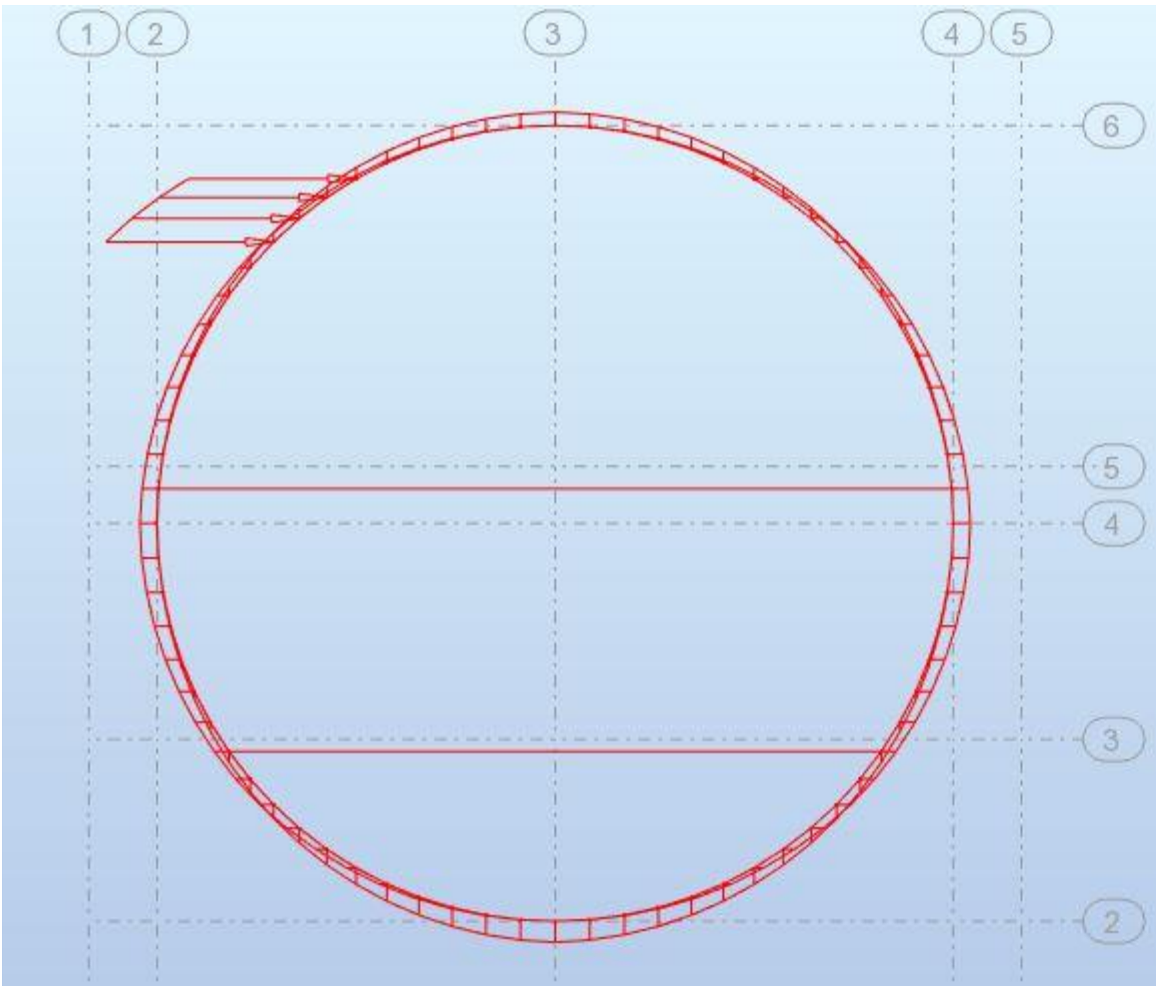

Figure 5-25 Loads on SFC with submarine loads

The simulation results are shown in Figure 5-26. The figure indicates the denting of around 1358mm. This indenting is quite high and it will distort the structure which will lead to the failure.

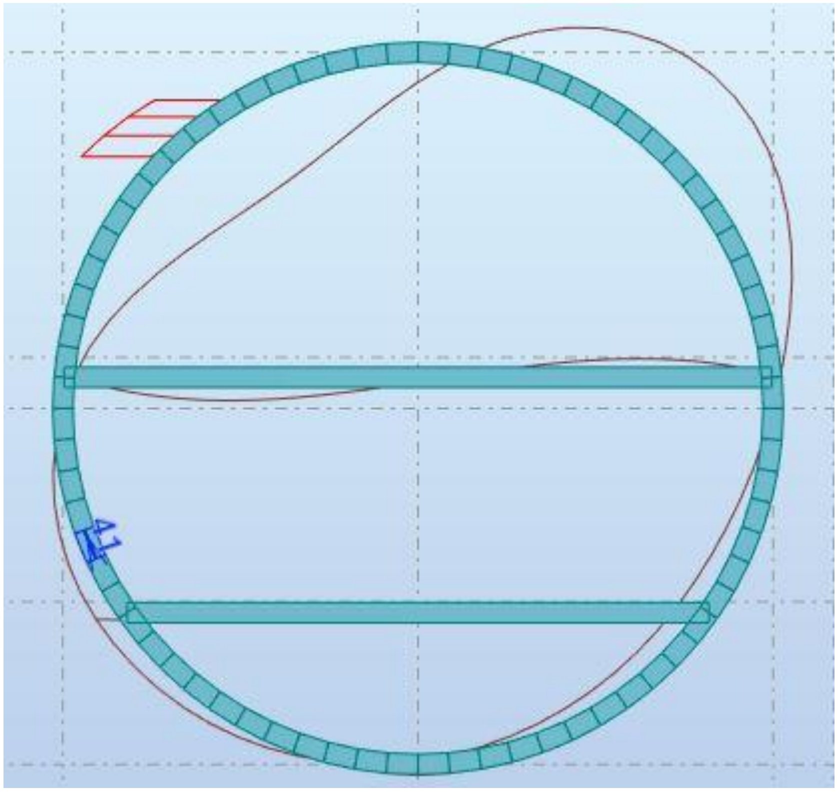

Figure 5-26 Indentation due to submarine collision

5.4.4 Summary of results

Table 5-3 Acceptable criteria for scenario 2

Consequences	Allowable value	Calculation (1D Beam)	Calculation (ROBOT)
Local denting	1.90 [m] / 10 m (Zhang, 1999)	0.56 [m] (Wierzbichki & Suh, 1988)	1.36m

5.5 Scenario 3: Flooding

5.5.1 Assumption

Gradient of Road

Gradient is an important operational design parameter so that any leakage and washing water will be drained to the lowest point where there is a pumping station (Eysink & Heins, 1976) and ensure a rapid drainage of the road surface so that vehicles will avoid driving in "brine" (Ovstedal & Melby, 1992). Therefore 0.2% has been chosen as a minimum longitudinal gradient. It is also assumed that the tunnel is designed with tightness class 3 which means that no leakage is permitted by generally applying special measure such as liners, injection and prestress (En 1992.3.2006)

Sources of flooding

The outer shell plates of the SFC will be welded putting together two adjoining segments during construction phase, which would reduce the probability of accidental leakage due to external damage. Thus, the following sources have been considered as flooding:

- Fire water
- Washing water drainage
- Spillage of truck liquid cargo

5.5.2 Acceptable criteria

A study by (Blindheim & Øvstedal, 1992; Espedal & Nærum, 1994) stated the acceptable amount of in-leaked water is 0.3 m^3/min per km tunnel. Whereas different study (Reinertsen, 2016) suggested that for SFC the acceptable level is 0.1 m^3/min per km which is considered conservative estimates. As the later study were related to SFC, this value is adopted especially since water tightening is implemented during the construction of the tunnel. Moreover, assumption of washing water drainage of 18 m^3/h and firewater of 108 m^3/h has also been taken from the same study.

5.5.3 Estimation of drainage

The amount of drainage shall not be greater than the acceptable level as set above. The following table shows the required pump capacity estimated based on the drainage accumulation.

Table 5-4 Drainage estimation

Drainage	Capacity
Fire water	108 m^3/h
Washing water drainage	18 m^3/h
Other leakage, spillage	30 m^3/h
Acceptable level	36 m^3/h (=0.1 m^3/min)
Required pump capacity	120 m^3/h

5.5.4 Safeguard: Drainage system

Drainage system is crucial for the safety and functionality of the SFC. As it was mentioned in the hazardous event analysis, existence of water in the tunnel might lead to structure failure. This failure could be due to flooding, corrosion/ crack on concrete, failure of the invert and other mechanisms. The ideal basic solution for such hazards are firstly by preventing the occurrence of such hazard by ensuring total water proof against pressurized water, and secondly by ensuring an effective drainage system. Figure 5-27 illustrates the component a waterproofing system.

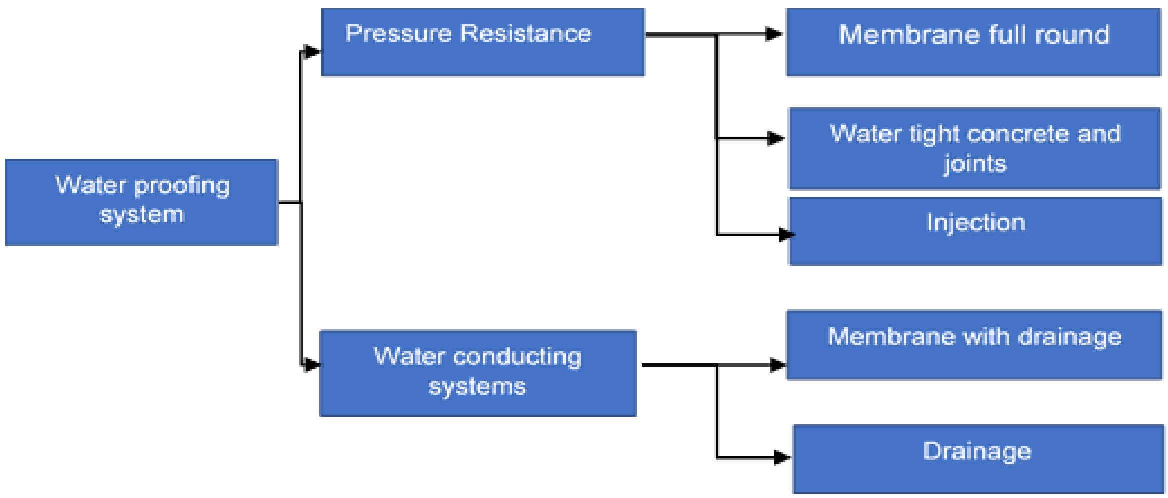

Figure 5-27 Main component of waterproofing system

Like subsea tunnels, the drainage system is important to remove water occurring in the tunnel either due to leakage from outside seawater, firewater from firefighting, spillage from road tanker, or water brought by cars. A drainage system consists of drain, bilge sumps, and pump stations.

Penetration of water into the tunnel tube in permanent condition is not permitted. However, even though water tightening is ensured through lining and injection, the fact that there will be lots of joints connecting different segment of the tunnel implies that probability of water penetrating the tunnel tube need to be considered. Thus, it is important to reduce the amount of in-leaking water to a level acceptable for pumping.

The total length of the tunnel is 6 km with the highest elevation at the middle of the tunnel and two lower elevation at the boundary of the tunnel. Therefore, there will be four pump station and pump sumps. Two main pump stations are equipped with total pump capacity of 120 m^3/hr together, whereas the other two auxiliary pump stations have a pump capacity of 60 m^3/hr together which provide 50% redundant capacity. The schematic diagram for the drain system is found in Figure 5-28.

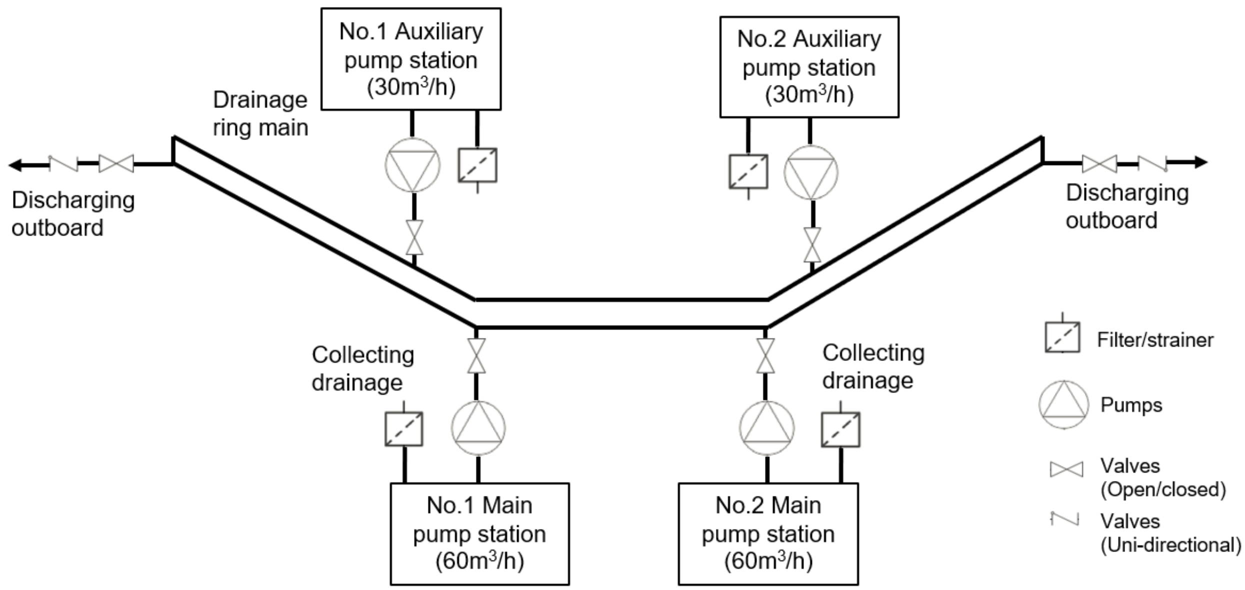

Figure 5-28 A schematic diagram for the drain system of the SFC

5.6 Vortex Induced Vibration (VIV) Analysis

For the VIV analysis the most relevant design guideline is DNV-RP-F105 (DNV, 2006) for subsea pipelines.

By following this guideline crossflow vortex induced vibration analysis has been done for the SFC and for the structure support tethers because it can be more vulnerable to both. The main idea behind is to calculate the reduced velocity and stresses and check that weather it will be in the permissible limit or not.

5.6.1 VIV analysis for SFC

SFC is a slender structure so in fluid action it may get oscillations. Basically, structures with less internal damping are vulnerable to VIV. Vortex shedding happens because the flow cannot take after along the surface of the structure and isolates from the surface, as appeared in Figure 5-29. This flow separation makes a vortex which causes a local increment in rotational velocity. Higher flow velocity yields a diminishment in dynamic pressure, which creates an attracting force by the vortex on the structure.

The position of the separation point changes between the top and bottom, and creates a vortex streak, as illustrated in Figure 5-29. These vortexes create a force variation due to the pressure changes. Due to the spatial properties of the problem, the forces in cross flow will have a period identical to the shedding period.

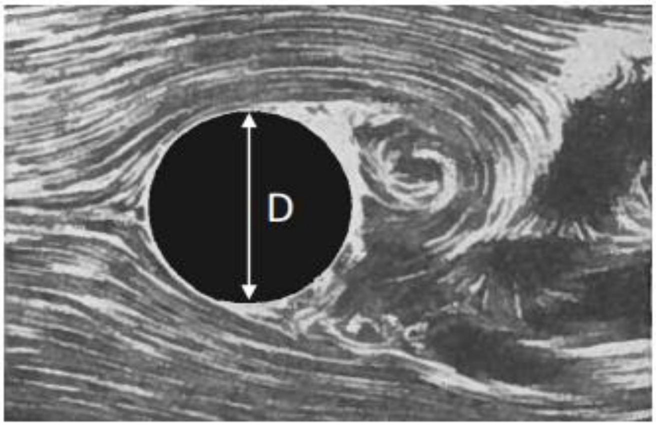

Figure 5-29 Flow around a circular cylinder vortex street

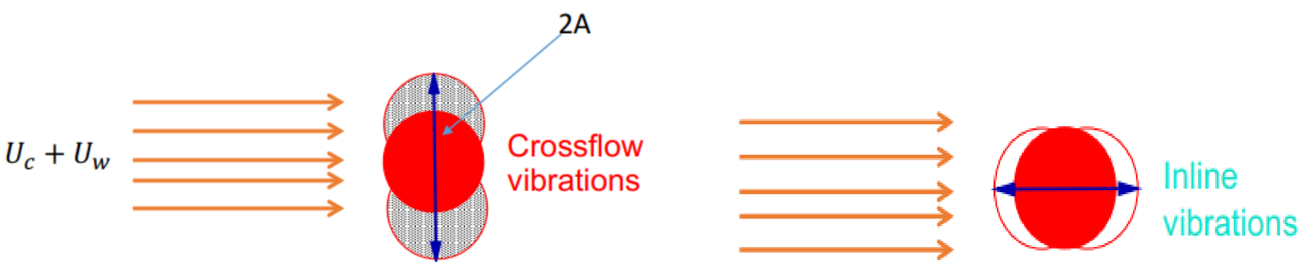

Figure 5-30 Crossflow and Inflow vibrations

Below are the results of cross-flow vortex induced vibrations analysis of the SFC.

Table 5-5 A simple check for cross-flow VIV stress amplification of SFC according to DNV-RP-F105

SFC Parameters	Notation	Values	Units
Outer diameter	OD:	18.00	m
Wall thickness	WT:	0.45	m
Inner diameter	ID:	17.10	m
Density of RCC	ρ_co	2500.00	kg/m^3
Density of water	ρ_w	1025.00	kg/m^3
Youngs modulus	E	270.00	GPa
Kinematic viscosity of water	u	1.00E-06	m^2/s
Moment of inertia	I	955.36	m^4
Bending stiffness	EI	2.58E+14	$Kg.m^3/s^2$
Subsea current speed	U_c	0.25	m/s
Significant Wave height	Hs	3.00	M
Peak period	Tp	5.60	S
Vertical position of structure	z	-30.00	M
Angular frequency	ω_w	1.12	rad/s
Particle velocity from waves	U_w	0.05	m/s
Total particle velocity	U_t	0.30	m/s
Reynolds number	Re	5.40E+06	
Strouhal number	St	0.22	
Length of the segment	L	200.00	m
Self-weight	W	13086.54	kg/m
Eigen frequency of span	w_b	34.60	rad/s
frequency of span	f	5.51	1/s
Reduced Velocity	V_r	0.003	No VIV

The reduced velocity of the SFC in cross flow motion is decided by the highest eigen frequency in a vertical mode. After the analysis it was found that reduced velocity V_R is 0.003 by keeping the length of the segment 200 m and the segment length longer than this also will not cause the cross-flow motion. As it can be seen in Figure 5-31 that for the cross flow to occur reduced velocity should be in the range of 2 to 16 but in this case if the segment length is up to 200m then there will be no cross-flow vertex induced vibrations. So in the nutshell, SFC will not have any significant vortex induced cross flow for the current velocities considered at 50m water depth.

