Creating a decision support matrix for the design of a submerged floating tunnel

BSc-Thesis

Design of submerged floating tunnel – advantages and limitations of different submerged floating tunnel types – creating a decision support matrix – the application of decision support framework on Unkapani tunnel

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Colophon

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Preface

Before you lies the bachelor thesis named: “Creating a decision support matrix for the design of a submerged floating tunnel”. This assignment has been performed to finish my bachelor Civil Engineering at the University of Twente.

I would like to use this opportunity to thank several people that helped me during my research and the writing of my report. First of all, I would like to thank Gerrit Snellink and Irina Stipanovic for the guidance during this project and the feedback they gave on my report.

Secondly, I would like to thank Arjan Luttikholt for the great opportunity to learn about submerged floating tunnels the process involved with the design and construction of these kind of projects. I would also like to thank him for his guidance and feedback on my report. As well as all the other employees of Witteveen+Bos that helped with my project.

Finally, I would also like to thank my family that helped me during this project and the rest of my time at the University of Twente.

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Ewoud van Lent

Content

Summary

During the design phase of a submerged floating tunnel not a limited amount for research time is available. This could leave some SFT types not thoroughly being investigated and can result in neglecting a possible good solution for a certain problem. To solve this problem a decisions support matrix has been created. This matrix gives a clear overview between the differences of the four SFT types. The decision support matrix has been made by performing a literature study and numerical modelling.

The literature study showed that the advantages and limitations of different design solutions for SFTs could be divided into general, SFT specific and SFT type specific advantages and limitations. It became clear that SFTs advantages are that they cannot be seen above water and could be a solution for crossing longer and deeper waters than has been done before. The elliptical or rectangular cross section shape seems to be preferable. Likewise the most common materials used for cross section underwater are concrete and steel or a combination of both. For the different SFT types the difference in foundations played the most important role towards the advantages and disadvantages of every SFT type.

For the numerical analyses four reference designs have been modelled. Before these reference designs could be modelled the loads on the designs and the requirements of the design should be determined. The loads can be divided in permanent, variable and accidental loads. The permanent and variable loads are always affecting the SFTs and therefore the SFTs should be designed to withstand these loads. The accidental loads are loads that hopefully do not occur, but the SFT should be able to withstand them in case of an accident. All loads have been determined and calculated so they could be used for the modelling of the reference designs. Following the requirements were calculated. The requirements are a maximum tension in the cross sections of 2 N/mm^2 and a maximum displacement of 1/300 of the SFTs length. Also the tension in the cables could not surpass the maximum tension steel cables can absorb and the pressure-bearing-poles could not exceed a tension of 355 N/mm^2.

With the loads and requirements determined the reference designs could be modelled. When the reference designs met the requirements the accidental loads were applied to see what SFT types were able to withstand these loads. The found results were used to create the decision support matrix.

After the decision support matrix was created, it could be used to assess what SFT type would be suitable for the Unkapani tunnel project. The outcome was that the pressure-bearing-pole type would be the most adequate solution. When the dept increases the tethered SFT would become more adequate.

In the end the created decision support matrix seems like a good tool to get a first impression of the characteristics form the four SFT types and give a clear overview what SFT type could be a preferable during certain circumstances. Although the matrix could be expanded more by also compare the SFT types in case of a submarine collision and a seismic event. After the decision support matrix has been used to determine what SFT type should be used, the specific SFT should be designed from scratch. Since the reference designs only goal were to compare the four SFT types.

1 Introduction

In Istanbul the Unkapani Bridge will be replaced with a tunnel under the water, because it has been decided to clean the view of the city and enhance the water flow (Hurriyet daily news, 2017). The tunnel will cross the Golden Horn, a side river of the Bosporus and connect the Fatih and Beyoglu districts in Istanbul. The crossing will be around 950 meters long and the bedrock will start at a depth of 80 meters (Witteveen+Bos, 2016).

The contractors Joint Venture, with TEC (Witteveen+Bos and RHDHV) as consultant, has won the rights to this project. For the project the Joint Venture considered two designs. One reference design for a submerged floating tunnel (SFT) built on piles and an alternative design for a submerged floating tunnel with a combination of tethers and pontoons. In the alternative design the SFT was a combination of pontoons and tethers (Rene Kuiper, 2017).

Since the tender phase of the project was suspected to be very short, most of the time spent on the design went into the reference design with the tunnel on piles. This was the design requested in the tender document. Therefore other options related to submerged floating tunnels were not sufficiently researched and developed, while one of these solutions might be a good option.

Although the contractors JV is confident that the most economical solution is proposed, they also wonder whether the alternative solution might become more economical when conditions and requirements change (e.g. regions with minor shipping traffic, different depths, current velocities and other accidental loads). Therefore the main problem analysed in this project is to analyse four typical design solutions for SFTs and determine the influencing factors for choosing a certain solution.

1.1 Problem context

Submerged floating tunnels are a new type of tunnel and have never been built before. This brings a lot of challenges during the design and construction process. SFTs have much resemblance to immersed tunnels and the existing knowledge of immersed tunnels can also be used during the construction of a SFT.

Before the SFT can be built, it needs to be designed. Since no SFT has been built yet the design has to be made from scrap. The literature states that four types of SFT can be built and a choice between them needs to be made. However no clear overview of the characteristics of every type of SFT can be found, which makes choosing between the four types very difficult. Furthermore the conditions at the construction site greatly influence what SFT type is best suitable for a project. Important parameters for the construction of SFTs are the length and depth of the crossing, the bottom conditions, current velocity, ship traffic and all kind of accidental loads.

TEC has designed a submerged floating tunnel on pressure-bearing-poles to replace the Unkapani Bridge in Istanbul. This design seems to have clear advantages to the other types of SFTs, although not all other types of SFT were thoroughly investigated. In the tender phase of project, the engineering company is not yet getting paid for their work. Therefore only a certain amount of time can be invested in the preliminary designs. That is why TEC chose to design the SFT on pressure-bearing-poles, since this seemed to be the best design.

Due to this limited time another good solution might be missed, because not all SFT types can be researched. Therefore a system has to be created that can shorten the amount of time needed to choose between the four different SFT types.

1.2 Theoretical context

There are many different tunnels that create solutions for various construction problems. With the increase of the construction of tunnels new problems arise and new solutions have to be created. The commonly used techniques are cut-and-cover, using tunnel boring machines (TBMs) and immersed tunnels (Ballantyne, 2012). The newest types of tunnels are submerged floating tunnels, but no SFT has been built yet.