5.6.2 VIV analysis for support structure (Tethers)

For the VIV analysis of the tethers again the design guideline (DNV, 2006) for subsea pipelines is used and checked that if there will be any crossflow motion of the tether, according to given wave and current speed. As the tether relates to the SFC which is placed at 30m water depth and with the bed and it is in vertical position. For the critical situation, it is considering that tether is placed at 50m water depth and checked that it will be vulnerable to VIV or not.

First based on the overall loading, breaking strength of the tether is calculated and based on this tether dimensions are selected using European standard EN 10025. The selected tether is checked weather it will be suitable or not. Below are the results of the Cross-flow vortex induced vibrations analysis of the Tether.

Table 5-6 A simple check for Crossflow VIV stress amplification of Tether according to DNV-RP-F105

Tether Parameters	Notation	Values	Units
Outer diameter	OD:	0.500	m
Wall thickness	WT:	0.046	m
Inner diameter	ID:	0.409	m
Density of steel	ρ_s	7850.000	kg/m^3
Density of water	ρ_w	1025.000	kg/m^3
Youngs modulus	E	210.000	GPa
Kinematic viscosity of water	u	1.00E-06	m^2/s
Outer Area	O_A	0.196	m^2
Inner Area	I_A	0.131	m^2
Total steel area	S_A	0.196	m^2
Self-weight	m_p	1541.298	kg/m
Moment of inertia	I	0.002	m^4
Bending stiffness	EI	3.57E+08	kgm^3/s^2
Length of the free span	L_p	443.500	m
Subsea current speed	U_c	0.250	m/s
Significant Wave height	Hs	3.000	m
Peak period	Tp	5.600	s
Vertical position of structure	z	-50.000	m
Angular frequency of wave	w_w	1.122	rad/s
Deep water wave length	L_0	48.922	m
frequency of wave	f_w	0.179	1/s
Wave number	K_o	0.128	1/m

Tether Parameters	Notation	Values	Units
Particle velocity from waves	U_w	0.042	m/s
Total particle velocity	U_t	0.300	m/s
Reynold Number	Re	1.50E+05	
Eigen angular frequency	w_b	0.024	rad/s
Eigen frequency	f	0.038	1/s
Strouhal number	St.	0.190	
Reduced velocity	V_r	15.782	
Current/total velocity fraction	α	1.042	
Keulegan carpenter number	KC	0.118	
Displacement amplitude VIV	Amp	0.120	m
Buoyancy forces on Tether	m_b	201.252	kg/m
Total mass	m_t	1340.046	kg/m
Distributed load	q_t	13145.852	kg/s^2
Bending moment midspan	M_p	2.620	kN.m
Resisting Moment	W_p	0.007	m^3
Stresses including VIV	σ	0.385	MPa
if <1 then Ok	=M_p/W_p	0.0014	OK

The reduced velocity of the tether in crossflow motion 15.78 which is in the range that can cause the crossflow VIV with amplitude of 0.12m. After calculating the midspan bending moment, resisting moment has been calculated. With the help of that resisting moment total stresses are calculated and checked either they are in allowable limit or not. So, according to the cross section of tether it is found that the stresses are within the allowable range with tether diameter of 0.5m but due to more VIV, it is recommended to optimize the diameter. After this VIV analysis, tether analysis has been carried out using Robot Structural Analysis for the optimization of diameter.

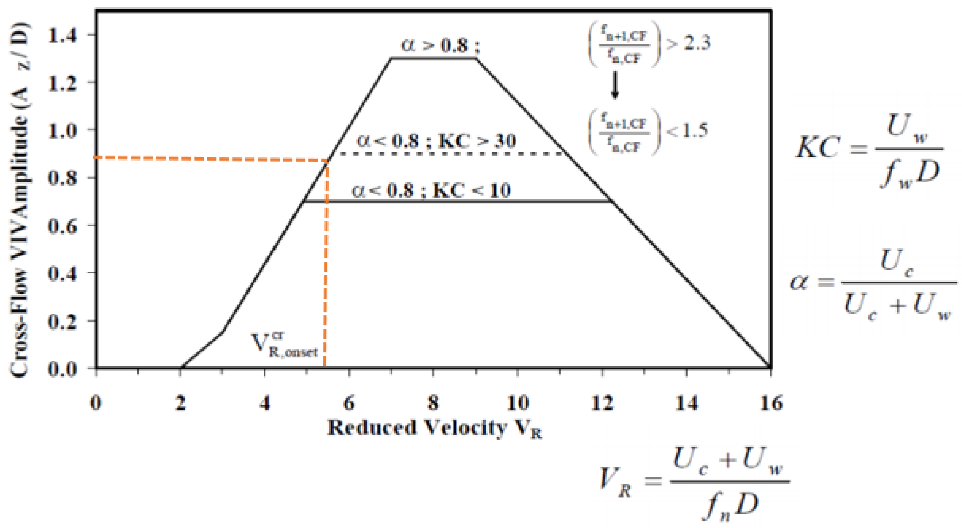

Figure 5-31 Basic cross-flow response model (DNV-RP-F105)

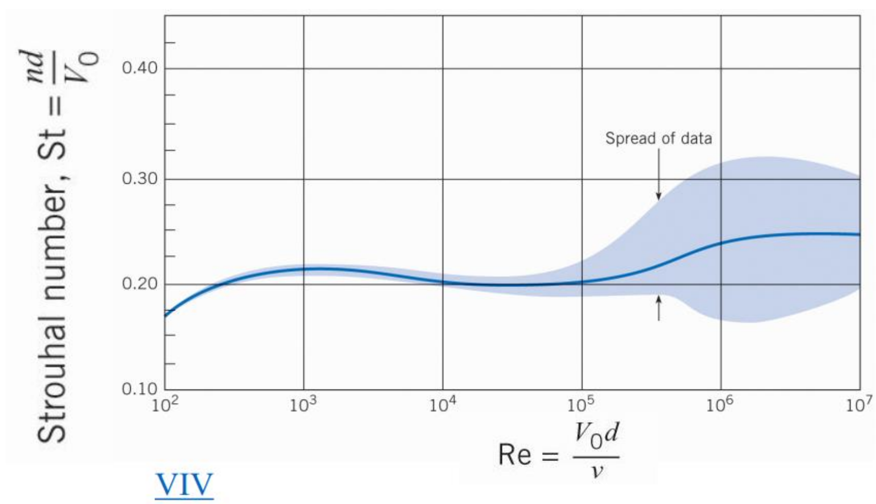

Figure 5-32 Strouhal number as a function of Reynolds number

Robot Analysis resulted in the diameter of 1m. After this selection, that VIV analysis is performed again and the results of analysis are shown in the table below:

Table 5-7 A simple check for Crossflow VIV stress amplification of Tether according to DNV-RP-F105

Tether Parameters	Notation	Values	Units
Outer diameter	OD:	1.067	m
Wall thickness	WT:	0.046	m
Inner diameter	ID:	0.975	m
Density of steel	ρ_s	7850.000	kg/m^3

Tether Parameters	Notation	Values	Units
Density of water	ρ_w	1025.000	kg/m^3
Youngs modulus	E	210.000	GPa
Kinematic viscosity of water	u	1.00E-06	m^2/s
Outer Area	O_A	0.894	m^2
Inner Area	I_A	0.747	m^2
Total steel area	S_A	0.894	m^2
Self-weight	m_p	7016.374	kg/m
Moment of inertia	I	0.019	m^4
Bending stiffness	EI	4.02E+09	kgm^3/s^2
Length of the free span	L_p	443.500	m
Subsea current speed	U_c	0.250	m/s
Significant Wave height	Hs	3.000	m
Peak period	Tp	5.600	s
Vertical position of structure	z	-50.000	m
Angular frequency of wave	w_w	1.122	rad/s
Deep water wave length	L_0	48.922	m
frequency of wave	f_w	0.179	1/s
Wave number	K_o	0.128	1/m
Particle velocity from waves	U_w	0.042	m/s
Total particle velocity	U_t	0.300	m/s
Reynold Number	Re	3.20E+05	
Eigen angular frequency	w_b	0.038	rad/s
Eigen frequency	f	0.060	1/s
Strouhal number	St.	0.190	
Reduced velocity	V_r	5.352	
Current/total velocity fraction	α	1.042	
Keulegan carpenter number	KC	0.252	
Displacement amplitude VIV	Amp	0.960	m
Buoyancy forces on Tether	m_b	916.151	kg/m
Total mass	m_t	6100.223	kg/m
Distributed load	q_t	59843.192	kg/s^2
Bending moment midspan	M_p	236.114	kN.m
Resisting Moment	W_p	0.035904546	m^3
Stresses including VIV	σ	6.576	MPa

Tether Parameters	Notation	Values	Units
if <1 then Ok	=M_p/W_p	0.0239	OK

After performing the VIV analysis and Robust structural analysis 1m diameter tether has been finalized. Six strand wires with core has been selected because of its high available strength and its less expensive than other options. The final design of tethers is presented in Table 5-8;

Table 5-8 Tether design parameters

Parameter	Value
Tether outer diameter	42 inches (1.067 m)
Wall thickness	1.8 inches (0.046 m)
Grade steel	S235
Tether span length	443.5 m

5.6.3 Mitigating Actions to VIV

According to DNV-RP-F105 standard crossflow VIV can be minimized by:

a. Justify the frequencies by change the mass and stiffness
b. Reducing the span length
c. Introducing helical strakes around the Tethers as shown in Figure 5-33

In this study, it is not feasible to change span length and in order to increase the stiffness, radius of tether has to be changed. The change of radius will induce its own consequences like increased self-weight. So the only reasonable option available is to add the helical strakes around the tether to increase riser drag which can limit production in the case of high currents to overcome the crossflow VIV.

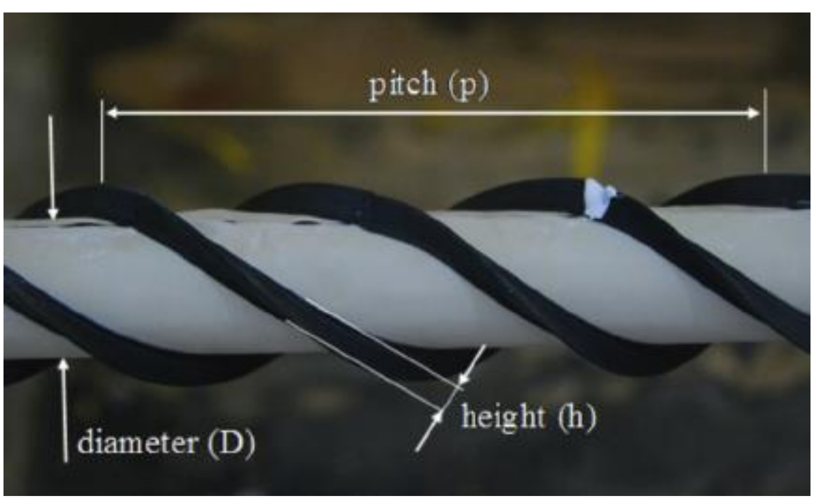

Figure 5-33 Strakes around the tether

6 Construction and Maintenance

6.1 General

The idea of submerged floating crossing depends on understood innovation connected to floating bridges and offshore structures, yet the construction is for the most part like that of immersed tunnels:

- One path is to assemble the tube in segments in a dry dock;
- at that point float these to the construction site and sink them, while fixed;
- and, when the segments are sealed to each other, the seals are broken.

Another methodology employed here is to weld the SFC segments together, and to ensure water tightness. The prefabricated segments in a construction site are loaded out to water and welded with two segments while they afloat on water free surface. To minimize underwater welding a floating structure can be introduced where the welding works are conducted.

The SFT has a total length of 6 km and will be assembled by segments with 200 m. These segments will be developed in a dry dock that dock area must choose such that it will reduce the construction time and production cost. The tethers will be fabricated in a shipyard and can bring the site by using heavy lift transportation vessels. The tethers will be installed after the SFC has been positioned and secured at the installation site.

Fundamental construction contents of SFC can be separated into five sections:

I. Selection of the site
II. Construction of tube segments
III. Transportation and fabrication of tube portions
IV. Weight stability and submerging tests
V. Installation of anchors and construction of foundation

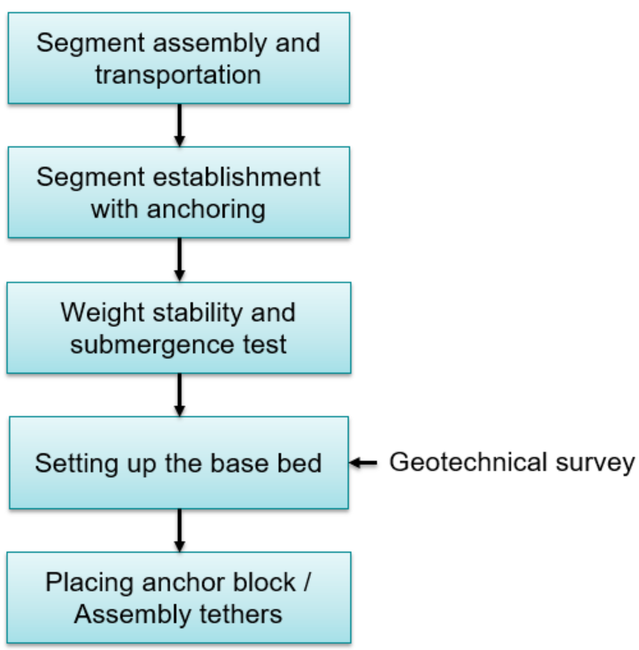

Figure 6-1 Work flow of the SFC construction / installation

6.2 Selection of the site

The site will be selected such that it should be near the fjord and can accommodate:

- Material storages
- Bathing plants
- Prefabrications plants
- Ware houses
- Offices

One of possible options for the construction site is Hanøytangen dock area (See Figure 6-2) which is the nearest dock area to the installation site. Manufacturing the segments will significantly reduce the transportation time and hence does construction cost also. It is known that the dock area is equipped with two dry docks the availability of which depend on the construction schedule and client requirements.

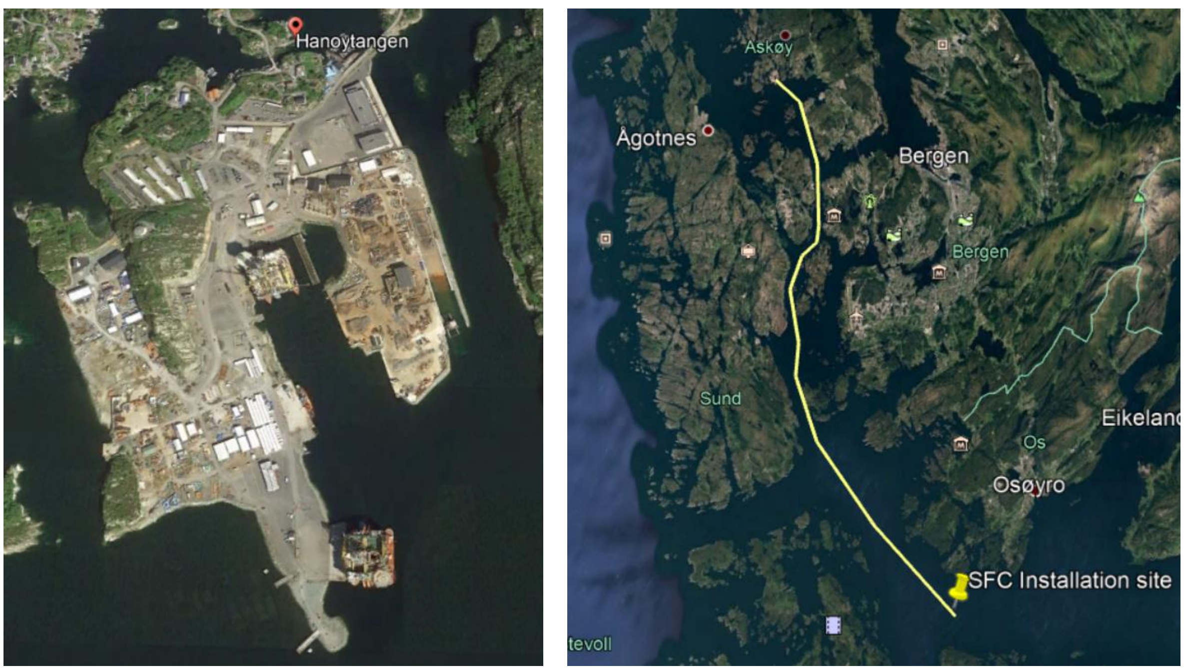

Figure 6-2 An example of construction site, Hanøytangen dock area (left), the transport path to the installation site (right) (Source : Google Earth)

6.3 Construction of tube segments

Each tube segment of SFC, 200m in length of which, is pre-assembled in dry dock. The segment is controlled by the anchor spacing and transport conditions. The inward space of tube portions comprises roadway, escape way, air convection channel, ventilating pipe et cetera. To guarantee the inside space to be impenetrable, a twofold walled area is normally implemented. The confounded cross-section and work conditions prerequisite convey a few challenges to construction:

- The precision of tube manufacture is high. The size of SFC segment must be entirely controlled to address the issues of submerged connection.
- Tube of SFC requires a high-level of water tightness, which is predominantly given by welding quality and the structure material. Entering cracks are not permitted and surface splits ought to be maintained a strategic distance from and controlled however much as could reasonably be expected. So high performance fiber reinforced concrete strongly recommended for lining even though the welding is performed in outer shell. In addition, cracks after welding due to the heat dissipation should be investigated.

6.4 Transportation and establishment of tube portions

There are two sorts of establishment approaches for tube sections: gliding and sinking technique, incremental propelling strategy. gliding and sinking technique is comparative as immersed passage. Incremental propelling strategy implies conveying the tube segments to slanted slide route onshore and utilizing pressure driven jack to drive them into water step by step.

Regardless of what sorts of installation strategies, when the tube portions are set in outline area, it ought to be anchored in a proper way. For gliding and sinking technique, perpetual anchor cables can be introduced specifically. Impermanent anchor cables or floats are likewise used to keep strength. While picking the incremental propelling technique, the tube segments should tie down by anchor cables. In the wake of completing establishment, perpetual anchor cables should apply.

- Although the similitudes amongst SFC and immersed passage, there is a lot of vulnerabilities and dangers in the development of SFC:
- Accurate connection of tube sections is extremely troublesome in submerged condition. It is difficult to control the tube portions in the extreme wave and current condition.
- The tube is in a phase of cantilever amid development. It is so helpless against awful climate, ocean currents, waves, which will cause general shakiness.
- The continuous vibration actuated by environmental activities will disturb the checking and control of SFC arrangement amid construction.

6.5 Weight stability and submergence tests

Weight stability and submergence tests will be performed, and weight and geometry will be monitored though the construction phase. In these stability tests the value of the vertical center of gravity and vertical center of buoyancy will be found out and these will be checked according to the respective standards and drawings.

6.6 Installation of anchors and construction of foundation

Before the design of foundation, the detailed geotechnical investigation will be made and according to steepness and soil conditions of that area, a foundation system will be proposed.

Construction of tether:

Setting up the base bed of the waterway to receive tethers:

Obviously, preceding the plan of the SFC construction, it will be important to complete a point by point program of geotechnical examination and testing to decide the attributes of the base profile. A hard or a delicate base could exhibit exceptional issues.