Immersed tunnels have the closed resemblance to SFTs. These tunnels consist of one or more hollow tunnel sections. These sections are constructed on a dry location, then the location is flooded and the elements are floating within (Lunniss, 2013). These floating elements are transported to their final locations, where temporary water ballast will be added to sink the element. After immersion the temporary water is exchanged for ballast concrete (Row, 2011). The sections are lowered in a pre-dredged trench and covered up with a layer of gravel (Ingerslev, 2010). Since the tunnel is built on the riverbed, dredging is a very important part of building the immersed tunnel. Dredging can be very costly if a lot of soil has to be transferred to and from the location. This also can greatly damage any sea life living at the riverbed (The Interstate Technology & Regulatory Council, 2014). Another problem is the maximum depth the immersed tunnels can be used at. The deeper the tunnel has to be placed, the more reinforcement is needed. Also the technique of placing the tunnel sections gets very complicated. These problems were experienced while building the tunnel connecting Busan and Geojo. It is presently the deepest built immersed tunnel, located at 48 meters below sea level. The placing one of the tunnel sections took 40 hours (COWI, 2016).

When the intension is to build tunnels in even deeper waters, immersed tunnels will not suffice. This problem has been known for a long time and some solutions have been thought of. Only in the last decade extensive research is done on how to cross those deep waters. One of the most popular solutions for this problem is submerged floating tunnels (SFTs). SFTs have been considered for a number of projects, for example to cross the Høgsfjord in Norway and the Messina strait in Italy (Ingerslev, 2010) These waters are too deep for immersed and bored tunnels and too wide for traditional suspension bridges. The most direct crossing is made by ferry, the other solution is driving around the water.

The different submerged floating tunnels can be divided in four categories (Xueji Wang, 2016):

A. The free submerged floating tunnel: In this case the tunnel supports itself and hangs loose in the water only supported to the land. There is no foundation or anchorage present.
B. The pontoon submerged floating tunnel: Some of the tunnel sections are hanging from pontoons that float on the water. The tunnel sections are made heavy enough to sink and the pontoons have a buoyancy to keep the whole structure floating.
C. The submerged floating tunnel with pressure-bearing-piers: This tunnel type resembles the immersed tunnel the most. Basically the same technique as immersed tunnels is used, but the tunnel sections are connected to poles.
D. The tethered type of submerged floating tunnel: This submerged tunnel uses tunnel sections that float, while they are hold down by cables.

Examples of these four types of submerged floating tunnels can be found in Figure 1.

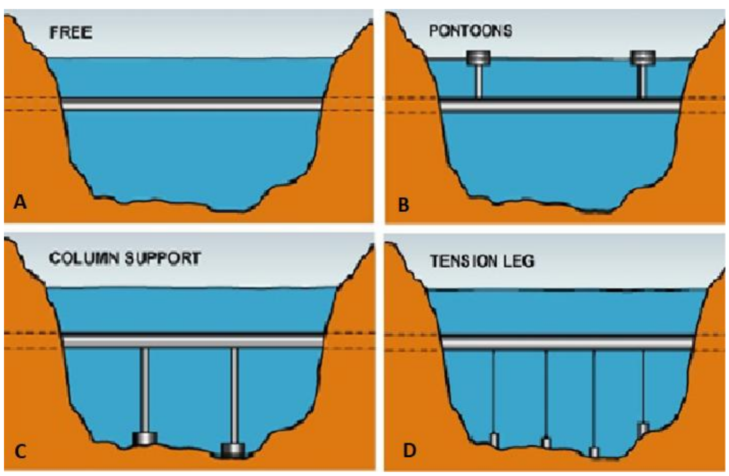

Figure 1 the four types of submerged floating tunnels (Mohan, 2011)

1.3 Research aim

The research aim of this project is analyse four main design solutions for submerged floating tunnels and to:

- **Identify the advantages and limitations of the four main submerged floating tunnel designs.**
- **Create a decision support matrix to support the preliminary design stage in order to choose the optimal design for a certain project.**
- **Using the created decision support matrix to analyse and propose good alternatives for the Unkapani tunnel project.**

1.4 Research questions

With the definition of research questions, the boundaries of the research are identified.
The research question of this report originates from the research aim. As mentioned before, the research aim of the report is to find what the advantages and disadvantages of the four SFTs are, create a decision support framework for the decision which SFT design best fits for a project and use it to support the choice for the Unkapani project. Therefore the main research question is:

- **Which submerged floating tunnel design solutions to choose in certain circumstances?**

To make answering this main research questions more manageable, it will be divided in six sub-questions. This also makes the boundaries of the research more clear. The first question that needs to be answered is what the differences are between the four designs. There has to be researched what the advantages and limitations of all four SFT designs are according to the literature. Consequently the first sub-question will be:

1. *What are the advantages and limitations of the four different submerged floating tunnel designs according to the literature?*

When this question is answered it will be clear how each SFT type differs from each other. The main differences will be the used type of foundation. Other differences that can be found are related to the shape of the tunnel, the way it reacts to different external forces and other advantages and limitations found in the literature.

Next there has to be researched which loads influence the designs of the SFTs and what generates these loads. This results in the following sub-question:

2. *Which loads are influencing submerged floating tunnels?*

This question will result in a list of loads that influence SFTs and how they influence the SFTs. There are three kinds of loads that will influence these SFTs: permanent loads, variable loads and accidental loads.

Since there is no SFT built yet, there are not many design regulations specified that apply to SFTs. Naturally the construction has to be safe, but it has to be investigated what the design requirements are for SFTs. Some will be defined by the client and some design requirements of other constructions might apply. Therefore the next question is:

3. *Which design requirements do the submerged floating tunnels need to meet?*

The answer to this question gives a clear overview of the requirements the SFT designs need to satisfy.

With the first three sub-questions answered it is clear what has to be taken into account when designing a SFT. Therefore it is now possible to create four reference SFTs designs. By reference designs is meant: 'a design that gives the blue prints for the SFT type that others can use to modify'. Creating the reference designs will be the answer to the next sub-question:

4. *What are possible reference designs for the four different types of submerged floating tunnels?*

The four reference designs will include a free floating SFT, a pontoon SFT, a SFT with pressure-bearing-piers and a tethered type of SFT. For comparison purposes the reference designs will correspond as much as possible. The forces on the designs of the SFTs will be assessed over the full length of the designs. The reference designs will be modelled in SCIA Engineer software, where all loading scenarios identified in question 2, can be modelled as forces. When the reference designs are correctly modelled the four different designs can be compared. Therefore the next sub-question will be:

5. *What are the maximum loads the four reference designs of submerged floating tunnels can withstand?*

With the help of SCIA Engineer the maximum loads on all four designs will be investigated. All modelled accidental loads will be increased separately until the construction fails. With these results a decision support matrix can be made that shows what conditions each design is able to handle.

To identify how useful the decision support matrix is at the start of the designing process of a SFT, the created decision support matrix can now be used to assess the situation for the Unkapani tunnel project. That leads to the last sub-question:

6. *What types of submerged floating tunnel are good solutions for the Unkapani tunnel project?*

This question will conclude the report and be used as a validation of the created decision support matrix. Most likely the optimal design following the decision making tool will be equal to the solution the contractors JV have chosen. Since SFTs have not been built yet, one of the other three SFT types might score better than expected.

1.5 Research method

The research method explains how the research will be conducted. Research can be done in different ways, but not all methods can be applied on the same subject. In the case of submerged floating tunnels a lot of theoretical studies are done, which resulted in a lot of available literature. However not many experiments have been done. A prototype of a submerged floating bridge was supposed to be built in Qiandao Lake in China to generate all kind of data about the SFTs (F. M. Mazzolani, 2008), but this SFT has not yet been built. With this generated data, a data analysis could be made. However with the absence of this sort of data it is not possible. Therefore this research is focussing on literature study and numerical modelling of the four different SFT types. With the found results a decision support matrix can be made and a case study can be done about the Unkapani tunnel project.

1.5.1 Literature study
The first part of this research will consist of a literature study. With the help of literature, the advantages and limitations of the four main design solutions for SFTs will be researched, as well as what loads influence submerged floating tunnels. Since no SFTs have been built yet, no specific design regulations have been created yet for building SFTs. Nevertheless the designs of the SFTs need some guidelines to which it is subjected. Therefore it will be investigated if design regulations of other constructions ought to be implemented on SFTs as well. The design regulations of tunnels in general will partly apply and some part of bridge design regulations as well, since a SFT could be compared with a bridge underwater.

1.5.2 Numerical modelling
When the necessary knowledge is acquired about SFTs, four reference designs of SFTs will be created. The designs of the SFTs will be observed over the full length, because this way the designs can best be used to show the effects on the different type of SFTs. The cross section of the reference designs will not be evaluated, since the interest of this study lies on the different types of SFTs. If the cross section would also be evaluated, the amount of possible different designs would be too extensive. To make viable supposition when comparing the different reference designs, they need to correspond as much as possible. Therefore the four designs will be similar and be analysed for a specific scenario.

The four created designs will be modelled in SCIA Engineer. SCIA Engineer is an integrated, multi-material structural analysis and design software for all kinds of structures (SCIA). In this program the SFTs will be modelled with the permanent, variable and accidental loads working on them. SCIA Engineer will be able to calculate the cross-sectional forces in the various structural elements. The variable and accidental loads will be increased separately up to the moment the capacity of one of the structural elements is reached. This is considered to be the ultimate load the structure can bear.

1.5.3 Creating a decision support matrix
With the generated information from SCIA engineer, the different reference designs of SFTs will be compared. Each design will have different maximum loads it can withstand before failing. To make this comparison evident the results are presented in a matrix. The matrix will show the range of every condition that each reference design can withstand before failing, as well as the found differences in the literature study.

1.5.4 Case study
Finally a case study will be done to consider the Unkapani tunnel project. As mentioned before, the Joint Venture is confident that the most economical solution is proposed. Nevertheless they want to know which design would be best suitable if conditions change. During this case study it will be researched what other SFT types can possibly be used to build the Unkapani tunnel. Therefore the conditions in the Golden Horn need to be researched and to be compared with the created matrix. These conditions include: what is the length needed to be spanned, the depth and composition of the riverbed, the forces created due to tsunamis, the flow of the river and the requirements set by the municipality of Istanbul for the Unkapani tunnel. Most of this data has already been acquired by the Joint Venture, but some additional data might be necessary to research. When this data is collected, the created framework can be used to find what types of SFTs are suitable for the construction of the Unkapani tunnel.

2 Theoretical study

2.1 The overview of the advantages and limitations of the four different submerged floating tunnel designs

In this paragraph the advantages and limitations of the four SFT designs will be analysed. This will be done with the help of a literature study. All advantages and limitations result from specific characteristics of the SFTs and their specific types. When studying the literature it became clear that the advantages and limitations for SFTs can be divided in three categories. They can also be described as characteristics:

- The general advantages and limitations compared with other waterway crossing methods.
- The general SFT design advantages and limitations: they are characteristic for SFTs specifics and are applicable to every type of SFT. These common characteristics are the shape of the tunnel tube and the material used for building the tunnel tube.
- Design specific advantages and limitations for SFTs: all four designs have their own specific characteristics.

2.1.1 Submerged floating tunnels compared with other waterway crossing methods

There are some general similarities between SFT that generate advantages:

- They are invisible: because the SFTs are placed under water, they cannot be seen. In some circumstances this makes SFTs preferable, because building another kind of crossing might result in a lot of protest from the general public(Østlid, 2010).
- SFTs can be built directly at both shore connections, which leaves the shores relatively untouched and results in minimum noise and air pollution. This also is the shortest way of crossing (Skorpa, 2010).
- The (initial) slope of the SFT can be reduced, because the construction does not have to be placed on the bottom of the waterway (Zhang, 2010).
- The construction of the SFT sections will mainly be done in docks and the installation will take place at the actual site. This reduces the disturbance in the local area and could improve the construction time (Østlid, 2010).
- The use of SFTs does not affect the environment a lot, since it has a small effect on the original currents in the water and does not require a lot of modification to the bottom of the waterway (Markey, 2010).
- The cost of the unit length construction will not significantly increase when the length of the waterway enlarges (Zhang, 2010).

There are some general limitations to SFTs as well:

- A SFT has never been built yet. This results in hesitance to build one, since some unforeseen accident might happen (Østlid, 2010).
- The fact that an SFT is completely surrounded by water might make people avoid using the SFT (Østlid, 2010).
- The safety of the structure has to be guaranteed in case of fatigue or accidents like leaking, collisions with ships or failure of a part of the construction (Jakobsen, 2010).
- The SFTs can be subjected to collisions with submarines (Ingerslev, 2010).
- It is a challenge to construct foundations in deep water where SFTs are viable, because of the complex marine geological conditions. The effectiveness of the construction methods will be important to create safety and economic advantages (Xiang, 2016).

2.1.2 The general advantages and limitations of the submerged floating tunnel designs

For the designs of SFTs two mayor components are the same, regardless of what type of SFT will be chosen. These are the shape of the tunnel cross section and the material used to build the tunnel cross section. The importance of the effects of these characteristics can differ for all types of SFT, because each type makes use of different foundation techniques.

Characteristics of different tunnel shapes

The shape of the cross section has a lot of influence on the interaction between the water and the tunnel (Martire, 2010). Many different shapes can be used for the designs, but not all would be logical. Therefore five cross section shapes will be discussed: circular, two circular tubes connected by a frame (ear shaped tube), polygonal, rectangular and elliptical.

A circular cross section has often been proposed by different studies, since it induces only compressive stresses and no bending in the cross section plane (Martire, 2010). However the circular cross section of the tunnel requires a more complicated construction process (Martire, 2010).