The base would first be uncovered down to the all-around united ground utilizing airdrops or clamshell dredge(s). At that point along segmented or adjustable pipe would convey pulverized stone or extensive rock in a matrix example to frame a steady layer. This layer would be smoothed to a moderate level surface utilizing a remotely controlled grading gadget. This unit would be brought down to the base and would smooth the rock to a coveted plane and height. CCTV would archive the consequence of the treatment, and sonic area and height transmitters would record correct vertical and even position of the evaluating edge ceaselessly continuously.

Placing of concrete anchor block and assembly of the tether:

After preparing the bed for connecting the tether concrete anchor blocks will be constructed and assembly of the tether will be fabricated as shown in Figure 4-6.

6.7 Operation and maintenance

The width of the SFC tube gives space to two traffic lanes. Be that as it may, just a single lane will be utilized for conventional movement at once. The extra lane gives space to emergency stops and a protected brief working spot for tunnel inspection, support and repair. In the upper part of the SFC tube, there will a space for boards, ducts, pipes, fans, cables etc. Permanent facilities for the repair and maintenance work is proposed to locate at the diagonal of the tunnel. Apart from the internal inspection, external inspection will also be done with help of remotely operated under water vehicles and divers.

From the purpose of monitoring and operating the SFC itself and its utilities, the SFC will also be equipped with the mechanical instrumentation systems:

- Traffic control system
- Ventilation
- Ballast system
- Corrosion protecting system
- Firefighting system

7 Outcomes of the study

7.1 Findings of the Study

Major hazardous events for the Submerged Floating Crossing (SFC) structure were identified throughout risk analysis by using Preliminary Hazard Assessment (PHA) and Fault Tree Analysis (FTA). The identified events include flooding, external damage due to marine collision and loss of support structure. Preliminary design of the structure was carried out considering the afore-mentioned hazards.

Loads on the SFC were calculated for a positively buoyant structure. The major loads the contribution of which is from hydrostatic pressure, self-weight of the SFC, traffic load and wave and current loads. Details of these loads have been mentioned from Table 4-4 to Table 4-7. Considering the ship traffic in the fjord and wave and current loads, the SFC is placed at 30 m below the water surface.

Based on the identified hazards and load calculations, two structural models (1D and 3D) and one Vortex Induced Vibration (VIV) model were established. To get a better understanding, for instance the purpose of verification, of the 3D model results, a 1D model is used to compare its results to those of the 3D model. The technical viability of the selected geometrical configuration of the SFC was checked through these structural analysis models. VIV analysis added was done to check the additional forces on SFC and to finalize the design of tethers.

Two 3D models were established using ROBOT Structural Analysis. One model represents a 200m segment of the crossing and it is used to assess the impact of loss of support. The second model is used to check the impact of marine collision on structure.

Four different support loss scenarios are considered in the model and a vertical displacement and rotation of the structure are calculated and compared with the allowable limits defined in Table 1-1.

- WCS I: In the case of loss of two tether (one on either side of SFC), vertical displacement in the structure goes up to 192mm which is within the allowable limits, however if two tethers on both sides of the structure are removed then deflection goes to 208mm. These displacements are within allowable limits hence this criterion may not be considered as the governing failure, so rotations have to be checked. With the loss of one tether on one side the rotation in the structure goes up to 0.001rad however, if two tethers are removed from one side then the deflection goes up to 0.006 rad. However, in the scenario of loss of two tethers on both sides of the SFC the angular deformation goes to 0.023 radian, which is higher than the allowable limit of 0.015 radian. These results have been compared to 1D analysis results and a comparison is presented in Table 5-2.
- WCS II: For the evaluation of second identified worst scenario, marine collision, another 3D model is made and collision load of 65MN is applied on indentation area of 2.25m^2. Model shows a total indentation of 1358mm, however 1D analysis results show an indentation of 560mm. These both values demonstrate clear failure of the structure.
- WCS III : For third worst case scenario, the amount of possible sources of drainage have been calculated and the drain system is suggested as a safeguard. The permissible drainage is considered to be as 0.1 m^3/min. A drainage system has been designed to cater the disposal of leakage water issue along with the disposal of water for fire safety hazard. The capacity of

the pumping system is 120 m^3/hr in the worst case scenario of maximum allowable leakage and fire hazard occurring at the same time.

A VIV model has been made to check the additional forces on SFC and tethers. The analysis for SFC gives a reduced velocity of 0.003 which cannot generate VIV in the structure. For the design of tethers, initially a tether diameter of 0.5m was selected and verified by 3D model results. The VIV analysis for this diameter tether give a reduced velocity of 15.78. This reduced velocity is capable of putting the tether in vibrations and endangering the structure. Therefore, to compensate this effect, diameter of the tether has been increased to 1m. The VIV analysis of this selected tether also shows effects for vibrations but these effects can be reduced by applying strakes around the tethers.

Construction and maintenance have been reviewed by comparison with those of immersed tunnels. The distinguished aspects have been identified, which are welding connections and refining the position where individual SFC segments are settled on the water.

7.2 Discussions

The objective of this study was to propose a feasible option for design of unsinkable submerged floating crossing. There are a number of assumptions which are made for simplification in realizations of actual SFC behaviors. In addition, it is inevitable to assume the model used in the feasibility study with a variety of uncertainties.

The followings are discussions in the study, where uncertainties might have dominated:

- High speed variable loads, e.g. variable traffic load, could not be taken into account due to the difficulty in defining that random load.
- A traffic of submarine could not be investigated due to the confidentiality of the information.
- Allowable limits of the cross-section deformation require profound research to be conducted: the response of the steel-concrete structure on the submarine hitting it is not fully clear.
- Accidental leakage by external damage have not been investigated due to the complexity in mechanism during the dissipation of the collision energy from the outside of the SFC.
- Regarding developments of joint and connection parts, it is required to take utmost care because these parts were identified to be vulnerable to fatigue leading to cracks escalating accidental leakage.

7.3 Conclusion

The SFC can be made unsinkable by keeping the deflections, leakage and other hazardous events in permissible limits. Based on the analysis, the SFC is technically feasible option for the waterway crossing at Bjørnafjorden. A comparison of worst case scenarios, analysis results and conclusion on these is presented in Table 7-1.

Table 7-1 Conclusion of Analysis for Worst Case Scenarios

Worst Case Scenario	Analysis Results	Recommendation
WCS-I :A loss of support structure	• In case of one tether loss on one side rotation of structure is within permissible limit (0.001<0.015) • For the loss of two tethers, rotation exceeds the acceptable rotation limit (0.006>0.015) • For tether loss, one on either side deflection and rotation are within acceptable limit • For tether loss, two on either side deflection is within acceptable limit but rotation exceeds the allowable limit (0.023>0.015)	SFC is feasible if only one tether fails at one time.
WCS-II External collision	Ship grounding or submarine collisions shows an indenting of 1.39m from 3D model and 0.59m from 1D model.	Profound research is needed
WCS-III Flooding	Accidental leakage, accumulation of drainage up to 120m^3/h	A drainage system has been designed to avoid the failure by the leakage. An in-depth needs to be performed for external damage

To conclude, submerged floating crossing considered in this study has demonstrated significant sustainability based on provided assumptions. Some major uncertainties were faced throughout the study as stated above, but these are manageable by means of modern technologies in civil engineering or some organizational arrangements. For instance, submarine collision is seen as the biggest threat and limiting submarine operations in the area would have improved SFC's safety (this measure is extensively used on offshore wind farm development: marine operations are majorly downsized in the areas of existing offshore wind farms). On the other hand, it is possible to equip SFC with SONAR technology which transmits the signals to the submarine within the vicinity. Thus, it is concluded that the submerged floating crossing is a feasible solution.

7.4 Future works

The preliminary design has been carried out mainly focusing on hydraulic and safety issues. It can be refined with by conducting a complete structural design and including other hazardous events like blast, fire etc. The safety measures of the tunnel are of utmost important and the design of protection measures should be carried out in detailed design stages.

Based on preliminary design in this report, a further detailed study or investigation can be required with regards to:

- Safety Assessment for fire/explosion
- Emergency Preparedness
- Joint Design / Land Connection
- Transport and installation
- Recoverability and maintenance
- Environmental Impact Assessment
- Welding analysis

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9 Appendices

Appendix A. Questionnaire on risk perception of a new type of waterway crossing

Dear Sir / Madam,

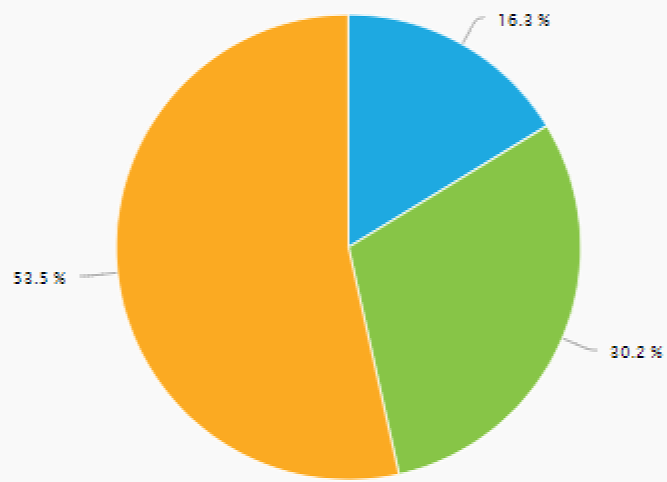
Could you please help us by answering this survey? It takes less than 3 minutes to answer.

A submerged floating tunnel/crossing is a new mode of transport. It floats in water about 30m below the surface, connected to short landfall tunnels at either side and supported by its buoyancy and tethers at the sea bed. It is proposed to be constructed in Norwegian Fjord where water depth is around 482m.

The dynamic behaviour of the structure is the major contribution in the fact that something like this has not been constructed so far anywhere in the world.

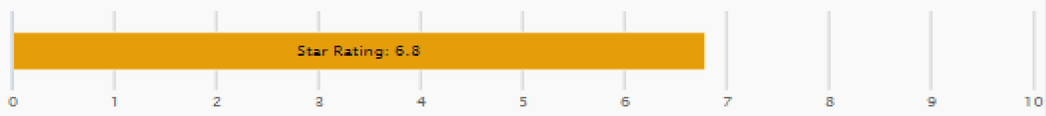
Total respondent = 43

1 Which type of waterway crossing would you prefer to cross 5km long fjord?



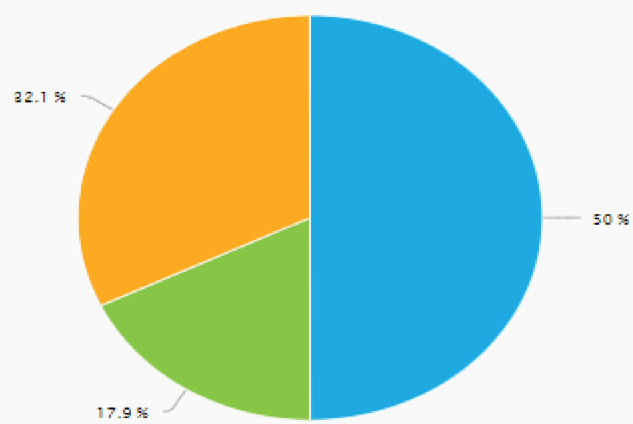
#	Answer Choices	Responses	Ratio
●	A. Detour Road connection	7	16.3 %
●	B. Ferry connection	13	30.2 %
●	C. Submerged Floating Crossing	23	53.5 %

2 On a scale of 1 to 10, would you be willing to travel through this tunnel on regular basis?



Answer Choices	Responses	Ratio
1 / 10	0	0 %
10 / 10	5	11.6 %
2 / 10	2	4.7 %
3 / 10	1	2.3 %
4 / 10	3	7.0 %
5 / 10	8	18.6 %
6 / 10	4	9.3 %
7 / 10	6	14.0 %
8 / 10	10	23.3 %
9 / 10	4	9.3 %

3 If the answer of Q2 is between 1 to 5, then what's the reason behind it?

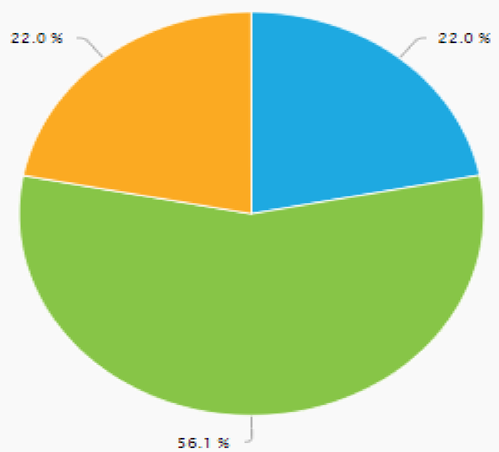


#	Answer Choices	Responses	Ratio
●	A. Scare of Collapse/Flooding	14	50 %
●	B. Scare of enclosed space	5	17.9 %
●	C. Other...	9	32.1 %

C. Other...:

I would travel through this tunnel , if there were a possiblity to see the deep sea while traveling.	scared of flooding and enclosed space	That's fantastic	its 6 to 10
		6-10 (4x)	1-6

4 If the answer of Q2 is between 6 to 10, then what's the reason behind it?

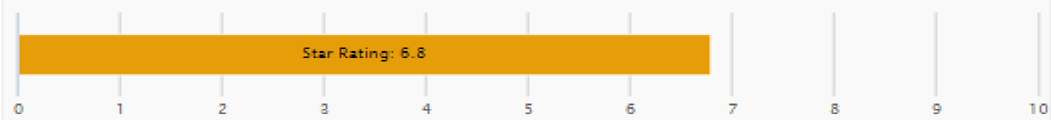


#	Answer Choices	Responses	Ratio
●	A. Adventure	9	22.0 %
●	B. Reduced Travel Time	23	56.1 %
●	C. Other...	9	22.0 %

C. Other...:

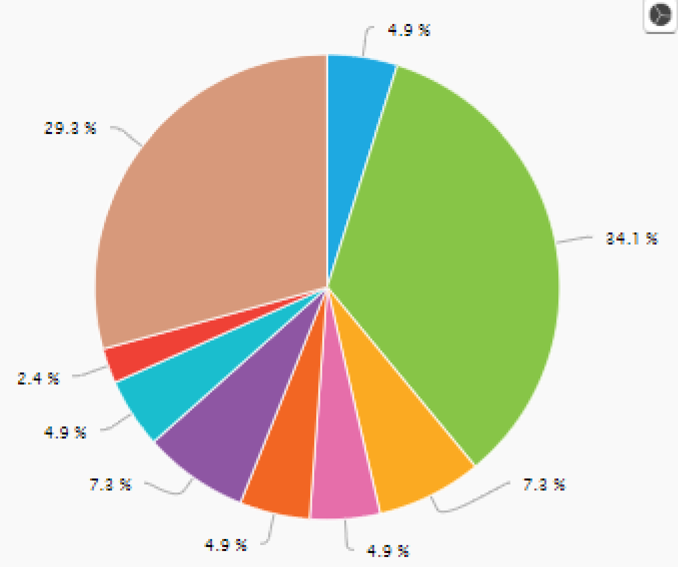
I think it's a good start for use technologies to building cities under water.	1-5 (6x)	5 (2x)

5 On a scale of 1 to 10, how much environmental friendly is this tunnel compared to other transport modes like ferry, land highway etc.?



Answer Choices	Responses	Ratio
1 / 10	0	0 %
10 / 10	3	7.0 %
2 / 10	1	2.3 %
3 / 10	2	4.7 %
4 / 10	2	4.7 %
5 / 10	5	11.6 %
6 / 10	6	14.0 %
7 / 10	9	20.9 %
8 / 10	12	27.9 %
9 / 10	3	7.0 %

6 What is your faculty?



#	Answer Choices	Responses	Ratio
	Faculty of Architecture and the Built Environment	2	4.9 %
	Faculty of Civil Engineering and Geosciences	14	34.1 %
	Faculty of Electrical Engineering, Mathematics and Computer Science	3	7.3 %
	Faculty of Industrial Design Engineering	2	4.9 %
	Faculty of Aerospace Engineering	2	4.9 %
	Faculty of Technology, Policy and Management	3	7.3 %
	Faculty of Applied Sciences	2	4.9 %
	Mechanical, Maritime and Materials Engineering (3mE)	1	2.4 %
	Other...	12	29.3 %

management and regulation of water resources	Public Relations	Water and waste	medicine
	Waiter	NTNU	UTM (2x)
IHE	UPM	IT	UM

Appendix B. Preliminary Hazard Analysis

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
1	Sudden change of light	Traffic accident	Blurred vision, Panic	3	3	6	Enhance with more natural light and natural colour	Minor to major damage to the structure	Hokstad et al 2012
2.1	Terrorism	Explosion	Bomb	1	5	6	CTV surveillance, emergency shelter room	Fatalities, total collapse	
2.2		collapse/ leakage	Explosion / fire	1	5	6			
3.1	Human error	Traffic accident	Speeding, not paying attention, driving too fast or too slow, impatience	3	3	6	Queue alert, speed camera, controls, submersible center dividers	Minor to major damage to the structure	
3.2		Inaccurate alignment and dimension	Motion of joint after grouting and before proper pre-stressing	4	2	6	Design review, Construction quality management	Minot to major damage to the structure	
4.1	Many vehicle at same time	Traffic accident	Inattentive driving, falling asleep in front of the wheel, driving too fast or too slow, opposite lane	4	3	7	submersible center dividers, queue alert, speed camera, controls, climbing lane, ITV surveillance, emergency shelter room, changeable signs.	Injuries and fatalities, Minor to major damage to the structure	
4.2		Fire	Traffic accident	4	4	8		Severe damage to the structure	

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
4.3		Explosion	Traffic accident	3	5	8		Partial to total collapse of the structure	
4.4		collapse/ leakage	Fire/ Explosion	1	4	5		total structure failure	
5.1	Heavy vehicles	Traffic accident	driving too fast/slow, inattentive driving	4	2	6	submersible center dividers, require more frequent controls of trailers, speed camera, controls, climbing lane, ITV surveillance, emergency shelter room, changeable signs.	Injuries and fatalities, Minor to major damage to the structure	
5.2		Fire	Brakes (downhill) and motor (uphill) overheats, trailers that do not meet EU requirements, traffic accident, leakage of flammable liquid	3	4	7		Injuries and fatalities, Partial to total collapse of the structure	
5.3		Explosion	Traffic accident, fire	2	5	7		Fatalities, Partial to total collapse of the structure	
6.1	Leakage from cargo	Fire	Traffic accident, technical failure vehicle	2	4	6	More frequent controls of trailers, emergency shelter room	Injuries and fatalities, Partial to total collapse of the structure	
6.2		Explosion	Traffic accident, technical failure vehicle	2	5	7		Injuries and fatalities, Partial to total collapse of the structure	

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
7.1	Passing vessel	Sinking /Grounding	Loss of power and flooding within the vessel	1	5	6	Monitoring the ship working safety requirements in the area, lower speed limit for ship, VTS coverage in the area	Injuries and fatalities, Partial to total collapse of the structure	Gamborg Hansen et al, 2012a and Gamborg Hansen et al, 2012b
7.2		Ship collision - damage to the structure (tube and/or supporting system)	ship drift-off / drive-off damaging tube and tethers supporting system	3	5	8			
7.3		Drop object / Anchor dragging	Mal-operation of anchoring / Mishap	1	5	6			
8.1	Submarine	Submarine collision damage to the structure (tube and/or supporting system)	Sailing too fast, poorly marked, intense tether lines	3	5	8	ITV surveillance, describing signs, keeping nautical chart updated, lower the speed limit for submarines in the area, minimize the military submarine activities in the area, and VTC coverage in the area	Injuries and Fatalities, partial to major damage to the structure	
8.2		destruction of Tether line	direct hit by submarine	2	5	7			Educated guess
9	Closed Space	Traffic accident	Driver gets panic, Claustrophobia	3	3	6	Natural light, establishing a non claustrophic environment	Injuries and Fatalities, partial to major damage to the structure	Hokstad et al 2012

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
10	Marine growth	Damage to the structure (Collapse/ leakage)	Structure being submerged	3	2	5	Regular maintenance and control, antifouling cladding, polymer coating	Severe damage to the structure	Educated guess
11	Corrosion and carbonization	Damage to the structure (Collapse/ leakage)		3	3	6	Regular maintenance and control, cathodic protection, corrosion inhibitors	Severe damage to the structure	Educated guess
12.1	Steep incline	Traffic accident	Driving too fast/slow, bad brakes, undersized brakes and engines, inattentive, technical breakdowns	5	3	8	Making the inclination as flat as possible, require more frequent controls of trailers and cars, ITV surveillance, emergency shelter rooms	Injuries and fatalities, Minor to major damage to the structure	Hokstad et al 2012
12.2		Fire	Brakes (downhill) and motor (uphill) overheats, traffic accident	3	3	6		Injuries and Fatalities, partial to major damage to the structure	
12.3		Explosion	Traffic accident, fire	1	5	6			
12.4		Collapse/leakage	Fire, explosion	1	3	4			
13	Obstruct-ion in the road	Traffic accident	react too slow, inattentive	4	3	7	More frequent controls of the road, climbing lanes, meetings points	Injuries and fatalities, Minor to major damage to the structure	

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
14	Water ingress	Accumulation of drainage, Flooding	Water brought by cars, water cargo accident, damage of joints, or crack in the tunnel's tube	3	5	8	Providing monitoring instrument for possible water influx and redundant bilge and ballast systems of adequate capacity to dewater the tunnel and to stop influx of water from outside. penetration of water at joints etc to be sealed by epoxy injection. Moreover, the tunnel is designed to survive partial water filling.	Minor to major damage to the structure	
15.1	SFC structure instability	Loss of support structure	Fatigue induced by repeated movement, external collision	4	3	7	Safety measures against fatigue and VIV	Excessive angular displacement. Minor to major damage to the structure	
15.2		Grounding of structure element during construction	Mal-operation of heavy lift vessel, loss of stability of buoyant structure elements	2	4	6	Reducing transit speed, Installation analysis	Injuries and fatalities, Major loss of asset or reputation	
16.1	Current /swells	Traffic accident	Structure flatulates, people get scared/ panicked	2	3	5	Solid anchorage that can withstand the swell and current	Injuries and fatalities, Minor to major damage to the structure	Based on LMG Marin (2012)

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
16.2	from ocean	collapse/ leakage	Structure flatulates	2	4	6		Injuries and Fatalities, partial to major damage to the structure	
17	Acceleration/ Deformat-ion	Traffic accident	current, swell, waves	2	3	5	Solid structure that can withstand deformation	Injuries and fatalities, Minor to major damage to the structure	
18.1	Underwat-er Landslide	Traffic accident	Structure flatulates, people get scared/ panicked	2	3	5	Solid structure that can withstand deformation	Injuries and Fatalities, partial to major damage to the structure	
18.2		collapse/ leakage	Structure flatulate	1	4	5		Severe damage to the structure	
19.1	Land connection failure	Disconnection of tunnel tube from landslide/ damage of supporting system	Earthquake	1	5	6	Solid structure that can withstand deformation	Injuries and Fatalities, partial to major damage to the structure	
19.2			Landslide	1	5	6			
20	Loss of oxygen	Asphyxia	Failure of ventilation system leading to reduction of oxygen accumulation	1	5	6	Redundant system design for ventilation system. In-depth analysis for ventilation capacity	Injuries and fatalities	

No	Hazard	Hazardous event	Cause	Risk			Risk Reducing measures (Barriers)	Consequences (worst case scenario)	Reference
				Freq	Con	RPN			
21.1	Utilities/ / System failures	Bilge/Ballast system failure	Loss of power	2	2	4	Redundant bilge pumps, Redundant power supply, In-depth failure mode and effect analysis	Accumulation of drainage, accidental flooding in case of exceedance of serviceable limit	
21.2		Winch and cable system failure	Breakage, Loss of power source (electric or hydraulic)	2	2	4	Reserve power source supply (Accumulator, emergency power supply)	Delayed construction / operation which might occur cost overrun	
21.3		Tug failure	Mal-operation, loss of power of tugs, Bad weather	3	2	5	Redundant power supply for tugs, Multiple number of tug operations, Acquisition of reliable environmental data	Delayed construction / operation which might occur cost overrun	

* RPN = risk priority number

Figure B1: Risk matrix for submerged floating tunnel crossing

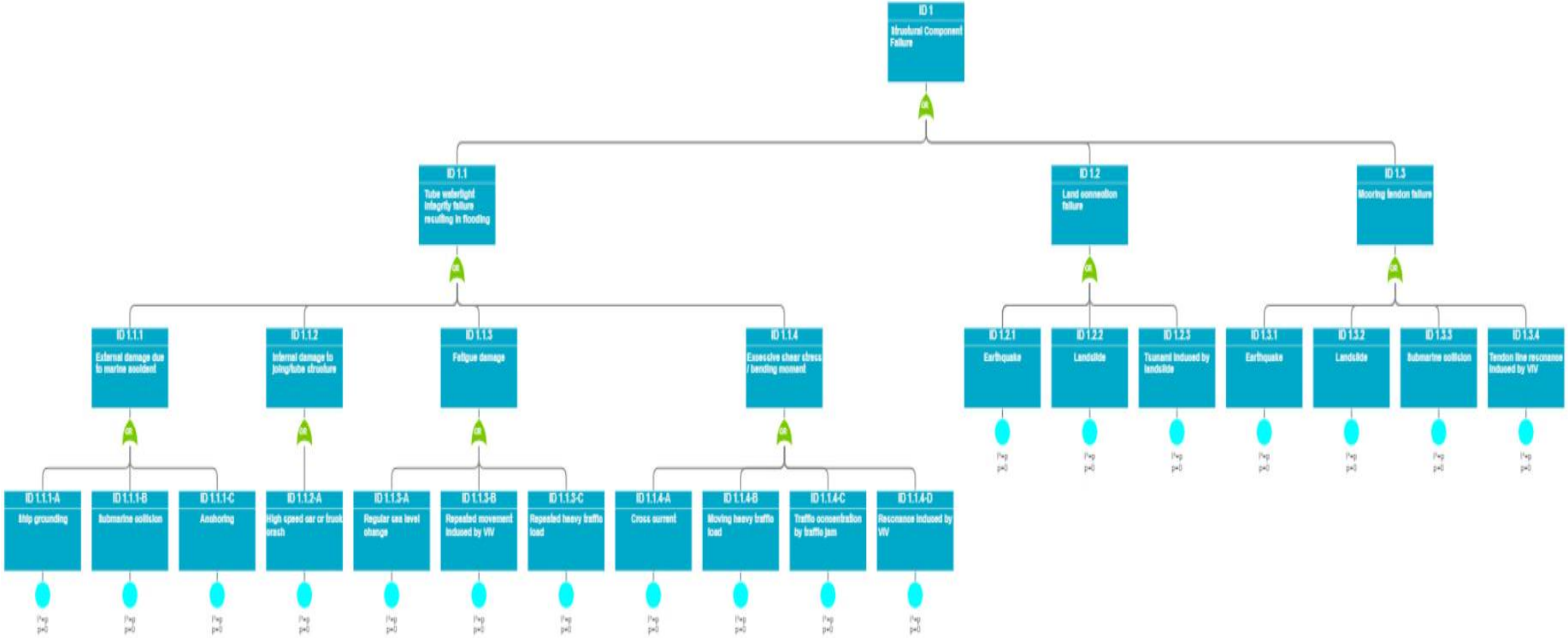
Frequency/consequence	1: Extremely rare	2: very rare	3. Seldom	4.Frequent	5. very frequent
5: Total collapse, over 20 months downtime	2.1, 2.2, 7.1, 7.3, 12.3, 19.1, 19.2, 20	5.3, 6.2, 8.2	4.3, 7.2, 8.1, 14		
4: Partial collapse, 5-20 months downtime	4.4, 18.2	6.1, 15.2, 16.2	5.2,	4.2	
3: Severe Damage 1-4 months unavailability	12.4	16.1, 17, 18.1	1, 3.1, 9, 11, 12.2	4.1, 13, 15.1	12.1
2: Major Damage		21.1, 21.2	10, 21.3	3.2, 5.1	
1: Minor damage					

1: Rarer than once every 1000 years

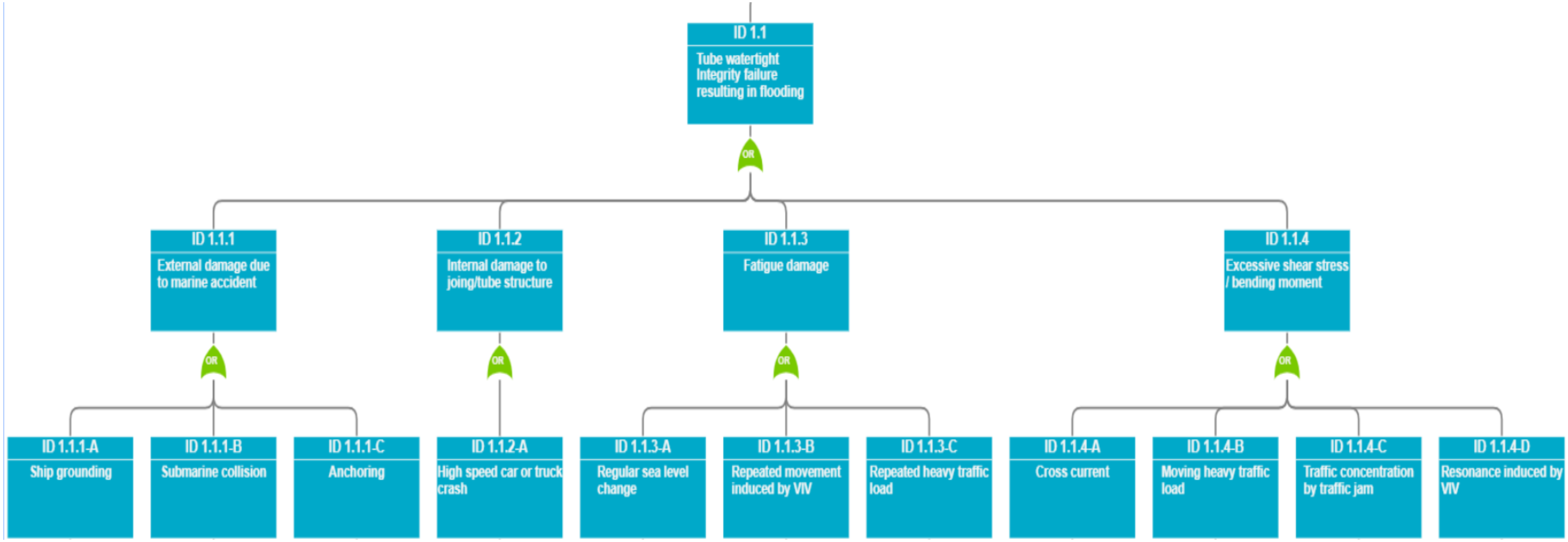
2: very rare: Once every 101-1000 years
3: Seldom: Once every 11- 100 years
4: Frequent: Once every 2-10 years
5: very frequent: At least once every 2 years

Appendix C. Fault Tree Analysis

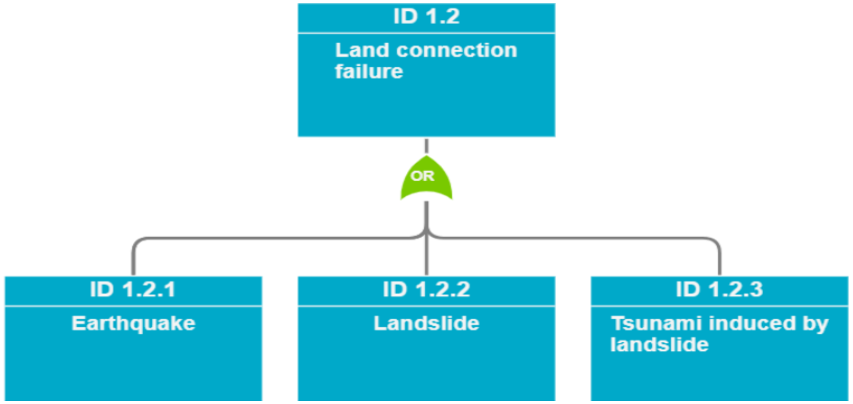
<Below ID 1 : Structural component failure>



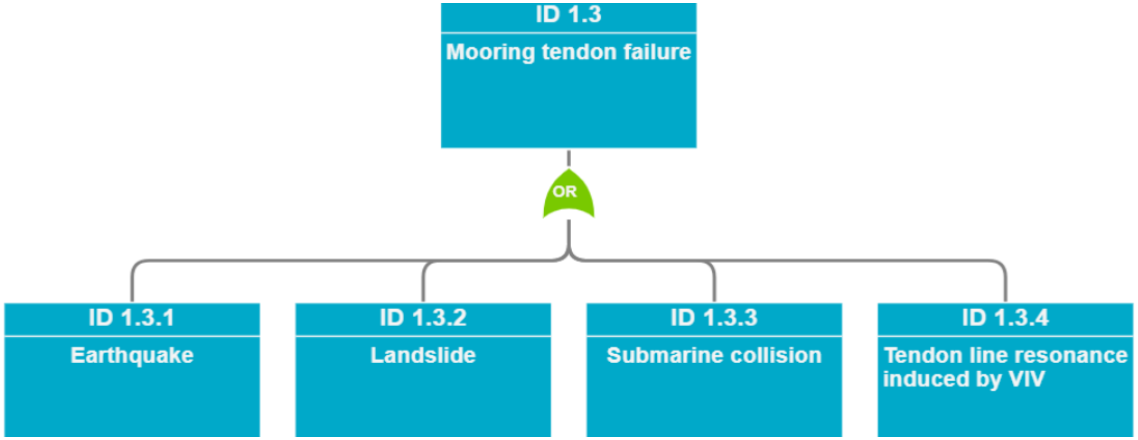
<Below ID 1.1 : Structural component failure-Tube watertight integrity failure>



<Below ID 1.2 : Structural component failure-Land connection failure>



<Below ID 1.3 : Structural component failure-Mooring tendon failure>



Appendix D. Ship Traffic Data on Bjørnafjord (Source : Kystverket, 2018)

Fartøy_Navn	Antall Passeringer	MMSI	IMO	Statcode5	Fartøy Type	Skipstype Lloyd	Lengde _loa	Skipsdybde	Dypgang Draught	Gross-tonnasje	Passasjer-kapasitet
Normand Ferking	24	258153000	9361770	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	90	9.6	8	7934	32
Falksund	30	258062000	8420725	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	75	5.69	3.66	1297	-
Oystrand	24	258487000	9772448	B12B2FC	Andre servicefartøy	Fish Carrier	85	7.6	6.6	3401	-
Ro Server	27	258534000	9773260	B12B2FC	Andre servicefartøy	Fish Carrier	82	8	6.87	3579	-
Skandi Hera	15	257411000	9424730	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	94	10	8	6838	68
Scan Fjord	30	314318000	8015879	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	95	9.22	5.125	2876	-
Brennholm	13	259454000	9268655	B11B2FV	Fiskefartøy	Fishing Vessel	75	8.97	7.06	2666	-
Nordvaag	22	220000000	7704849	A31B2GP	Stykkgods/roro-skip	Palletised Cargo Ship	88	9.43	5.2	2854	-
Oysund	113	257262000	9652129	B12B2FC	Andre servicefartøy	Fish Carrier	70	5.9	5.3	1718	-
Norbar	39	257152000	9115901	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	5.67	4.45	1685	-
Hamaroey	5	257362500	9056313	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	84	4.5	4.1	3695	399
Pirholm	31	259998000	9030515	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	75	5.5	4.352	1540	-
Bona Sea	35	258041000	8602012	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	74	5.72	3.602	1525	-
Seihav	97	259076000	9773600	B12B2FC	Andre servicefartøy	Fish Carrier	79	8	7.29	4048	-
Hoeydal	36	257725000	9596791	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	70	9.8	6.23	2692	-
Nordkinn	35	231711000	9333644	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	80	6.1	5.95	2990	-
Rana Express	48	258598000	9210048	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	87	7.1	5.52	2532	-
Rem Hrist	5	259778000	9521655	B21A2OS	Offshore supply skip	Platform Supply Ship	88	8	6.6	4157	-
Tifjord	8	257114000	9190353	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	95	7.15	6.19	2999	-
Troms Arcturus	2	257131000	9694000	B21A2OS	Offshore supply skip	Platform Supply Ship	95	8.5	7.031	4969	-
Klevstrand	55	219128000	7034969	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	72	5.85	3.023	1194	-
Sula	16	257115000	9006306	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	87	7.103	5.48	2449	-
Hagland Saga	9	258809000	9238404	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.15	5.69	2999	-
Wilson Ems	4	314258000	9117117	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	73	5.75	4.05	989	-
Falkbris	9	248216000	9006291	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.103	5.468	2449	-
Edda Flora	8	258245000	9386380	B31A2SR	Andre servicefartøy	Research Survey Vessel	95	9.8	8	6074	-
Karmsund	34	219023116	7724203	A31B2GP	Stykkgods/roro-skip	Palletised Cargo Ship	90	9.5	4.571	2728	-
Bergfjord	23	246483000	9166455	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.65	5.6	2451	-
Bergen Star	118	258310000	9321603	A13B2TP	Oljetankskip	Products Tanker	90	8.05	6.17	3618	-
M Ytterstad	3	257685800	9683972	B11B2FV	Fiskefartøy	Fishing Vessel	75	9	8.125	2906	-
Froan	16	376317000	8505941	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.12	5.49	2367	-
With Harvest	58	257586000	9692117	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	70	9.5	6.6	3450	-
Olympic Zeus	10	258060000	9424728	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	94	10	8	6838	-
Bergen Viking	109	257684000	9285213	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	95	7.7	5.91	3960	-
Ronia Diamond	15	257269000	9814947	B12B2FC	Andre servicefartøy	Fish Carrier	80	8.6	Ukjent	4632	-
Amalie	90	219016713	9163702	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	5.3	3.7	1624	-
Trans Fjell	17	248886000	9329306	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	88	8.1	6	3049	-
Falkland	9	258725000	8505953	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.12	5.488	2367	-
Tinto	16	258879000	7369168	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	6.51	4.22	1739	-
Heroey	4	259432000	9151591	B11B2FV	Fiskefartøy	Fishing Vessel	73	8	Ukjent	1914	-
Oytind	82	258053000	9743801	B12B2FC	Andre servicefartøy	Fish Carrier	70	5.9	5.306	1747	-
Cyprus Cement	13	244110544	9037173	A24A2BT	Bulkskip	Cement Carrier	97	8.35	7.1	4069	-
Skandi Iceman	6	258738000	9660073	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	93	9.8	6.5	8269	-
Kirsti H	32	257009000	9807932	B12B2FC	Andre servicefartøy	Fish Carrier	70	5.9	5.42	1828	-
Kings Bay	1	258654000	9617985	B11B2FV	Fiskefartøy	Fishing Vessel	77	Ukjent	7.5	4027	-
Siem Opal	7	259704000	9442419	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	91	9.6	7.95	7473	-
Silver River	30	231104000	9359650	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	83	12.1	6	3538	-
Far Sigma	10	259827000	9659062	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	87	9.3	7.78	6170	-
Hav Atlantic	22	231522000	9129122	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.2	5.69	2820	-
Normand Drott	7	257468000	9447964	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	95	9.8	7.8	8053	70
Wilson Goole	1	249359000	9126687	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.094	5.51	2446	-
Hagland Borg	13	258709000	9173563	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.498	2456	-
Sletringen	15	375258000	9052666	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	6.2	4.5	1598	-
Olympic Pegasus	6	257174000	9257929	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	82	9.5	7.5	4477	-
Wilson Ruhr	9	314218000	9145542	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	78	5.75	4.35	1169	-
Nica	5	304563000	9272670	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	8.4	6.65	4450	-
Marus	8	305707000	9110559	A33A2CC	Konteinerskip	Container Ship (Fully Cellular)	99	6.4	4.9	2906	-
Carten Maria	35	314319000	8405878	A31B2GP	Stykkgods/roro-skip	Palletised Cargo Ship	85	10.22	5.85	3176	-
Heroyhav	2	258991000	9657210	B11B2FV	Fiskefartøy	Fishing Vessel	70	9.2	7.5	2293	-
Frakt Sund	5	210803000	9374727	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.85	6.21	2967	-
Nystein	56	258824000	9137284	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	83	6.1	4.798	1864	-
Kv Bergen	34	257492000	9389368	B34H2SQ	Andre servicefartøy	Patrol Vessel	92	8.6	6.5	4025	-
Lady Nola	1	244150000	9243863	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	80	6.45	4	1978	-
Green Atlantic	9	325350000	8320585	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	94	6.82	5.952	3402	-
Norholm	20	258656000	9107136	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	94	8	6.274	3443	-
Hagland Bona	21	258295000	9132038	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.5	2456	-
Kristian With	20	259983000	9375898	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.1	5.54	2638	-
Key North	5	236669000	9020417	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	90	7.48	6.147	2634	-
Bona Safir	41	257614000	9030228	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	5.223	4.12	1576	-
Falknes	40	671135000	7053264	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	73	5.69	4.633	1276	-
Svartfoss	26	304882000	9323089	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	80	6.1	5.95	2990	-
Vitin	20	231114000	9006289	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.468	2449	-