The ear shaped tube (shown in Figure 2) and elliptical shaped cross sections are very similar and therefore show the same reaction in the water. Circular sections are the most hydrostatic structures, but the ear shaped and elliptical cross section can better resist the lift and drag created by the water (Li, 2016). (Hao, 2016) states that the lift and drag on a SFT tube is more important, since it keeps the tunnel more stable in the water. However this tunnel shapes are also difficult to construct.

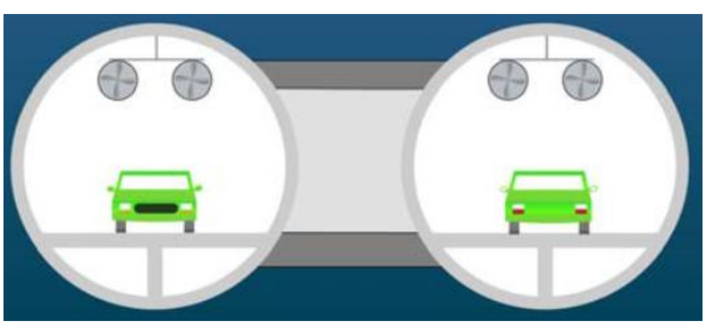

Figure 2 example of an ear-shaped tube (Skorpa, 2010)

When looking at a rectangle cross section, the pressure on that section is higher compared to the elliptical shaped section (Li, 2016). That results in a higher displacement and main stress in the section. The main advantage of a rectangle cross section is the simple production and the versatility in the organization of the internal spaces and facilities (Martire, 2010). To reduce the effect of the water pressure on the section it is possible install triangular steel frame on the sides to redirect the water (Martire, 2010). Another option would be to cut the sharp edges of the rectangle so it has an improved aerodynamic shape. An example of these shapes can be found in Figure 3 and are now reshaped to give it a polygonal shape.

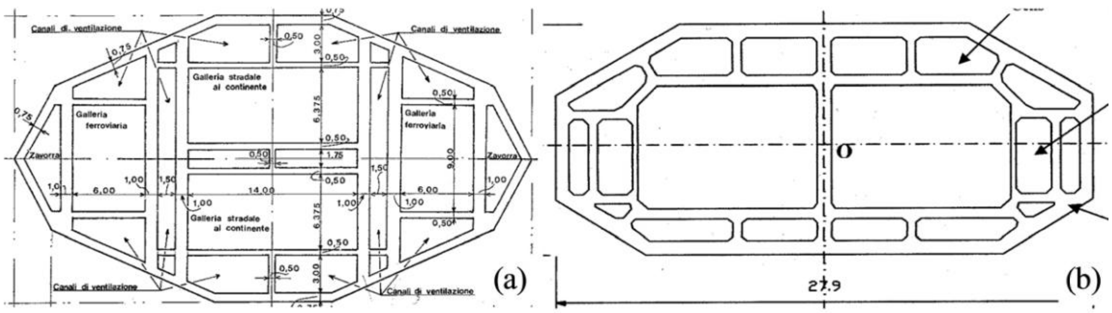

Figure 3 rectangular tunnel with triangular steel frame (a) and rectangular tunnel with smoothed edges (b) (Martire, 2010)

A distinct preference for a shape is not available. It is clear that the ear shaped and eclipse shaped cross sections are best resistance against the force created within the water, but also are more complicated to fabricate. While the forces created by the water affect the rectangle and polygonal shapes a lot more, it would be cheaper to build these sections (Li, 2016). The choice between the two shapes should be determined by the most economical option. The elliptical shaped section has a larger area than a rectangular shaped section and the transportation of an elliptical shaped section is more difficult than the rectangular shaped section (Li, 2016). However rectangular shaped section would need thicker walls to withstand the loads.

The advantages and limitations of used materials for the tunnel sections

The tunnel sections of SFTs can be constructed out of different materials. To create a safe and economical solution not all materials are applicable for the construction. The materials that would be suitable for the construction of the tunnel sections are (Martire, 2010):

- Steel;
- Reinforced concrete;
- Aluminium alloy.

The most common solutions will include steel and concrete, because they are widely used in offshore projects and therefore more knowledge is available about the use of these materials in the construction (Martire, 2010). Aluminium alloy is theoretical possible, but it is not often used for underwater structures.

Using steel as material of the sections would be possible, because it has good resistance to fatigue, good mechanical properties, it can be easily worked with and has a large strength-to-weight ratio. Nevertheless steel also has some limitations: the welds are the weak spots of the structure and will collapse before the rest of the structure will. Steel will also easily corrode when exposed to water (Professor J Billingham, 2003). At last the weight of a full steel structure is too small to prevent it from floating and more weight needs to be added to the structure. An example of a steel tunnel section can be found in Figure 4.

Figure 4 a steel tunnel section

A better solution is to combine the use of steel and concrete. Therefore a steel cast would have to be constructed and afterwards has to be filled with concrete. This is a technique that would increase the cost in comparison to the separate use of steel or concrete, but the construction time of the section would be faster and the section would be easier to make waterproof (Zhang, 2010). Figure 5 shows the construction of tunnel section with steel and reinforced concrete combined. The outside of the tunnel consists of steel, while the rebar is already placed on the steel plates.

Figure 5 a tunnel section of steel and concrete combined under construction

The use of reinforced concrete for the tunnel sections is already widely used for immersed tunnels and therefore makes sense to consider for SFTs as well. The use of concrete contributes to the structural strength and stiffness of the section as well as generates enough weight to counter the created buoyancy. Besides that, concrete can also be formed in complex shapes, it has good resistance to corrosion, has low construction costs and has a good resistance to high temperatures. Of course concrete also has some disadvantages: it cannot resist huge amounts of tensile stress and making the section waterproof is more challenging (Martire, 2010). Figure 6 shows an example of a concrete tunnel section.

Figure 6 a concrete tunnel section

Some literature suggests that aluminium alloys can be used for the construction of the tunnel sections(Martire, 2010). These alloys are similar to steel, but have some different characteristics. The weight is relatively low, it has a good workability, its strength is comparable to steel and it has a high resistance to corrosion. However aluminium alloy has a lower resistance to fire, a lower stiffness and is more expensive than steel (Martire, 2010).

2.1.3 The design specific advantages and limitations for the SFT types

To get a better insight in the different types of SFTs all four types will be evaluated. This will result in advantages and limitations for all four types of SFTs.

The free submerged floating tunnel

The free type of SFT is the simplest type of SFT. It does not use an anchor system or foundations, but depends on the stiffness of the structure to cross the desired distance. As a result of its simplicity it can be built in small scales and therefore saves materials, which can be economical beneficial.
This type of SFT also has a few downsides (Yan, Zhang, & Yu, 2016). It is difficult to construct, because the tunnel sections need to be kept in place until the whole construction is finished. The free SFT is also significantly affected by external influences like current velocity, traffic loads and accidental loads. Therefore this type can best be used for small crossings in calm waters. The estimate is that the length of this type of SFT can be 300 meters when used for only pedestrians and 150 meters when used by normal traffic (Østlid, 2010).

The pontoon submerged floating tunnel

This type of SFT uses pontoons to support the structure. The tunnels sections have a gravity that is larger than its buoyancy, therefore the sections would sink without the pontoons. The pontoons are constructed in a way that makes them float on the water with the tunnel section connected to it. Because this SFT is afloat it is not affected by the depth of the water and the characteristics of the soil. The pontoons could also support fishery and tourism as overwater facilities (Yan, Zhang, & Yu, 2016). There are also some limitations to the use of the pontoon type SFT. The pontoons will not add any horizontal stiffness to the construction, using pontoons will create restrictions for the ship traffic and create collision risks. Also the pontoons will be affected by wind, current and wave loads. Furthermore the visibility above the water could be seen as a disadvantage (Yan, Zhang, & Yu, 2016).
The estimate distance this pontoon type of SFT can be used for is around 2000 meters (Østlid, 2010).

The submerged floating tunnel with pressure-bearing-piers

The SFT with pressure-bearing-piers also makes use of tunnel sections that have higher gravity than buoyancy. Instead of using pontoons the tunnel section is supported by piers that keep the tunnel at a predetermined depth.
The advantages of this type of SFT are (Yan, Zhang, & Yu, 2016): the structure is able to absorb vertical and horizontal forces, it a simple structure and a lot of knowledge is already acquired by building immersed tunnels and bridges.
Nevertheless the pressure-bearing-piers SFT has also some limitations (Yan, Zhang, & Yu, 2016). It is depending of the depth of the water and suitability of the soil. This construction comes with high costs and the maintenance and administration can be difficult.

The tethered submerged floating tunnel

The tethered type of SFT makes use of higher buoyancy than gravity for every tunnel section. This makes the tunnel sections want to float. To prevent the tunnel sections from floating to the surface, the sections are anchored down with cables.
Advantages of the tethered type of SFT are: the use of cables makes the structure have a flexible form, the structure is not affected by waves and wind, it does not add restrictions to ship traffic and is not visible above water (Jakobsen, 2010). The downsides of this type of SFT are: a large net buoyancy is required to prevent slack in the cables, the tethers are subjected to dynamic loading, the cables could fail due to fatigue failure, the foundation is dependent on the soil conditions (Jakobsen, 2010)(Yan, Zhang, & Yu, 2016).
In Norway, a tethered SFT for the Høgsfjord-project has been designed for a depth of 450 meters and a length of 4500 meters. This could be a manageable distance and depth for constructing a tethered type SFT, while bigger depths and distances might also be possible.

The tether system can have several arrangements and the difference between them can have a severe impact on the structure. Therefore the arrangement of the cables will have to be evaluated further. Three types of arrangements are possible for this kind of SFT: the use of vertical cables, inclined cables or a combination of vertical and inclined cables as shown in Figure 7.

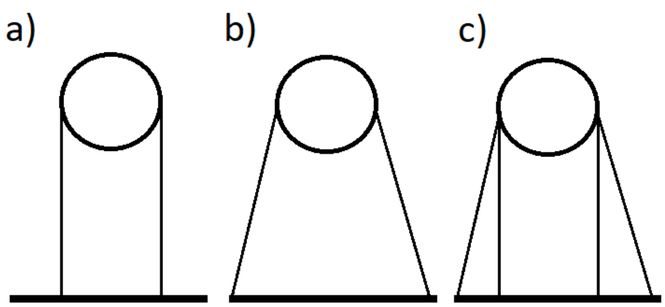

Figure 7 different arrangements of the tether systems

To get a clear overview of these different arrangements, the advantages and disadvantages will be compiled in Table 1. This table is created with the literature of (Yan, Zhang, & Yu, 2016) and (Lin, Mengjun, Guangdi, & Peng, 2016).

Table 1 advantages and disadvantages of the tether arrangements

	Advantages	Limitations
Vertical cables	This arrangement of cables can resist vertical loads effectively and the loads on the pile foundations are small.	The horizontal forces created by the water flow and other phenomenon should be small or keep the same direction
Inclined cables	The inclined cables can resist horizontal and vertical loads. Also it has a high anti-disturbance ability.	The foundations of the cables are subjected to higher forces, due to the distribution of the forces. Therefore the structure needs more cables to absorb the forces. The horizontal displacement of the tube can make the tube rotate, because angle the tethers will differ. Therefore the length end of the tethers will not be on the same height.
Combination of vertical and inclined cables	This arrangement of tethers results in the highest stability of the tunnel sections.	Because of the use of extra tethers, there is also need for extra foundations. This will increase the demands on the underwater soil environment.

The literature study has been summarized in Table 2 and will be used for the creation of the decision support matrix.

Table 2 summary of the literature study

	Advantages	Limitations
General	Invisible, can be built directly at shore connections, reduced slope of the SFT, small effect on the environment.	SFT has never been built yet, possible collisions with underwater vehicles, challenge to construct in deep waters.
Round shaped cross section	Induces only compressive stress and no bending in the cross section plane.	A complicated construction process.
Elliptical shaped cross section	Good resistance to lift and drag created by the water.	Larger area than other cross sections, will be difficult to transport and also difficult to construct .
Rectangular shaped cross section	Simple production and versatile in the organization of the internal spaces and facilities.	Subjected to higher displacement and main stress in the section.
Steel cross section	Good resistance to fatigue, good mechanical properties, it can be easily worked with and has a large strength-to-weight ratio	Welds are weak spot in the structure, steel will corrode easily and the weight of a steel structure is too small to be used for tunnel sections.
Reinforce concrete cross section	Widely used for immersed tunnels, good strength and stiffness, can be formed in complex shapes, good corrosion resistance and low construction costs	Cannot resist huge amounts of tensile stress and making the section waterproof is more challenging
Steel/concrete combined cross section	Fast construction time and easy to waterproof	Increased construction cost
Aluminium cross section	The weight is relatively low, it has a good workability, its strength is comparable to steel and it has a high resistance to corrosion.	Has a lower resistance to fire, a lower stiffness and is more expensive than steel
Free SFT	Simple design and fewest materials needed	difficult construction, limited possible length and significantly affected by external influences
Pontoon SFT	Not affected by water depth and characteristic of the soil, pontoons can support fishery and tourism. Estimated maximum span is around 2000 meters	No horizontal stiffness, limits ship traffic, will be largely affected by wind, current and waves
SFT with pressure-bearing-poles	Able to absorb vertical and horizontal forces, it a simple structure and a lot of knowledge is already acquired by building immersed tunnels and bridges.	It is depending of the depth of the water and suitability of the soil. This construction comes with high costs and the maintenance and administration can be difficult.
Tethered SFT	The use of cables makes the structure have a flexible form, the structure is not affected by waves and wind, it does not add restrictions to ship traffic and is not visible above water. Can be used with depths of at least 450 meters and length of 4500 meters.	A large net buoyancy is required to prevent slack in the cables, the tethers are subjected to dynamic loading, the cables could fail due to fatigue failure, the foundation is dependent on the soil conditions

2.2 The loads affecting the submerged floating tunnels

Before the reference designed can be created, the loads need to be determined. Without the loads it is impossible to create reference designs, since these designs need to withstand the loads SFTs are subjected to. Submerged floating tunnels are subjected to all kinds of loads. These loads can be separated in 3 categories: the permanent loads, variable loads and accidental loads. These loads will be investigated to provide a clear picture of sort of loads submerged floating tunnels need to withstand.