Fartøy_Navn	Antall Passeringer	MMSI	IMO	Statcode5	Fartøy Type	Skipstype Lloyd	Lengde _loa	Skipsdybde	Dypgang Draught	Gross-tonnasje	Passasjer-kapasitet
Framfjord	27	341392000	8913473	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	80	5.5	4.3	1508	-
Silver Lake	33	231103000	9359648	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	82	12.1	6.1	3538	-
Titran	14	259255000	9100188	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.15	6.095	2744	-
North Barents	11	258613000	9742766	B21A2OS	Offshore supply skip	Platform Supply Ship	92	8.5	6.95	4508	-
Havila Charisma	5	257419000	9631890	B21A2OS	Offshore supply skip	Platform Supply Ship	95	8	6.57	4327	-
Havstaal	2	257001650	9429728	B11B2FV	Fiskefartøy	Fishing Vessel	71	8.45	7.8	2943	-
Optimar	19	375088000	8300262	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	6.76	4.67	1939	-
Skandi Marstein	6	259357000	9122978	B21A2OS	Offshore supply skip	Platform Supply Ship	84	7.45	6.014	3171	-
Hagland Captain	7	259017000	9521356	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.85	6.23	2984	-
Gloppen	5	257264400	8304775	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	90	5.05	3.85	1984	850
Normand Skude	9	257982000	9731250	B21A2OS	Offshore supply skip	Platform Supply Ship	87	8.6	7	4609	-
Skandi Flora	8	258239000	9372896	B21A2OS	Offshore supply skip	Platform Supply Ship	95	8	6.6	4469	25
Frakt Fjord	7	212530000	9356581	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.35	6.3	2999	-
Stigfoss	4	305844000	8911504	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	93	10.5	5.6	3625	-
Olympic Energy	5	257626000	9603829	B21A2OS	Offshore supply skip	Platform Supply Ship	94	8.3	6.8	5197	-
Wilson Saar	8	314261000	9125841	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	73	5.75	4.35	1043	-
Hav Streym	31	231251000	9126625	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	83	6.65	5.31	2345	-
Langfoss	1	305845000	8915536	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	93	10.5	5.6	3625	-
Vidfoss	26	305846000	8915524	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	93	10.5	5.6	3625	-
Eidsvaag Pioner	4	258729000	9660449	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	75	7.9	5.1	2145	-
Norsund	23	258829000	9007075	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7	5.337	2705	-
Viking Queen	12	258865000	9372901	B21A2OS	Offshore supply skip	Platform Supply Ship	92	9.6	7.624	6111	25
Norfrakt	6	258657000	8713811	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	74	5.4	4.383	1524	-
Juanita	3	258906000	9665011	B21A2OS	Offshore supply skip	Platform Supply Ship	89	8.8	7.294	4902	-
North Cruys	5	257184000	9654098	B21A2OS	Offshore supply skip	Platform Supply Ship	92	8.5	6.95	4513	-
Eidsvaag Sirius	24	257414000	9279044	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	83	8	5.35	2409	-
Hagland Chief	10	257207000	9521344	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.85	6.08	2984	-
Norne	11	258763000	9082403	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	94	8	6.27	3443	-
Sundstraum	4	259360000	8920567	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	96	8.05	6.211	3206	-
Samskip Glacier	1	309146000	9140956	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	98	10.1	6	3817	-
Hav Nes	7	231099000	8719097	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	75	8.6	6.02	2026	-
Island Valiant	6	259367000	9356191	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	93	9.5	7.7	6335	-
Selvaagsund	20	377134000	9052678	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	6.2	4.5	1598	-
Bjornefjord	12	257022800	9013098	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	87	7.42	4.3	2871	399
Sea Spider	1	538005742	9656644	B21A2OS	Offshore supply skip	Platform Supply Ship	89	8.001	6.65	4007	-
Ness	14	314152000	9123570	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	9.9	6.5	3998	-
Sjoborg	2	231065000	9591923	B21A2OS	Offshore supply skip	Platform Supply Ship	86	8	6.6	4000	-
Island Clipper	5	257346000	9722871	B21A2OS	Offshore supply skip	Platform Supply Ship	97	8.2	7	5068	-
Holmfoss	21	257302000	9359662	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	82	9.1	6	3538	-
Feed Trondheim	8	305371000	9226798	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	7.35	5.1	3925	-
Vestbris	21	375103000	8410316	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	77	5.9	3.812	1477	-
Hav Nordic	5	231812000	8719085	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	75	8.62	6.02	2030	-
Havila Jupiter	9	257461000	9418042	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	92	9	7.534	6455	60
Trondheim	2	257015700	9018634	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	97	7.5	4.6	3418	500
Normand Ranger	5	257587000	9413432	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	91	9.6	7.95	7480	-
Arklow Rogue	3	250000962	9344526	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.15	6.1	2999	-
Arklow Rambler	1	245843000	9250426	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.35	6.31	2999	-
Arklow Clan	1	250004424	9757113	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	87	7.12	6.26	2999	-
Feed Stavanger	5	305224000	9155951	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.2	5.713	2863	-
Lofoten	4	258477000	5424562	A32A2GF	Passasjerbåt	General Cargo/Passenger Ship	88	7.37	4.623	2621	500
Wilson Alster	1	314019000	9222429	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	6.05	4.7	1550	-
Casino	6	259321000	7107730	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	6.05	4.73	1732	-
Gaasoe Viking	7	257906000	9694799	B12B2FC	Andre servicefartøy	Fish Carrier	78	8.5	6.77	3685	-
Zeus	1	304011025	9199684	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	5.8	4.45	1846	-
Normand Prosper	9	257463000	9447952	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	96	9.8	7.8	8053	70
Wilson Borg	3	249211000	9106924	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.511	2446	-
Troms Sirius	2	257825000	9628386	B21A2OS	Offshore supply skip	Platform Supply Ship	94	8	6.5	4201	26
Boa Jarl	1	258072000	9544425	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	91	9.6	7.94	7328	-
Freyja	4	248384000	7392610	A12A2TC	Kjemikalie-/produkttankskip	Chemical Tanker	77	7.01	5.204	1665	-
Ferro	1	314415000	9005730	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	6.35	5.001	1986	-
Suledrott	14	219021313	8318063	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	76	5.72	3.86	1525	-
Bulk Carrier	6	258168000	9017202	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	70	6.05	4.38	1425	-
Havbris	12	377444000	8800157	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	74	5.4	4.383	1524	-
Arklow Cadet	2	250004022	9757084	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	87	7.12	6.26	2999	-
Alice	2	244790715	9677399	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	8.7	6.14	2911	-
Island Captain	1	257024000	9579482	B22F2OW	Andre offshore fartøy	Well Stimulation Vessel	93	8.2	6.8	6632	39
Nonfjell	2	258747000	9108427	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	6.4	4.95	2061	-
Mercator	33	258993000	7047356	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	77	6.41	5.26	1406	-
Mekhanik Semakov	1	273113800	8904393	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	85	6	5.06	2489	-
Far Sun	2	257428000	9665786	B21A2OS	Offshore supply skip	Platform Supply Ship	95	8.5	7.04	4797	28
Ro West	11	259204000	9794977	B12B2FC	Andre servicefartøy	Fish Carrier	82	8	6.864	3579	-

Fartøy_Navn	Antall Passeringer	MMSI	IMO	Statcode5	Fartøy Type	Skipstype Lloyd	Lengde _loa	Skipsdybde	Dypgang Draught	Gross-tonnasje	Passasjer-kapasitet
Sule Viking	37	219019955	8611958	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	80	5.92	4.374	1599	-
Falkberg	22	229385000	9375446	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	6.2	4.8	1867	-
Havila Borg	2	257431000	9430753	B21A2OS	Offshore supply skip	Platform Supply Ship	79	7.7	6.5	2933	23
Wilson Waal	4	314262000	9178446	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	78	5.75	4.35	1170	-
Ocean Pride	6	257011000	9526021	B21A2OS	Offshore supply skip	Platform Supply Ship	86	7.7	6.4	3309	-
Nao Storm	6	257734000	9722510	B21A2OS	Offshore supply skip	Platform Supply Ship	84	8	6.7	3636	-
Wilson Harrier	1	249066000	9064891	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	91	7.15	5.77	2811	-
Lelie C	8	246449000	9166443	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.65	5.6	2450	-
Leiro	2	314298000	8017085	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	98	6.2	4.81	2468	-
Normand Mermaid	9	258612000	9249348	B22A2OR	Andre offshore fartøy	Offshore Support Vessel	90	9	7	5528	69
Lindo	6	314303000	8028527	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	98	5.72	4.35	2495	-
Teigenes	2	259390000	9286841	B11B2FV	Fiskefartøy	Fishing Vessel	76	9	7.2	2883	-
Fjellstraum	2	249425000	9140815	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	100	8.3	6.8	3726	-
Wilson Dvina	1	314220000	9005742	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	87	7.1	5.075	2481	-
Havila Mercury	3	257295000	9364265	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	86	8.8	6.8	4727	-
Nestor	3	304011028	9234305	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	9.45	4.48	1846	-
Wilson Cork	3	314180000	9178460	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	7.55	5.63	2999	-
Edmy	5	518515000	7926409	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	86	8.51	7.014	2768	-
Stril Mar	4	258527000	9740354	B21A2OS	Offshore supply skip	Platform Supply Ship	93	8.2	6.798	4811	-
Polfoss	24	257307000	9393917	A34A2GR	Stykkgods/roro-skip	Refrigerated Cargo Ship	82	9.1	5.995	3538	-
Rem Leader	9	257793000	9627772	B21A2OS	Offshore supply skip	Platform Supply Ship	90	9.6	8	5335	-
Nordic Sund	1	258714000	9375977	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	89	7.7	5.65	2613	-
Fri Star	5	311257000	8100636	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	82	5.41	3.545	1499	-
Siem Pride	4	258132000	9703679	B21A2OS	Offshore supply skip	Platform Supply Ship	89	9	7.412	5321	-
Wilson Rhine	4	314260000	9168116	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	78	5.75	4.35	1171	-
Rogne	1	258637000	9657208	B11B2FV	Fiskefartøy	Fishing Vessel	70	8.7	7.5	1964	-
Thebe	2	304011026	9199696	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	5.8	4.48	1846	-
Berit	1	236386000	9156187	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	83	6.09	4.79	1864	-
Peak Bordeaux	4	246474000	9545039	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	6.8	5.35	2978	-
Wilson Alicante	2	248835000	9507374	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	6.7	5.139	2451	-
Siem Emerald	6	257434000	9417701	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	91	9.6	7.97	7473	-
Siem Commander	2	258555000	9420150	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	74	8	6.79	2807	-
Malta Cement	2	244090800	8911841	A24A2BT	Bulkskip	Cement Carrier	88	7	5.46	2429	-
Torpo	1	314419000	8908791	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	6.35	4.898	1986	-
Far Sapphire	8	257282000	9372169	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	93	9.5	7.8	7176	-
Viscaria	6	258897000	7330052	A12A2TC	Kjemikalie-/produkttankskip	Chemical Tanker	83	6.61	4.753	1859	-
Hav Skandic	2	231837000	8719114	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	75	8.6	6.1	2026	-
Gotland	4	245190000	9361366	A24A2BT	Bulkskip	Cement Carrier	89	7.5	5.95	2999	-
Arklow Freedom	1	250001396	9361756	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.35	6.27	2998	-
Fonnland	2	209950000	9041306	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	85	6.9	5.44	2416	-
Thopas	1	209143000	9085481	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.7	5.311	2561	-
Winter Bay	2	341433000	8601680	A31B2GP	Stykkgods/roro-skip	Palletised Cargo Ship	80	10.01	5.4	2731	-
Arklow Rover	2	250515000	9291717	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.15	6.1	2999	-
Far Searcher	4	259332000	9388950	B21A2OS	Offshore supply skip	Platform Supply Ship	93	8.2	6.6	4755	-
Rodholmen	3	257250000	9118044	B11B2FV	Fiskefartøy	Fishing Vessel	75	8	6.92	1874	-
Ingvild	22	257836000	7633387	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	98	8.21	5.73	3694	-
Artic Fjell	8	257659800	9688960	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	70	9.82	6.745	2768	-
Troms Pollux	2	258467000	9439022	B21A2OS	Offshore supply skip	Platform Supply Ship	85	8.6	7.16	4366	-
Wilson Leer	1	249720000	9150482	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.51	2446	-
Elektron 2	8	258208000	6930520	A35A2RR	Stykkgods/roro-skip	Ro-Ro Cargo Ship	78	6.41	3.022	1628	-
Ro North	4	258685000	9794965	B12B2FC	Andre servicefartøy	Fish Carrier	82	8	6.864	3579	-
Ro Fjord	3	257430000	9544542	B12B2FC	Andre servicefartøy	Fish Carrier	72	6.9	6.4	2310	-
Key Bora	1	236385000	9316024	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	92	7.2	5.6	2627	-
Key Breeze	2	236111791	9344265	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	95	7.65	6.2	2885	-
Stril Challenger	1	258286000	9420174	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	75	8	6.9	2807	-
Eldborg	6	231700000	9451422	B21A2OS	Offshore supply skip	Platform Supply Ship	79	7.7	6.51	2814	-
Wilson Calais	2	314255000	9156101	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	7.55	5.68	2994	-
West Stream	8	308241000	7814254	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	80	7.35	5.85	1845	-
Manon	1	259526000	9125633	B11B2FV	Fiskefartøy	Fishing Vessel	70	8.4	7	1793	-
Wilson Lahn	3	314259000	9198458	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	83	6.05	4.772	1559	-
Frakt Vik	9	212979000	9356579	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.35	6.3	2999	-
Far Scorpion	1	258532000	9417816	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	87	9.3	7.8	6107	40
Stella Lyra	3	244503000	8801084	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	96	8.3	5.712	2874	-
North Pomor	11	258895000	9643465	B21A2OS	Offshore supply skip	Platform Supply Ship	92	8.5	6.95	4513	-
Gardar	2	257203000	9167928	B11B2FV	Fiskefartøy	Fishing Vessel	71	6	7.4	2188	-
Far Serenade	1	257143000	9408229	B21A2OS	Offshore supply skip	Platform Supply Ship	94	8.8	7.282	5206	-
Viking Prince	1	257787000	9596296	B21A2OS	Offshore supply skip	Platform Supply Ship	90	9.6	8	5381	-
Visnes	4	236561000	7928251	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	95	8.3	5.912	3136	-
Wilson Maas	3	314217000	9145554	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	78	5.75	4.35	1169	-
Nor Viking	8	258902000	7600287	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	80	6.35	5.582	2133	-
Kvannoy	2	257997000	9710919	B11B2FV	Fiskefartøy	Fishing Vessel	78	9.2	8	2786	-