The described loads will be the loads that influence the total SFTs and disregard the internal loads that are important to the strength of the cross-section. Every load will first be described generally and a figure will show how the load is distributed on the SFT. The figures show the loads on the pressure-bearing-poles SFT reference design, but the loads are modelled exactly the same on the other reference designs. Thereafter the specific loads working on the SFTs will be calculated.

Some of the loads are depended of the dimensions of the cross section. Since the time limit of this research did not allow for designing a new cross section, the by TEC created cross section for the Unkapani tunnel has been taken. This cross section can be found in Figure 8. It has a width of 35,44 m, a height of 10,02 m, an area of 355,1 m^2, the area of the concrete is 133,2 m^2 and one tunnel section is 50 meters long. The tunnel will have three traffic lanes in both directions, with a width of 3 meters each.

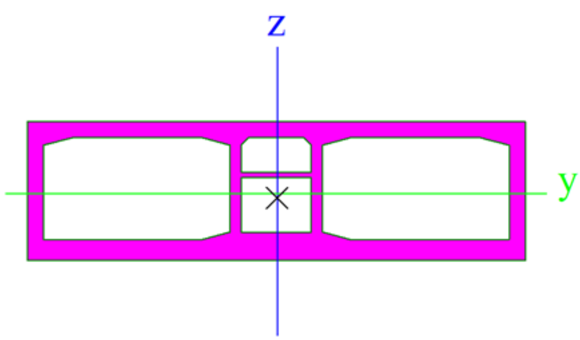

Figure 8 the cross section of the reference designs

2.2.1 Permanent loads

The permanent loads acting on the SFT are the weight of the structure, the water buoyancy, concrete ballast and the hydrostatic pressure (Martire, 2010). With the combination of these loads it can be determined if the tunnel sections are able to float to the right location, being sunk into place and stay stable when placed on its final location.

Self-weight of the tunnel

One of the most influential loads is the self-weight of the structure. This load is created by the weight of the total construction, which includes the weight of the used concrete, steel and other materials in the construction phase.

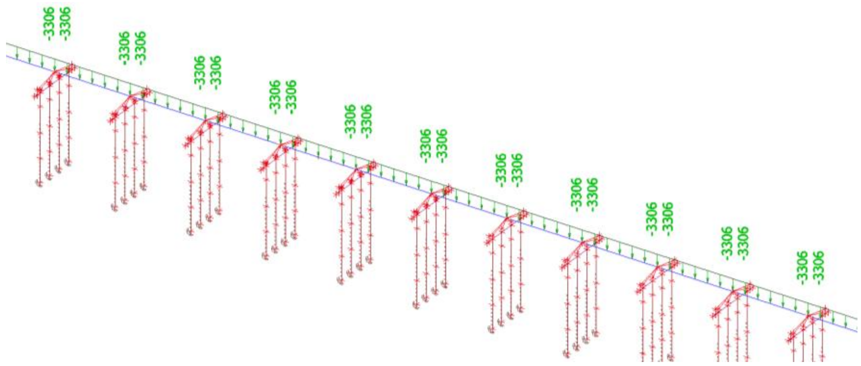

Figure 9 the load created by the self-weight modelled on the pressure-bearing-poles SFT reference design

To calculate the load created by the self-weight of the structure, the volume of the used construction materials has to be multiplied by the density of the used materials.

$$Self\ weight = V_{conrete} \times \rho_{reinforce\ \ concrete}$$

As mentioned before the cross sections dimensions of the Unkapani tunnel design from TEC (Barten & Ürkmez, 2016) have been used. This results in:

- Area of cross section reinforced structural concrete = 132,2 m^2
- Properties of used reinforced structural concrete = 25 kN/m^3
- $Self\ weight\ of\ a\ tunnel\ section = 132{,}2 \times 25 = 3.305\ kN/m$

Buoyancy

The buoyancy counteracts the gravity and generates an upward load. This is a very important load for SFTs, because it will absorb most of the downward loads on the SFT. In case of the tethered and the free type SFT it has to absorb almost all the loads on the SFT. The tethered and free type SFT can only counteract forces they are subject to with the help of the buoyancy and its connection to land. The buoyancy needs to be higher than the downward forces created. Proposed ratios in account to the self-weight are 120% to 130% (Faggiano, Martire, & Mazzolani, 2010). This would mean a buoyancy of 3966kN/m to 4296.5 kN/m is needed. The formula for the $\text{buoyancy} = \rho_{\text{water}} \times A_{\text{tunnel}}$

- The current cross section design has a buoyancy area of 355,1 m^2.
- The properties of water are 10 kN/m^3
- $The\ buoyancy\ of\ a\ tunnel\ section = 355{,}1 \times 10 = 3.551\ kN/m$

This does not meet the proposed ratio of 120% to 130%. First the calculated buoyancy will be used to see how the designs react. If the model does not meet the requirements, because of the buoyancy, this will be adjusted to the 120% or 130%.

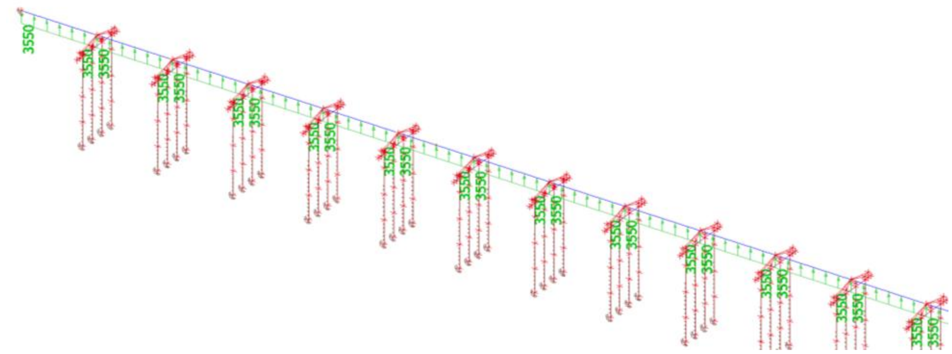

Figure 10 the load created by the buoyancy modelled on the pressure-bearing-poles SFT reference design

Ballast concrete

Another load considered as permanent load is the ballast concrete. The ballast concrete is a small layer of concrete to replace the used ballast tanks for sinking the tunnel section. This load will be added when the tunnel section is in position and thereafter will be permanent. Therefore this load is considered a permanent load. The amount of needed ballast is the load difference between the self-weight and the buoyancy. To make sure enough ballast is used and the tunnel sections will not flow, a factor of safety (FoS) will be applied on the amount of ballast. TEC applies a FoS of 1,06 for ballast concrete and therefore the needed ballast will be 6% higher than needed.