Fartøy_Navn	Antall Passeringer	MMSI	IMO	Statcode5	Fartøy Type	Skipstype Lloyd	Lengde _loa	Skipsdybde	Dypgang Draught	Gross-tonnasje	Passasjer-kapasitet
Dr. Fridtjof Nansen	12	259215000	9762716	B12D2FR	Andre servicefartøy	Fishery Research Vessel	74	8.6	5.4	3853	-
Telmo	1	212657000	9786798	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	8	6.2	3978	-
Stolt Sandpiper	1	235089284	9566758	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	91	8	6	3327	-
Energy Swan	3	258069000	9319985	B21A2OS	Offshore supply skip	Platform Supply Ship	93	8.4	6.85	4200	-
Rignator	2	257798800	9224116	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	79	6.25	4.92	2171	-
Elektron	1	258538000	9386811	A35A2RR	Stykkgods/roro-skip	Ro-Ro Cargo Ship	87	6.5	4.8	3438	-
Solvik Supplier	1	311070200	9589607	B21A2OS	Offshore supply skip	Platform Supply Ship	85	8.6	7	4366	-
Nordic Nelly	1	220234000	9130808	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	100	9.1	6.713	4137	-
Arklow Forest	1	250002443	9527685	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.35	6.28	2998	-
Hagland Boss	1	249934000	9171058	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	87	7.1	5.45	2446	-
Melderskin	2	257332400	8412261	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	90	5.05	3.85	1974	850
Far Solitaire	5	257867000	9616175	B21A2OS	Offshore supply skip	Platform Supply Ship	92	8.8	6.3	5346	-
Eco Universe	4	538006288	9713557	A11B2TG	Gasstankskip	LPG Tanker	99	7.8	6.163	4258	-
Pluto	2	314417000	8518340	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	6.35	5.001	1998	-
Arklow Future	2	250001594	9361768	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.35	6.27	2998	-
Siem Garnet	1	259083000	9442421	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	92	9.6	7.95	7473	-
Ruth	1	220026000	9729829	B11B2FV	Fiskefartøy	Fishing Vessel	88	9.6	8.5	3720	-
Isafold	2	220461000	9350616	B11B2FV	Fiskefartøy	Fishing Vessel	76	9.5	7.7	2499	-
Birthe Bres	2	220506000	9365491	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	6.8	5.3	2658	-
Uglen	5	257231000	7721079	Y11B4WL	Andre servicefartøy	Ukjent	78	6.43	3.27	3977	-
Hordafor V	1	257986000	9148843	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	80	6.55	5.012	1655	-
Olympic Commander	1	257334000	9602904	B22A2OR	Andre offshore fartøy	Offshore Support Vessel	94	8	6.5	5773	60
Arklow Ruler	3	250000609	9344502	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.15	6.1	2999	-
Havila Troll	1	259520000	9283576	B21B2OT	Offshore supply skip	Offshore Tug/Supply Ship	92	8	6	4537	24
Bourbon Front	2	311000471	9530101	B21A2OS	Offshore supply skip	Platform Supply Ship	89	8	6.6	4071	-
Kv Sortland	10	257736000	9432646	B34H2SQ	Andre servicefartøy	Patrol Vessel	94	8.6	6.2	4025	-
Magne Viking	1	219375000	9423839	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	85	9	7.6	6279	-
Siem Symphony	4	258737000	9690066	B21A2OS	Offshore supply skip	Platform Supply Ship	89	9	7.4	4768	25
Omalius	4	205682000	8406470	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	83	7.95	5.577	3364	-
Kaprifol	1	210445000	9200081	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	90	6.1	5.1	1845	-
Serene	1	235072137	Ukjent	B11A2FS	Fiskefartøy	Ukjent	71	Ukjent	Ukjent	Ukjent	-
Ampere	3	257642000	9683611	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	80	6	Ukjent	1598	360
Pioneer Knutsen	2	259393000	9275074	A11A2TN	Gasstankskip	LNG Tanker	70	5.5	3.3	1687	-
Haugagut	1	257852000	9710907	B11B2FV	Fiskefartøy	Fishing Vessel	70	9.2	8	2365	-
Triton	1	236673000	9749099	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	6.6	5.68	3450	-
Anne	1	311913000	9118006	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	5.55	4.27	2035	-
Atlantis Antalya	1	248252000	9305350	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	88	7.25	5.95	2314	-
Fosen	1	257256400	8808496	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	86	4.5	4.5	2835	650
Csl Clyde	1	249375000	910154600	A23A2BD	Bulkskip	Ukjent	100	Ukjent	Ukjent	Ukjent	-
Bulk Trans	14	257108000	7729033	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	72	5.62	5.311	1552	-
Norderveg	1	258265000	8710778	B11B2FV	Fiskefartøy	Fishing Vessel	75	10.6	8.5	2574	-
Stril Pioner	1	258169000	9258430	B21A2OS	Offshore supply skip	Platform Supply Ship	95	9.6	7.899	5073	24
G.o.sars	2	257105000	9260316	B11B2FV	Fiskefartøy	Fishing Vessel	78	9.1	6.2	4067	30
Peak Belfast	1	246403000	9544891	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	6.8	5.35	2978	-
North Purpose	3	257491000	9439462	B21A2OS	Offshore supply skip	Platform Supply Ship	86	8	6.63	3639	-
Far Superior	1	257911000	9766877	B22A2OR	Andre offshore fartøy	Offshore Support Vessel	98	9	6.6	7652	-
Skandi Gamma	2	259699000	9508067	B21A2OS	Offshore supply skip	Platform Supply Ship	95	8	6.7	5054	-
Bergen Nordic	16	258430000	9257591	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	96	7	5.75	2490	-
Rem Mermaid	3	258423000	9418705	B21A2OS	Offshore supply skip	Platform Supply Ship	80	7.45	6.22	3131	-
Kl Saltfjord	4	257577000	9470478	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	95	9.8	7.8	8360	-
Ocean Response	1	257954000	9616163	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	75	8	6.7	3824	-
Siem Sapphire	1	257544000	9417696	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	91	9.6	7.9	7473	-
Lecko	1	244063000	9263576	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.5	5.85	2556	-
Skandi Pacific	2	311061700	9447653	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	75	8.5	7	3181	-
Stril Orion	1	259977000	9584554	B21A2OS	Offshore supply skip	Platform Supply Ship	93	8	6.6	4323	24
Kl Sandefjord	1	257576000	9470466	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	95	9.8	7.789	8360	-
Mv Wilson Dundee	1	305761000	9390159	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.49	2452	-
Eems-Dart	1	236453000	9195640	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7	5.42	2535	-
Wilson Bilbao	1	249077000	9014705	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.49	2446	-
Key West	3	236668000	9020429	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	90	7.48	6.147	2634	-
Wilson Ghent	1	249647000	9150236	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.51	2446	-
Key Marin	2	236342000	9297228	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	88	7.25	5.95	2262	-
Wilson Gdynia	2	314192000	9056064	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.52	2506	-
Bornholm	2	244234000	9361354	A24A2BT	Bulkskip	Cement Carrier	90	7.5	5.95	2999	-
Eros	1	257913000	9617973	B11B2FV	Fiskefartøy	Fishing Vessel	77	7.5	6.95	4027	-
Kl Brofjord	3	257638000	9482354	B21A2OS	Offshore supply skip	Platform Supply Ship	94	8	6.7	4518	-
Trader Bulk	1	231759000	7233060	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	84	8.77	7.16	2677	-
Christina E	3	257032500	9554573	B11B2FV	Fiskefartøy	Fishing Vessel	81	10	8.2	3623	-
Amiko	2	229107000	9125669	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	100	6.52	5.9	3821	-

Fartøy_Navn	Antall Passeringer	MMSI	IMO	Statcode5	Fartøy Type	Skipstype Lloyd	Lengde _loa	Skipsdybde	Dypgang Draught	Gross-tonnasje	Passasjer-kapasitet
Kv Harstad	4	259050000	9312107	B34H2SQ	Andre servicefartøy	Patrol Vessel	83	7.2	6	3132	-
Havila Subsea	1	259073000	9505508	B22A2OR	Andre offshore fartøy	Offshore Support Vessel	98	10	8	8552	78
Larissa	1	259949000	9521033	B22A2OR	Andre offshore fartøy	Offshore Support Vessel	95	8	6.6	6072	-
Oceanic	1	244918000	9624550	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	92	10	4.9	2989	-
Sulafjord	5	257212400	8512114	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	86	4.5	Ukjent	3692	650
Ardea	2	212048000	9503902	A13C2LA	Oljetankskip	Asphalt/Bitumen Tanker	99	9	6.35	4657	-
Wilson Limerick	1	210041000	9617301	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.1	5.54	2589	-
Nataly	1	304523000	9370288	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7	5.425	2545	-
Wilson Horsens	1	304060000	9518426	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.15	5.81	2997	-
Dina Scout	1	257909000	9663025	B21A2OS	Offshore supply skip	Platform Supply Ship	77	7	5.87	2418	-
Hardingen	2	257051700	9036040	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	84	5	3.346	2631	399
Seabed Prince	3	258647000	9489651	B31A2SR	Andre servicefartøy	Research Survey Vessel	84	9.1	6.8	4398	62
Mergus	1	212052000	9503914	A13C2LA	Oljetankskip	Asphalt/Bitumen Tanker	99	9	6.35	4657	-
Siem Pilot	2	257458000	9510307	B21A2OS	Offshore supply skip	Platform Supply Ship	88	8.6	7.21	5106	-
Peak Bremen	3	246779000	9612533	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	6.8	5.35	2978	-
Viking Avant	3	258403000	9306914	B21A2OS	Offshore supply skip	Platform Supply Ship	92	9	7.25	6545	-
Willeke	1	245377000	9232486	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	80	4.8	3.6	1435	-
Skandi Mogster	2	259495000	9166613	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	73	8	6.88	2598	-
Arklow Fortune	1	250000963	9361744	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.35	6.27	2998	-
Normand Server	1	259961000	9591856	B21A2OS	Offshore supply skip	Platform Supply Ship	94	8.3	6.77	4590	-
Blue Note	1	305565000	9491915	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	7.6	6.13	3845	-
Statsraad Lehmkuhl	6	258113000	5339248	X11B2QN	Annet	Ukjent	85	7.31	5.2	1516	-
Nordstjernen	1	257276000	5255777	A32A2GF	Passasjerbåt	General Cargo/Passenger Ship	80	7.17	4.509	2191	435
Key Fjord	1	236445000	9318216	A12B2TR	Kjemikalie-/produkttankskip	Chemical/Products Tanker	100	7.45	6.05	3178	-
Normand Supporter	1	257337000	9591868	B21A2OS	Offshore supply skip	Platform Supply Ship	94	8.3	6.77	4590	-
Mekhanik Fomin	1	273112800	8904381	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	85	6	5.06	2489	-
Stril Merkur	2	231076000	9407897	B21B2OT	Offshore supply skip	Offshore Tug/Supply Ship	97	8	6.5	6272	-
Serenissima	4	376439000	5142657	A37A2PC	Cruiseskip	Passenger/Cruise	87	7.35	4.92	2598	117
Viking Dynamic	2	311000456	9244568	B21A2OS	Offshore supply skip	Platform Supply Ship	90	8.4	6.98	3524	-
Gambler	1	258412000	6926622	B11B2FV	Fiskefartøy	Fishing Vessel	70	7.22	5.8	1298	-
Fountainhead	2	319028100	1010753	X11A2YP	Annet	Ukjent	85	Ukjent	Ukjent	2463	-
Wilson Grimsby	1	314193000	9056040	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.52	2506	-
Stavanger	1	259419000	9263758	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	84	5.98	Ukjent	2434	400
Talitha	1	310051000	1004625	X11A2YP	Annet	Ukjent	80	Ukjent	Ukjent	1103	-
Havila Venus	1	259305000	9418030	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	92	9	7.534	6455	60
Evita	1	257819000	9649562	B21A2OS	Offshore supply skip	Platform Supply Ship	85	8.6	7	4258	-
Bucentaur	1	311474000	8112548	B22B2OD	Andre offshore fartøy	Drilling Ship	78	8.41	5.565	2768	-
Vendla	1	258944000	9646091	B11B2FV	Fiskefartøy	Fishing Vessel	76	9.3	8.3	2987	-
Normand Fortune	2	258759000	9683659	B21A2OS	Offshore supply skip	Platform Supply Ship	86	8.6	7.2	4560	-
Frank W.	1	218110000	9374674	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	8	5.429	2528	-
Siem Ruby	4	257733000	9413444	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	91	9.6	7.95	7558	-
Kine	1	311117000	9145140	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	89	6.4	4.95	2061	-
Ocean Star	2	257297000	9667241	B21A2OS	Offshore supply skip	Platform Supply Ship	89	8.6	7.05	4800	-
Theseus	1	304011027	9199256	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	5.8	4.48	1846	-
Hebridean Sky	1	311000253	8802882	A37A2PC	Cruiseskip	Passenger/Cruise	91	5.85	4.25	4200	120
Island Vanguard	2	259121000	9356189	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	86	9.5	7.7	5733	-
Wilson Dale	1	305370000	9462500	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7	5.41	2545	-
Havila Foresight	1	259632000	9382944	B21A2OS	Offshore supply skip	Platform Supply Ship	93	7.85	6.35	4309	-
Sandnes	2	258126000	5310905	B34K2QT	Andre servicefartøy	Training Ship	73	6.96	4.801	1432	550
Bb Troll	1	258202000	9203203	B21B2OA	Ukjent fartøy	Anchor Handling Tug Supply	74	7.6	6.5	2528	16
Fjord Cat	1	220574000	9176060	A36A2PR	RoPax-skip	Passenger/Ro-Ro Ship (Vehicles)	91	4.08	3.7	5619	800
Beaumagic	1	244615000	9373266	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7	5.42	2545	-
Wilson Brest	1	249377000	9126900	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	88	7.1	5.498	2446	-
Siddis Sailor	1	258268000	9370070	B21A2OS	Offshore supply skip	Platform Supply Ship	85	8.6	7.2	4601	-
Feed Fiskaa	1	305662000	9115999	A31A2GX	Stykkgods/roro-skip	General Cargo Ship	90	7.2	5.713	2840	-

Appendix E. Construction Cost Data (Source : Faber Maunsell Aecom (2007), Henning et al. (2007), Ovstedal & Melby (1992))

Name of tunnels	Country	Type	Year of cost published	Original cost currency	Original cost	Converted cost	Depth (deepest)	Length	Segment length	Maximum Grade	Const. cost per unit length
						[USD]	[m]	[m]	[m]	[%]	[USD/m]
Western harbour crossing	HK china	IM	1996	USD	5.70E+09	7.91E+09		1250			6.33E+06
Silvertown river tunnel (Expected),	UK	IM	2014	GBP	4.14E+08	6.84E+08	30	1400			4.88E+05
Fehmarn Belt	DK	IM	2014	Euro	6.60E+09	9.31E+09		19000			4.90E+05
Geoje-Busan link	KOR	IM	2010	KRW	5.90E+11	5.73E+08	48	3700	180		1.55E+05
Izmir (Expected)	Turkey	IM	2008	USD	2.00E+09	2.32E+09	25	7600			3.05E+05
Caland tunnel	NL	IM	2004	EURO	1.60E+08	2.45E+08		1500			1.63E+05
Thomassen Tunnel	NL	IM	2004	DFL	3.50E+08	1.57E+08		1000			1.57E+05
Warnow Tunndel	DE	IM	2003	EURO	2.24E+08	3.17E+08		790			4.01E+05
Jack Lynch tunnel	IR	IM	1999	IEP	7.00E+07	1.09E+08		1900	120		5.73E+04
Oresund Crossing	DK	IM	1998	DNK	3.80E+09	6.33E+08		3500	120		1.81E+05
Medway Tunnel	UK	IM	1996	GBP	8.00E+07	1.60E+08		585	126		2.74E+05
Boryung link	KOR	UN	2018	KRW	4.64E+11	4.37E+08	80	6900		4.95	6.34E+04
Eurasia Tunnel	Turkey	UN	2016	USD	1.20E+09	1.24E+09	106	5400			2.29E+05
Channel tunnel	UK-FR	UN	1994	GBP	1.20E+10	1.86E+10	240	37900			3.17E+05
Eiksund Tunnel	NO	UN	2008	NOK	8.00E+08	1.35E+08	287	7700		9.6	1.75E+04
Bømlafjord Tunnel	NO	UN	2000	NOK	4.87E+08	7.32E+07	260.4	7800		9	9.38E+03
Hitra Tunnel	NO	UN	1994	NOK	3.39E+08	6.92E+07	264	5645		10	1.23E+04
Nordkapp Tunnel, NO	NO	UN	1999	NOK	3.41E+08	5.81E+07	212	6826		10	8.51E+03
Froya Tunnel, NO	NO	UN	2000	USD	5.20E+07	6.80E+07	164	5305		10	1.28E+04

IM = Immersed Tunnel, UN = Undersea Tunnel, HK = Hong Kong, UK = United Kingdom, DK = Denmark, KOR = South Korea, NL= Netherlands, DE = Germany, IR = Ireland, FR = France, NO = Norway

Appendix F. Results for Robot Structural Model Analysis

Author: SFC Group

Structure View

Data - Bars

Bar	Node 1	Node 2	Section	Type	Material	Length (m)
2	12	23	Tether	Cables	S235	443.52
3	13	24	Tether	Cables	S235	443.52
4	14	25	Tether	Cables	S235	443.52
5	15	26	Tether	Cables	S235	443.52
6	16	27	Tether	Cables	S235	443.52
7	17	28	Tether	Cables	S235	443.52
8	18	29	Tether	Cables	S235	443.52
9	19	30	Tether	Cables	S235	443.52
10	20	31	Tether	Cables	S235	443.52

Bar	Node 1	Node 2	Section	Type	Material	Length (m)
11	21	32	Tether	Cables	S235	443.52
12	22	33	Tether	Cables	S235	443.52
13	1	34	Tether	Cables	S235	443.52
14	2	35	Tether	Cables	S235	443.52
15	3	36	Tether	Cables	S235	443.52
16	4	37	Tether	Cables	S235	443.52
17	5	38	Tether	Cables	S235	443.52
18	6	39	Tether	Cables	S235	443.52
19	7	40	Tether	Cables	S235	443.52
20	8	41	Tether	Cables	S235	443.52
21	9	42	Tether	Cables	S235	443.52
22	10	43	Tether	Cables	S235	443.52
23	11	44	Tether	Cables	S235	443.52

Materials

	Material	E (MPa)	G (MPa)	NI	LX (1/°C)	RO (kN/m3)	Re (MPa)
1	B65	40000.00	16666.67	0.20	0.00	24.53	65.00
2	S235	210000.00	80800.00	0.30	0.00	77.01	235.00

Supports

Support name	List of nodes	List of edges
Pinned	23to44	
Fixed	1 11 12 22	

Support name	List of objects	Support conditions
Pinned		UX UY UZ
Fixed		UX UY UZ RX RY RZ

Loads - Cases

Case	Label	Case name
1	DL1	DL1
2	DL2	Hydrostatic
3	DL21	Waves
4		COMB1

Case	Nature	Analysis type
1	Structural	Nonlinear Static
2	Structural	Nonlinear Static

Case	Nature	Analysis type
3	Structural	Nonlinear Static
4	Structural	Nonlin. Combination

Loads - Values

Case	Load type	List
1	self-weight	1to23
2	Assembling:self-weight	1to23
3	Assembling:self-weight	1to23
2	(FE) hydrostatic pressure	1
3	uniform load	
3	(FE) linear 2p (3D)	

Case	Load values
1	PZ Negative Factor=1.00
2	PZ Negative Factor=1.00
3	PZ Negative Factor=1.00
2	GAMMA=1025.00(kG/m3) H=38.75(m) NDIR=-Z Geometrical limits:P1(-24.3, 200, -443) P2(-23.3, 200, -443) P3(-24.3, 201, -443) P4(-24.3, 200, -442)
3	PX=18.75(kN/m)
3	FX1=18.75(kN/m) FX2=18.75(kN/m) N1X=-8.75(m) N1Y=0.0(m) N1Z=0.0(m) N2X=-8.7-5(m) N2Y=200.00(m) N2Z=0.0(m)

Combinations

Combinations	Name	Analysis type	Combination type	Case nature
4	COMB1	Nonlin. Combinati-on	ULS	Structural