The concrete ballast will not be used for the tethered and free type SFT. In this case the tunnel sections need to have a positive buoyancy to make it float and the ballast used to move the tunnel sections in place will be removed after it is placed in the right position (Barten & Ürkmez, 2016).

The ballast concrete is calculated as follows:

- To the ballast concrete is a FoS of 1,06 applied.
- To formula for the FoS is:
  $FoS = \frac{load\ \ self\ \ weight + load\ \ ballast\ \ concrete}{buoyancy\ \ load}$.
- $1{,}060 = \frac{3.305 + load\ \ ballast\ \ concrete}{3.551}$.
- Therefore the ballast concrete has to be $1{,}06 \times 3.551 - 3.305 = 459{,}06\ \mathrm{kN/m}$

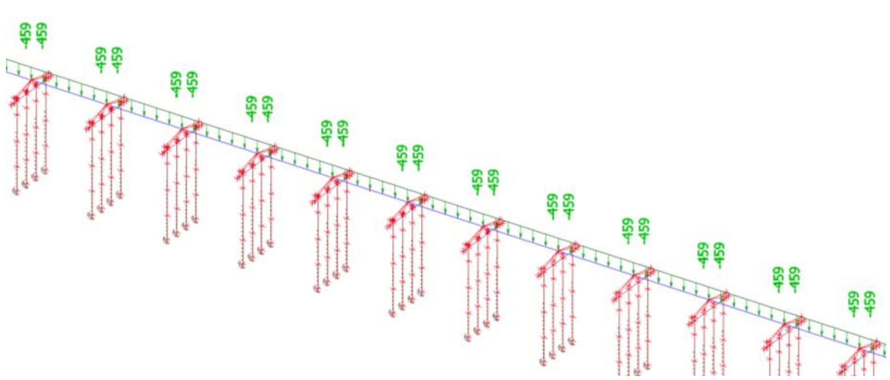

Figure 11 the load created by the ballast concrete modelled on the pressure-bearing-poles SFT reference design

2.2.2 Variable loads

Variable loads are loads that the tunnel has to absorb constantly, but the magnitude of the loads will be variable and the position at which the load will work can differ. Variable loads the SFTs are subjected to are: road traffic loads, wave loads, current loads, concrete creep and shrinkage, thermal loads and temporary loads. Naturally the tunnel has to be designed to absorb the maximum variable load possible (Barten & Ürkmez, 2016).

Traffic loads

All traffic, that will use the SFT, will generate the road traffic loads. The largest magnitude of forces will occur, when a traffic jam with several trucks occurs in the tunnel. The Eurocode has created a standard that has to be met when building tunnels that transport traffic. This standard can be found in NEN-EN 1991-2. Table 3 shows the loads that the SFT needs to absorb without failing, depending on the amount of traffic lanes that are used in the SFT.

- The first column of Table 3 shows the point load produced by one axle of a truck. Since a truck has two axes this number has to be multiplied.
- The standard dictates that the load of 1 truck on a tunnel section has to be accounted for.
- The axle load generated by a truck $= (300 + 200 + 100) \times 2 = 1200\ kN$
- The second column of Table 3 shows the distributed load that represents the normal traffic through the SFT.
- As mentioned before the Unkapani tunnel cross section is used, which has 3 traffic lanes in both directions, so 6 lanes in total. Every road has also an spare part of asphalt next to the created traffic lanes. To account for possible vehicles on that lane an extra distributed load of 2,5 kN/m^2 for the whole construction has to be taken into account.
- The widths of the lanes are 3 meters each.
- The distributed load can be calculated by adding the three loads applied to the first three traffic lanes. Multiplying this number because 6 traffic lanes are used. Next another 2,5 kN/m has to be added for the spare asphalt. At last the number has to be multiplied by 3, because the width of the traffic lanes are 3 meters.
- $The\ distributed\ load\ is = ((9 + 2{,}5 + 2{,}5) \times 2 + 2{,}5)\ \times 3 = 91{,}5\ kN/m$

Table 3 loads tunnels need to satisfy when transporting traffic (Nederlands Normalisatie-instituut, 2015)

Positie	**Tandemstelsel *TS***	**Gelijkmatig verdeelde belasting (GVB)**
	Aslast Q_{ik} (kN)	q_{ik} **(of q_{rk})** (kN/m^2)
Rijstrook nummer 1	300	9
Rijstrook nummer 2	200	2,5
Rijstrook nummer 3	100	2,5
Overige rijstroken	0	2,5
Resterende oppervlakte (q_{rk})	0	2,5

NEN-EN 1991-2 also states that loads for breaking and accelerating traffic have to be accounted for. This can be calculated with the following two formulas (Nederlands Normalisatie-instituut, 2015):

$$Q_{1k} = 0.6(2Q_{1k)} + 0.1q_{1k}w_1L$$

$$180\ kN \leq Q_{1k} \leq 900\ kN$$

With Q_{1k} = the axle load generated by a truck, q_{1k} = the distributed load generated by the road traffic, the w_1 = the width of the lane and L = the length of the tunnel section.