Combinations	Definition
4	(1+2+3)*1.35

Reactions - Values

Case	FX(kN)
Case 2	Hydrostatic
Sum of val.	-1258.49
Sum of reac.	-1258.49
Sum of forc.	0.00
Check val.	-1258.49
Precision	1.36340e-01

Case 3	Waves
Sum of val.	-1509.20
Sum of reac.	-1509.20
Sum of forc.	93.75
Check val.	-1415.45
Precision	1.21279e-01
Case 4	COMB1
Sum of val.	-124.46
Sum of reac.	-124.46
Sum of forc.	126.56
Check val.	2.10
Precision	8.71484e-02

Case 1	FZ(kN)
Sum of val.	282359.64
Sum of reac.	282359.64
Sum of forc.	-282359.64
Check val.	-0.00
Precision	
Case 2	FZ(kN)
Sum of val.	305915.87
Sum of reac.	305915.87
Sum of forc.	-270286.26
Check val.	35629.61
Precision	
Case 3	FZ(kN)
Sum of val.	270286.51
Sum of reac.	270286.51
Sum of forc.	-282359.64
Check val.	-12073.14
Precision	
Case 4	FZ(kN)
Sum of val.	260657.17
Sum of reac.	260657.17
Sum of forc.	-268531.22
Check val.	-7874.05

Node/Case	MX (kNm)
Case 1	
Sum of val.	-0.00
Sum of reac.	28235964.46
Sum of forc.	-28235964.46
Check val.	-0.00
Precision	
Case 2	
Sum of val.	-544.23
Sum of reac.	30679218.48
Sum of forc.	-27028625.65
Check val.	3650592.83
Precision	
Case 3	
Sum of val.	-201.06
Sum of reac.	26624572.68
Sum of forc.	-28235964.46
Check val.	-1611391.78
Precision	
Case 4	
Sum of val.	455.72
Sum of reac.	25901387.00
Sum of forc.	-26853121.76
Check val.	-951734.76
Precision	

Node/Case	MY (kNm)	MZ (kNm)
Case 2		
Sum of val.	-32765.07	-17.82
Sum of reac.	-314901.29	144389.69
Sum of forc.	-0.00	0.00
Check val.	-314901.29	144389.69
Precision		
Case 3		
Sum of val.	-6116.91	-0.37
Sum of reac.	-354175.82	188612.49
Sum of forc.	0.00	-9375.00
Check val.	-354175.82	179237.49

Node/Case	MY (kNm)	MZ (kNm)
Precision		
Case 4		
Sum of val.	-6440.76	14.92
Sum of reac.	525.48	-9363.98
Sum of forc.	-0.00	-12656.25
Check val.	525.48	-22020.23
Precision		

Reactions ULS: global extremes

	FX (kN)	FY (kN)	FZ (kN)	MX (kNm)	MY (kNm)	MZ (kNm)
MAX	3429.73	3304.90	77810.04	86911.58	26369.54	291.83
Node	22	11	23	12	22	12
Case	4	2	4	1	4	4
MIN	-3703.73	-2945.17	-125172.12	-86911.58	-35415.68	-282.97
Node	11	1	1	22	11	22
Case	2	2	2	1	2	4

Displacements SLS: global extremes

	UX (mm)	UY (mm)	UZ (mm)	RX (Rad)	RY (Rad)	RZ (Rad)
MAX	27	65	72	0.007	0.007	0.011
Node	839	99	6	835	844	812
Case	2	1	2	1	2	1
MIN	-23	-65	-73	-0.007	-0.006	-0.011
Node	783	829	6	93	834	82
Case	2	1	1	1	2	1

Appendix G. Results for Submarine Collision Model Analysis

Author: SFC Group

Reactions ULS: global extremes

	FX (kN)	FZ (kN)
MAX	470.72	4471.83
Node	1	37
Case	3	5
MIN	-9243.27	-5363.13
Node	37	1
Case	4 (C)	4 (C)

Displacements SLS: global extremes

	UX (mm)	UZ (mm)	RY (Rad)
MAX	1356	272	0.123
Node	12	25	5
Case	5	5	5
MIN	-203	-267	-0.086
Node	63	12	17
Case	5	5	5

Member Forces ULS: envelope

Bar	FX (kN)	FZ (kN)	MY (kNm)
1 / MAX	2641.17	2631.25	49.62
1 / MIN	-3992.76	-499.31	-5843.60
2 / MAX	2605.64	6854.06	111.86
2 / MIN	-3478.92	-57.49	-15168.14
3 / MAX	2602.20	6463.42	68.45
3 / MIN	-4025.47	-45.47	-10079.21
4 / MAX	2602.96	6037.80	47.18
4 / MIN	-4541.30	-42.82	-5283.45
5 / MAX	2605.88	5578.28	3318.89
5 / MIN	-5022.61	-68.62	-868.00
6 / MAX	2609.42	5085.89	7072.59
6 / MIN	-5465.64	-89.52	-20.14
7 / MAX	2612.62	4561.57	10427.14
7 / MIN	-5867.11	-107.64	-26.01
8 / MAX	2615.05	4006.42	13357.98
8 / MIN	-6223.91	-125.35	-27.38
9 / MAX	2616.90	3421.60	15841.35
9 / MIN	-6533.39	-144.93	-27.38

Bar	FX (kN)	FZ (kN)	MY (kNm)
10 / MAX	2621.22	2808.76	16884.83
10 / MIN	-6793.07	-161.58	-25.25
11 / MAX	2629.15	67.52	16884.83
11 / MIN	-4009.45	-2735.35	-20.53
12 / MAX	5918.42	60.36	15795.79
12 / MIN	-795.15	-4847.52	-14.12
13 / MAX	6327.12	60.82	12988.39
13 / MIN	-15.12	-4621.03	-40.18
14 / MAX	6714.82	67.12	9578.14
14 / MIN	-6.95	-4355.30	-73.74
15 / MAX	7077.74	77.39	6390.93
15 / MIN	1.81	-4054.50	-98.80
16 / MAX	7412.72	89.51	3459.16
16 / MIN	11.01	-3723.41	-114.70
17 / MAX	7717.59	101.43	771.27
17 / MIN	20.47	-3366.73	-1791.87
18 / MAX	7990.82	111.03	22.17
18 / MIN	30.00	-2989.73	-3955.94
19 / MAX	8221.68	116.48	22.17
19 / MIN	39.43	-2589.74	-5815.68
20 / MAX	8417.27	121.86	21.19
20 / MIN	40.97	-2165.78	-7353.78
21 / MAX	8574.95	131.41	18.30
21 / MIN	42.19	-1722.91	-8554.94
22 / MAX	8692.80	143.03	13.70
22 / MIN	43.09	-1267.17	-9408.41
23 / MAX	8770.17	154.70	7.68
23 / MIN	43.66	-804.28	-9907.83
24 / MAX	8806.67	164.27	0.67
24 / MIN	43.91	-340.34	-10051.50
25 / MAX	8802.92	428.49	41.66
25 / MIN	43.81	-60.36	-10051.50
26 / MAX	8761.49	885.75	81.01
26 / MIN	43.39	-67.52	-9842.08
27 / MAX	8684.70	1329.63	111.32
27 / MIN	42.63	-83.66	-9286.60
28 / MAX	8572.21	1754.82	127.08
28 / MIN	41.55	-103.07	-8436.63
29 / MAX	8421.20	2165.99	128.86
29 / MIN	40.15	-120.46	-7255.40
30 / MAX	8232.23	2565.95	128.86

Bar	FX (kN)	FZ (kN)	MY (kNm)
30 / MIN	38.45	-138.25	-5748.67
31 / MAX	8006.76	2948.72	117.23
31 / MIN	36.45	-158.74	-3927.99
32 / MAX	7747.93	3308.18	703.99
32 / MIN	34.18	-184.22	-1807.17
33 / MAX	7458.58	3638.78	3352.00
33 / MIN	31.65	-216.74	-18.76
34 / MAX	7141.70	3935.08	6222.45
34 / MIN	28.87	-258.18	-112.89
35 / MAX	6805.05	4192.57	9322.99
35 / MIN	25.88	-309.96	-242.41
36 / MAX	8075.58	9252.77	4963.63
36 / MIN	29.58	80.94	-1955.87
37 / MAX	5229.61	341.07	49.62
37 / MIN	-260.44	-274.67	-5843.60
38 / MAX	5223.78	405.94	22.75
38 / MIN	-257.69	-230.53	-5732.89
39 / MAX	5209.28	475.79	56.95
39 / MIN	-253.19	-185.06	-5570.32
40 / MAX	5185.97	546.36	76.63
40 / MIN	-247.11	-141.58	-5353.34
41 / MAX	5154.61	613.61	82.83
41 / MIN	-239.65	-103.14	-5082.70
42 / MAX	5116.89	673.43	82.83
42 / MIN	-230.98	-72.78	-4762.21
43 / MAX	5075.37	722.16	76.65
43 / MIN	-221.31	-53.13	-4487.23
44 / MAX	5025.72	407.16	14.22
44 / MIN	-161.21	-182.36	-1908.68
45 / MAX	5017.98	424.88	27.78
45 / MIN	-157.26	-180.96	-1757.36
46 / MAX	5014.44	425.77	36.16
46 / MIN	-153.22	-182.58	-1598.46
47 / MAX	5010.58	424.19	39.92
47 / MIN	-149.21	-176.76	-1441.60
48 / MAX	5004.07	432.78	39.92
48 / MIN	-145.36	-166.30	-1281.67
49 / MAX	4993.48	447.90	39.67
49 / MIN	-141.78	-154.03	-1112.26
50 / MAX	4978.36	465.50	36.07
50 / MIN	-138.57	-142.99	-943.80

Bar	FX (kN)	FZ (kN)	MY (kNm)
51 / MAX	4959.23	481.60	29.87
51 / MIN	-135.82	-136.11	-771.50
52 / MAX	4937.57	492.09	38.29
52 / MIN	-133.59	-136.34	-591.63
53 / MAX	4915.82	493.32	59.69
53 / MIN	-131.93	-146.20	-405.54
54 / MAX	4897.26	481.76	91.14
54 / MIN	-130.89	-168.05	-214.67
55 / MAX	4878.34	454.81	264.25
55 / MIN	-130.89	-190.08	-20.46
56 / MAX	4864.13	426.51	421.53
56 / MIN	-131.93	-200.64	-19.70
57 / MAX	4851.22	411.73	572.11
57 / MIN	-133.59	-201.54	-24.63
58 / MAX	4837.03	407.21	760.06
58 / MIN	-135.82	-195.37	-28.12
59 / MAX	4819.91	409.55	948.68
59 / MIN	-138.57	-184.77	-30.14
60 / MAX	4802.03	414.78	1131.78
60 / MIN	-141.78	-172.77	-33.15
61 / MAX	4780.79	419.01	1307.97
61 / MIN	-145.36	-162.33	-33.15
62 / MAX	4756.55	418.19	1475.91
62 / MIN	-149.21	-156.44	-42.94
63 / MAX	4730.84	408.61	1634.32
63 / MIN	-153.22	-157.82	-65.51
64 / MAX	4706.15	386.63	1782.00
64 / MIN	-169.79	-156.69	-93.14
65 / MAX	4687.08	365.86	1917.82
65 / MIN	-186.01	-141.96	-126.55
66 / MAX	4151.87	370.94	4570.61
66 / MIN	-554.33	-259.77	-59.31
67 / MAX	4140.80	332.69	4717.93
67 / MIN	-573.33	-230.85	-104.65
68 / MAX	4130.54	304.67	4826.54
68 / MIN	-587.97	-193.59	-139.49
69 / MAX	4121.48	283.89	4895.63
69 / MIN	-598.13	-150.75	-143.14
70 / MAX	4111.73	266.87	4924.66
70 / MIN	-603.74	-108.18	-143.14
71 / MAX	4100.13	250.16	4933.69

Bar	FX (kN)	FZ (kN)	MY (kNm)
71 / MIN	-604.76	-127.00	-112.77
72 / MAX	4087.01	274.67	4963.63
72 / MIN	-601.17	-152.63	-92.95
73 / MAX	7990.82	254.42	91.14
73 / MIN	-130.48	-2989.73	-3955.94
74 / MAX	7990.82	2631.25	49.62
74 / MIN	-3992.76	-2989.73	-5843.60
75 / MAX	5217.98	341.07	91.14
75 / MIN	-260.44	-168.05	-5843.60
76 / MAX	8221.01	8874.11	4963.63
76 / MIN	29.58	-2412.54	-3955.94
77 / MAX	4876.18	454.81	4963.63
77 / MIN	-601.17	-152.63	-92.95
78 / MAX	7990.82	2631.25	49.62
78 / MIN	-3992.76	-2989.73	-5843.60
79 / MAX	5217.98	341.07	91.14
79 / MIN	-260.44	-168.05	-5843.60
80 / MAX	8221.01	8874.11	4963.63
80 / MIN	29.58	-2412.54	-3955.94
81 / MAX	4876.18	454.81	4963.63
81 / MIN	-601.17	-152.63	-92.95
82 / MAX	33.05	87.91	2431.55
82 / MIN	-272.37	-447.31	-2680.64
83 / MAX	4911.89	106.91	11200.44
83 / MIN	43.60	-1408.69	-11240.62

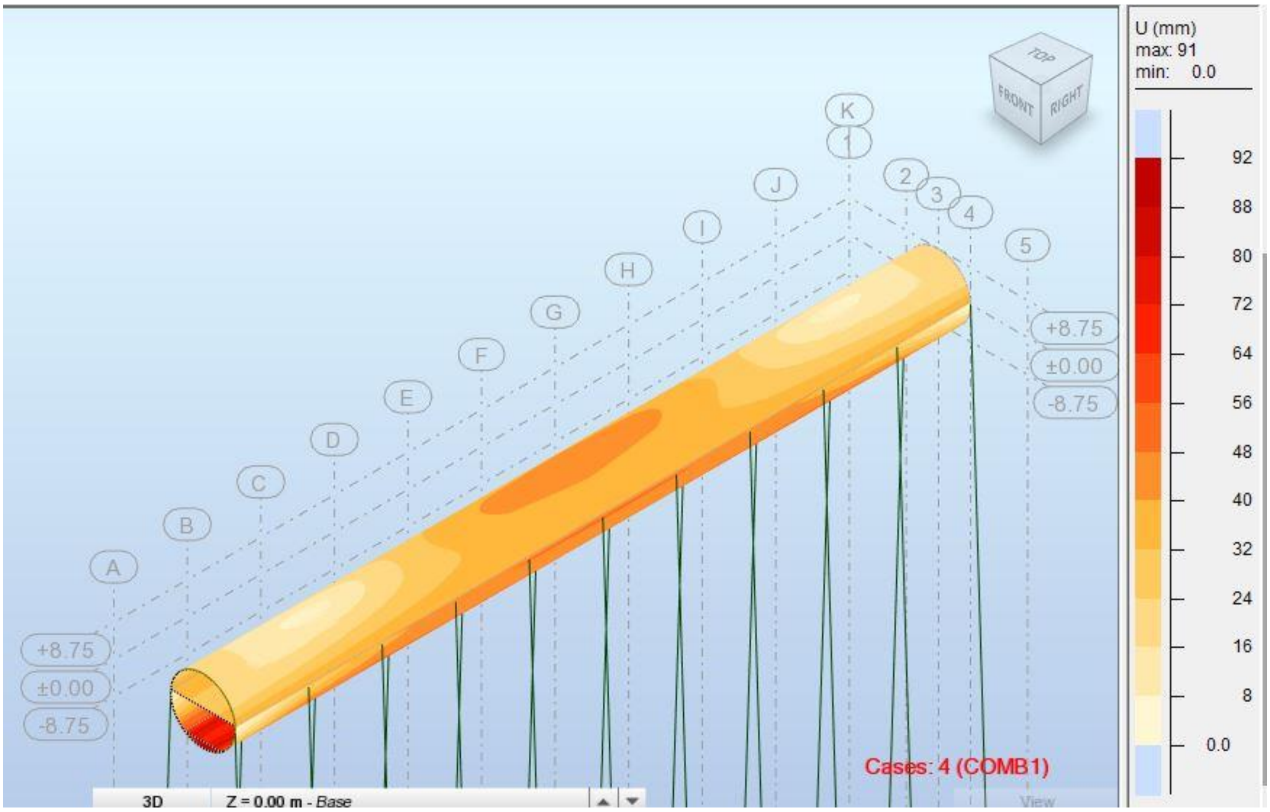


Figure G-1: Vertical Displacement Corresponding to 100mm Diameter Tether

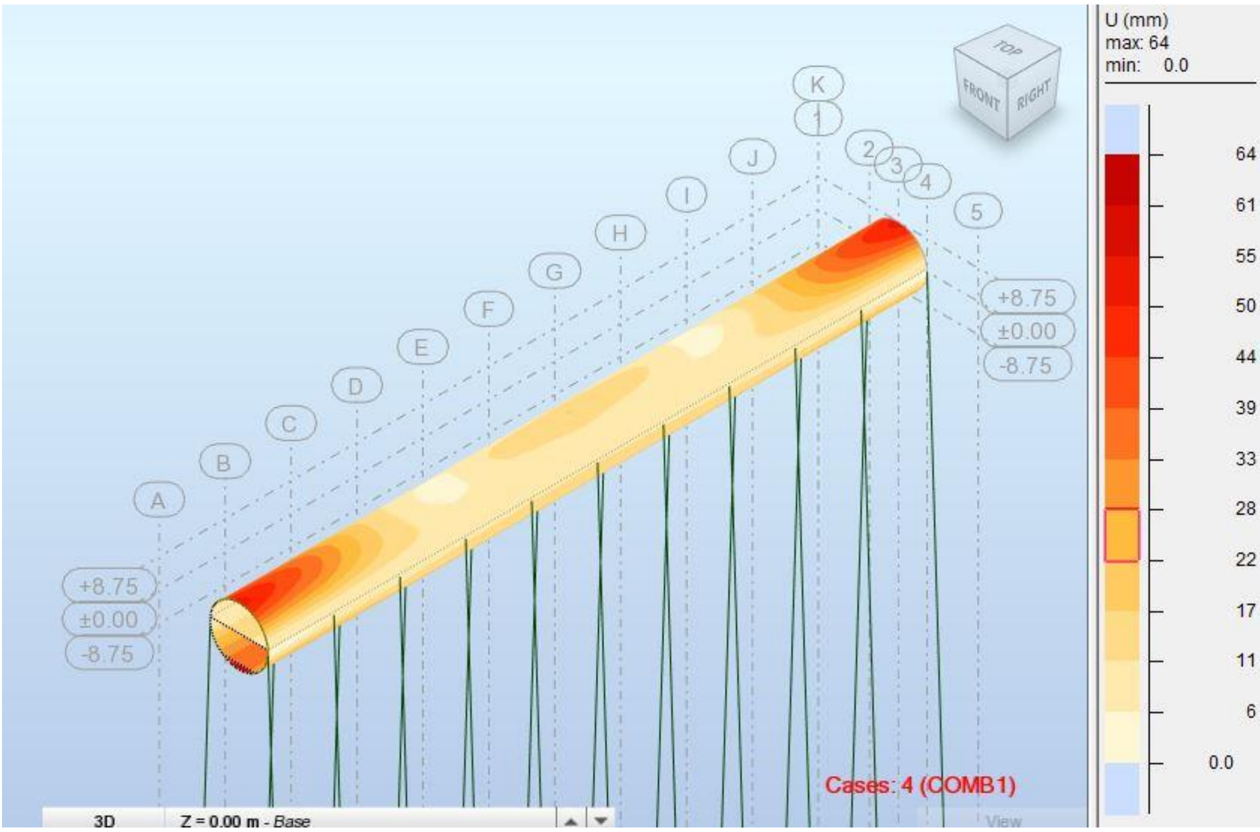


Figure G-2: Vertical Displacement Corresponding to 300mm Diameter Tether

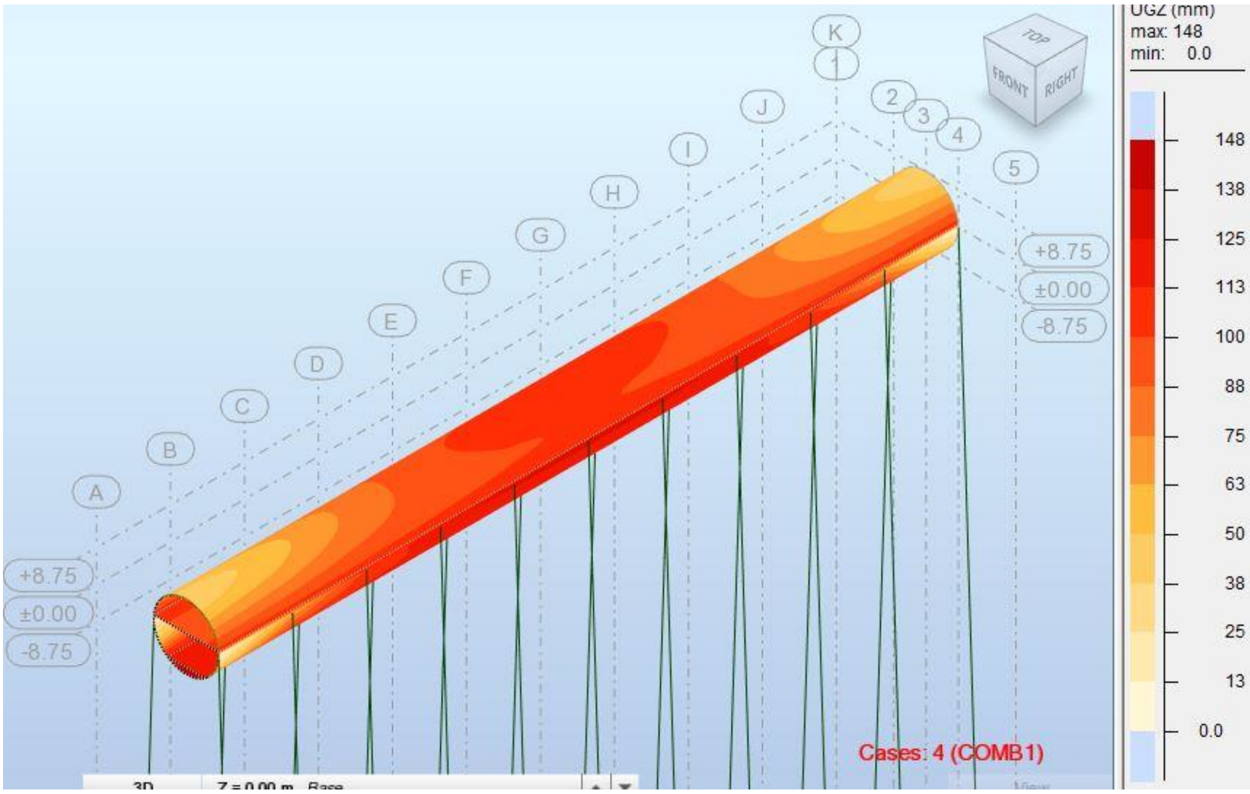


Figure G-3: Vertical Displacement Corresponding to 500mm Diameter Tether

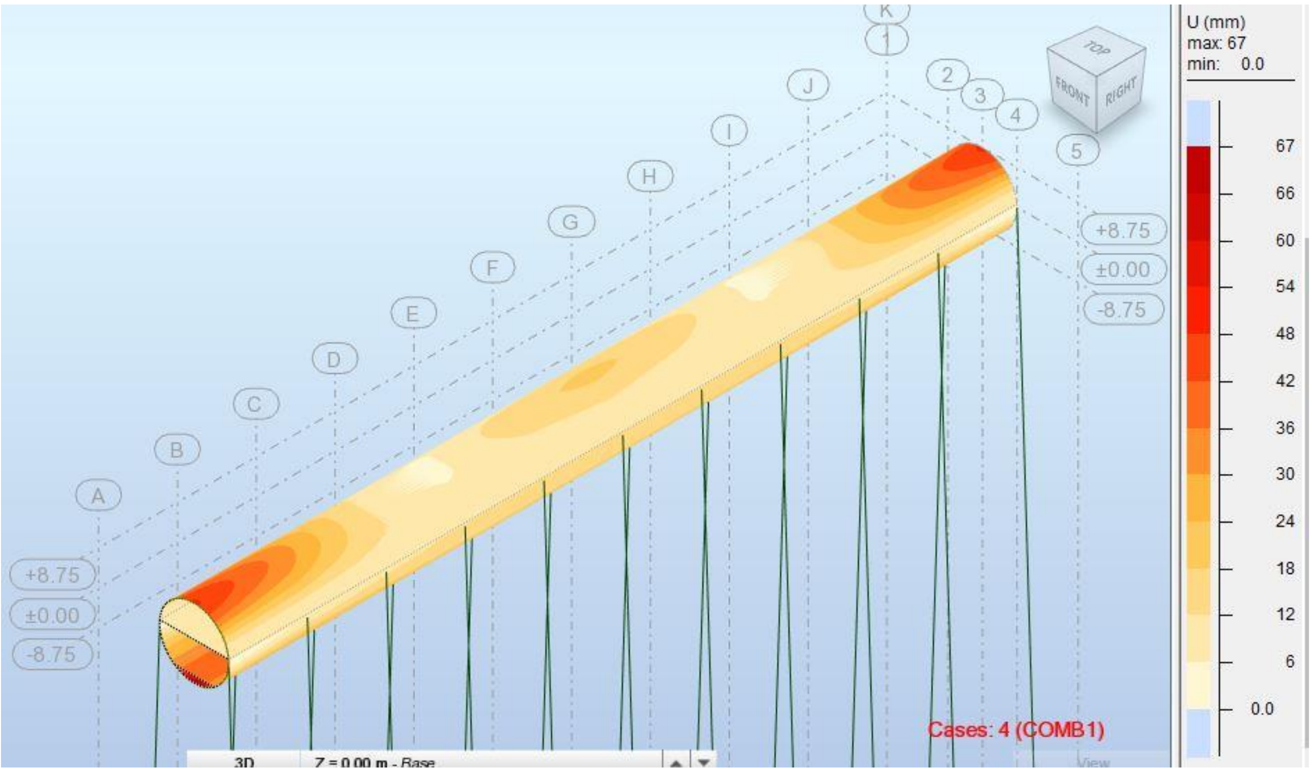


Figure G-4: Vertical Displacement Corresponding to 800mm Diameter Tether

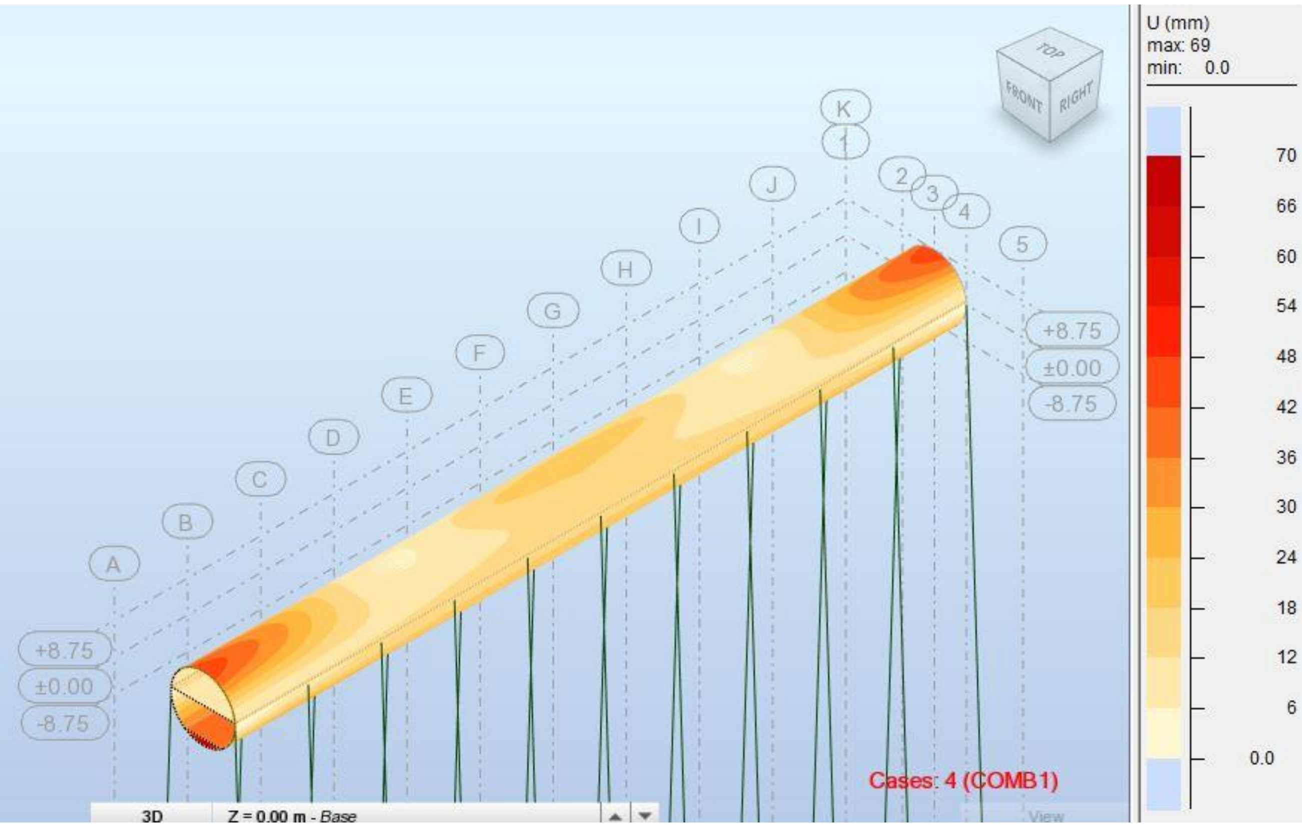


Figure G-5: Vertical Displacement Corresponding to 1000mm Diameter Tether

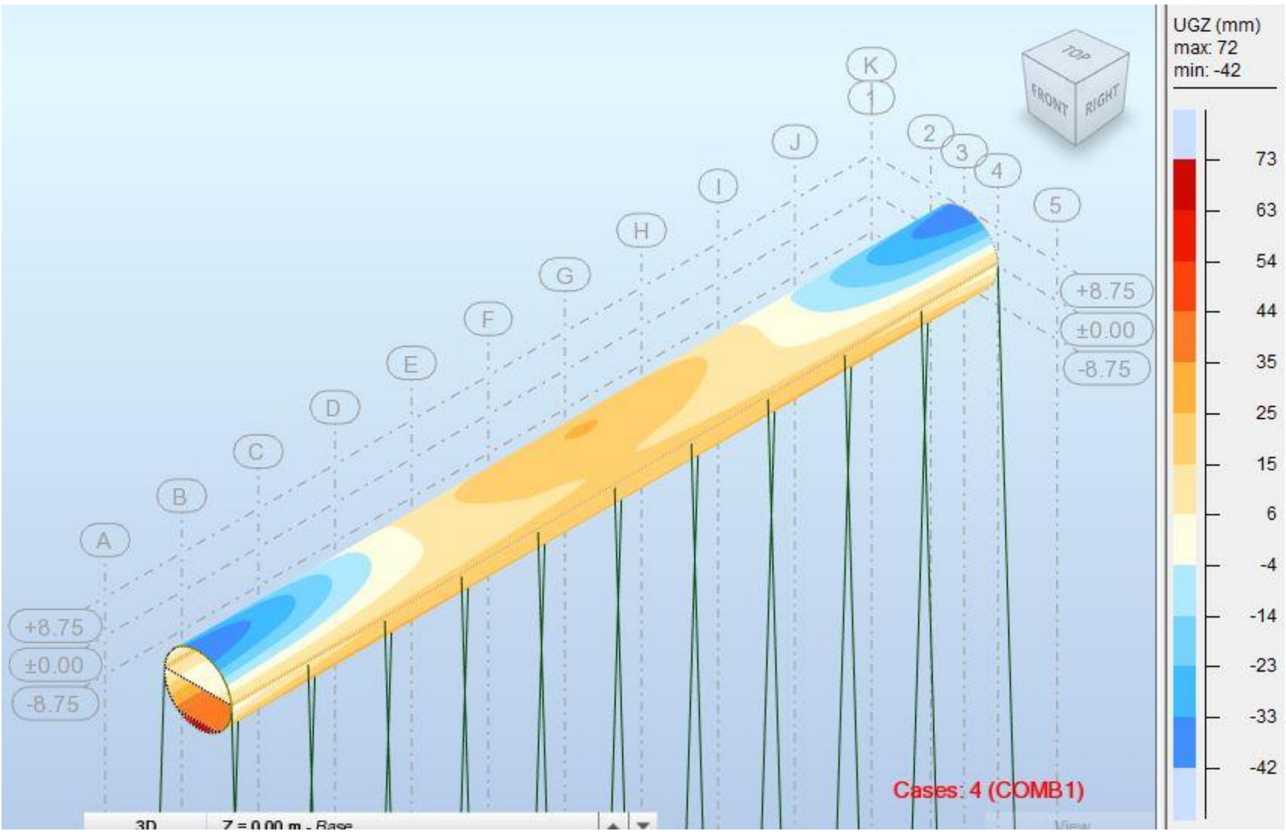


Figure G-6: Vertical Displacement Corresponding to 1200mm Diameter Tether

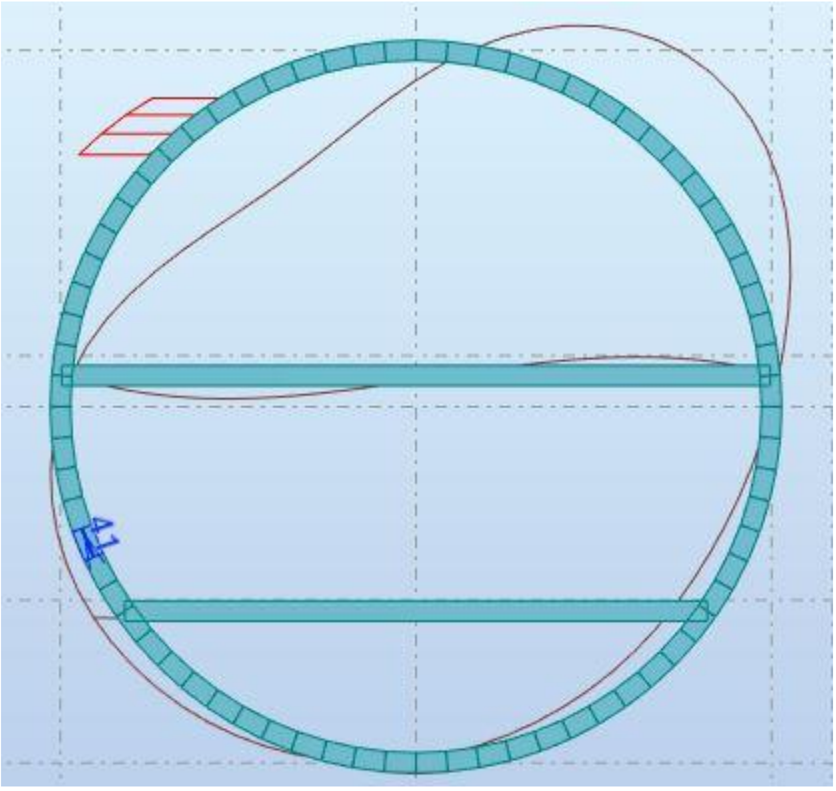


Figure G-7: Indented Shape of SFC after Marine Collision

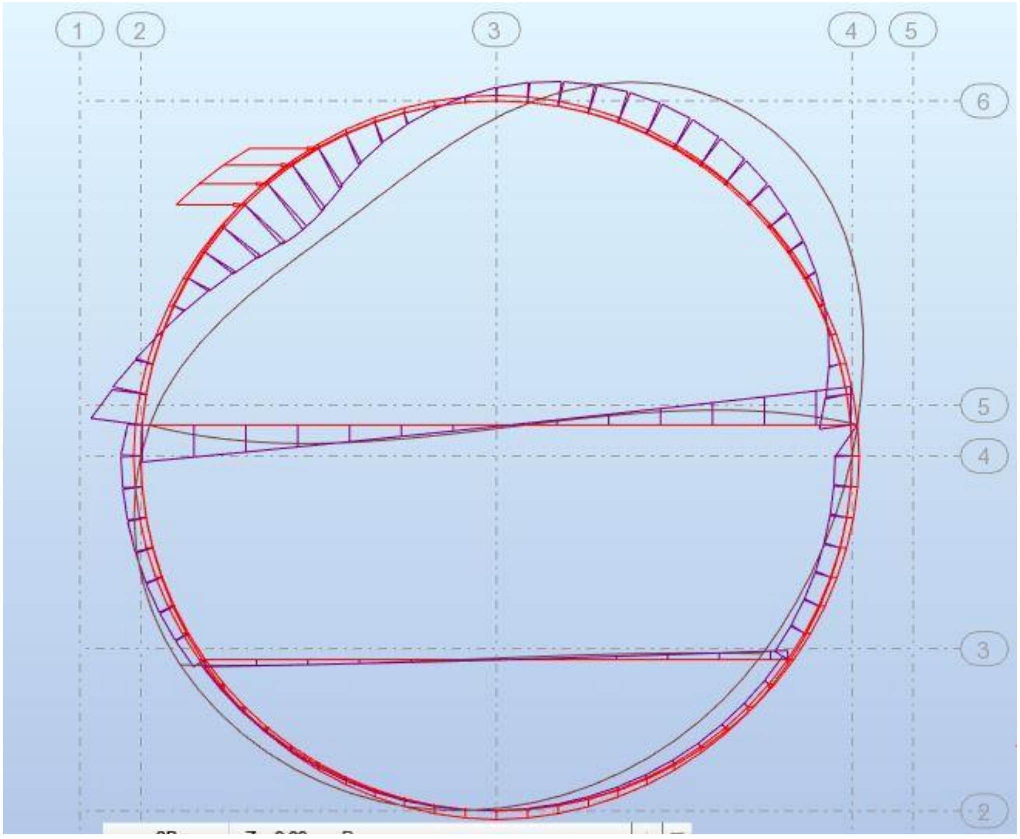


Figure G-8: Forces on SFC after submarine collision