- The maximum of only one traffic lane has to be accounted for in the given formula.
- The horizontal brake and acceleration loads will be:
  $Q1k = 0,6\ (2 \times 300) + (0,1 \times 9 \times 3 \times 50) = 495\ kN$

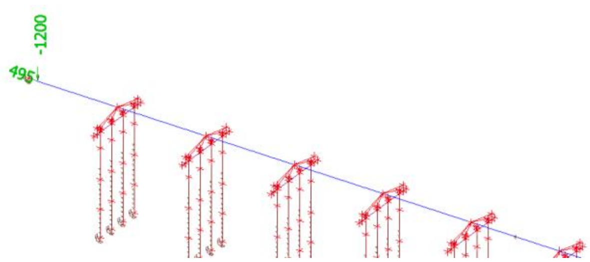

Figure 12 the load created by a truck and acceleration modelled on the pressure-bearing-poles SFT reference design

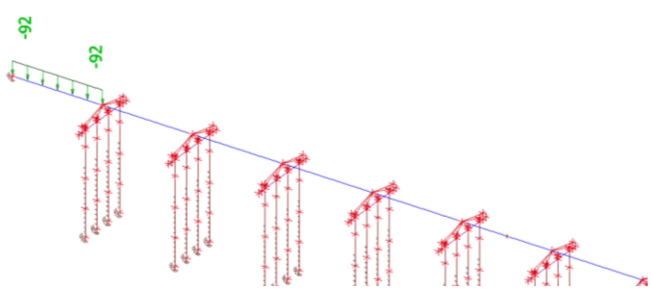

Figure 13 the load created by the traffic modelled on the pressure-bearing-poles SFT reference design

Wave loads

There are two types of waves that can be generated: wind generated waves and internal waves (Martire, 2010). Wind generated waves are on top of the water and are created by the wind. These kinds of waves only affect the pontoon type SFT. Lots of research is needed to find out the effect on waves on pontoon SFTs. For the research of this report it is assumed the pontoon SFT will not be influenced by waves. This means it cannot be built in places where waves occur that are big enough to affect the pontoons.

The internal waves are created by differences in density in the water, created by difference in temperature, salinity or concentration of sediment (Martire, 2010). This occurs only in specific situations and it will be assumed that internal waves have no effect on the SFTs.

Current loads

Current loads are generated by the current of the water and mostly occur in horizontal direction. Due to the tide, loads in vertical direction can also occur (Martire, 2010), nevertheless they can be neglected when the structure has been placed in deep water. Since SFTs are built in deep waters, the vertical loads generated by currents are neglected.

- The force created by current on the SFT is the drag force.
- The drag force can be calculated with the formula: $F_D = \frac{1}{2}\rho C_D A u^2$
- ρ = the density of water 1020 kg/m^3, C_D is the drag coefficient, that can reach 2 for very wide square shaped structures as SFTs(Barten & Ürkmez, 2016), A is the cross sectional area of the structure and u is the speed of the water.
- A = 10 m x 1 m = 10 m^2
- For u different values can be taken. It depends on the situation and the flow of the river. The value of the flow will be taken at 0.5 m/s, since this value was also taken for the designed Unkapani tunnel.
- $The\ drag\ force = 0{,}5 \times 1020\ \mathrm{kg/m^3} \times 2 \times 10m \times (0{,}5\ m/s)^2 = 2{,}55\,\frac{kN}{m}$

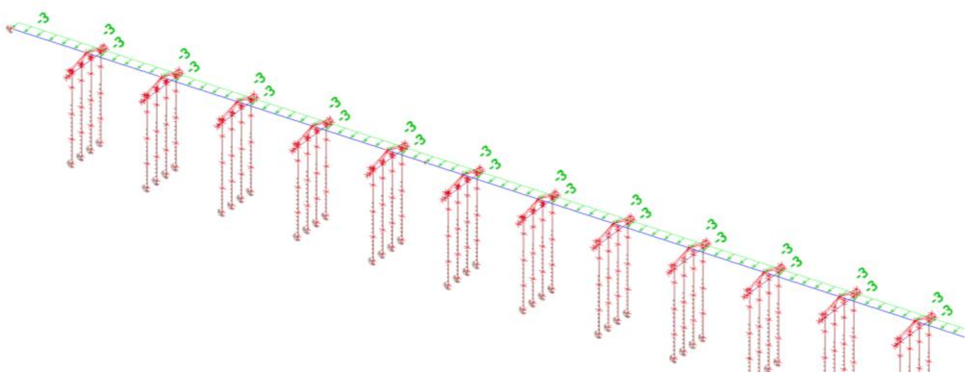

Figure 14 the load created by the current modelled on the pressure-bearing-poles SFT reference design

Thermal loads

SFTs are subjected to thermal loads. These loads are generated by the difference in temperature at the inside of the tunnel and the outside of the tunnel. The inside temperature of the tunnel section is the result of the air temperature, while the temperature of the outside of the tunnel results from the water temperature. The difference in these temperatures can make the structure expand and create significant loads on the structure. These loads can be calculated with the eurocode NEN-EN 1991-1-5 (Nederlands Normalisatie-instituut , 2011). For the SFTs reference designs an average temperature of 15°C is taken and a maximum temperature difference of 15°C. This could mean that the temperature in the tunnel can be 30°C or 0°C, while the water temperature is 15°C. The thermals loads are inputted in scia engineer.

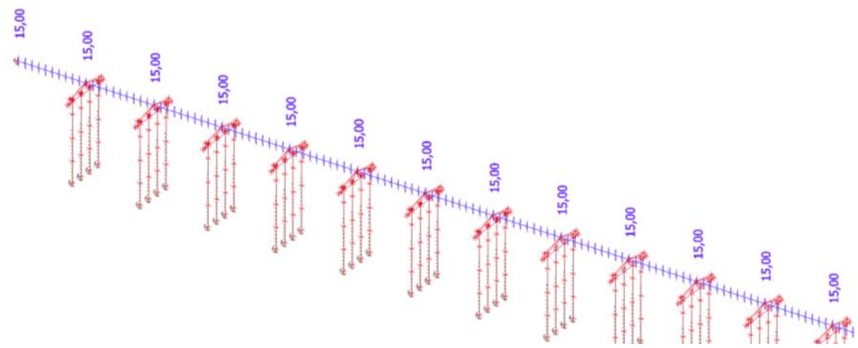

Figure 15 the thermal load modelled on the pressure-bearing-poles SFT reference design

Temporary loads

The last variable load is the temporary load. This load consists of loads during the construction and transportation. Since the research is about the loads the SFT can handle when completed, these loads are not taken into account.

2.2.3 Accidental loads

There are also loads that hopefully do not happen, but when they do the consequences are enormous. These loads are called accidental loads. Accidental loads that are applicable to SFTs are: the flooding of the tunnel, a falling anchor, a dragging anchor, a sunken vessel, tsunami loads and seismic loads (Barten & Ürkmez, 2016).

Tunnel flooding

The flooding of a tunnel is one of the worst accidental loads that can be encountered, because all the air in the tunnel will be replaced by water. Therefore a flood will result in decreased buoyancy and increased loads that the structure has to absorb. This is an extreme load that a SFT cannot be designed for. So during the design it has to be made sure a tunnel will not be completely flooded. This can be calculated by:

- $total\ flooding\ load = hydrostatic\ load\ \times area\ of\ air\ inside\ the\ tunnel$
- $Area\ of\ air = total\ area\ of\ the\ cross\ section - area\ of\ reinforced\ concrete$
- $Area\ of\ air = 355{,}1\ m^2 - 133{,}2\ m^2 = 221{,}9\ m^2$
- $Total\ flooding\ load = 10\ kN/m^3 \times 221{,}9\ m^2 = 2.219\ kN/m$

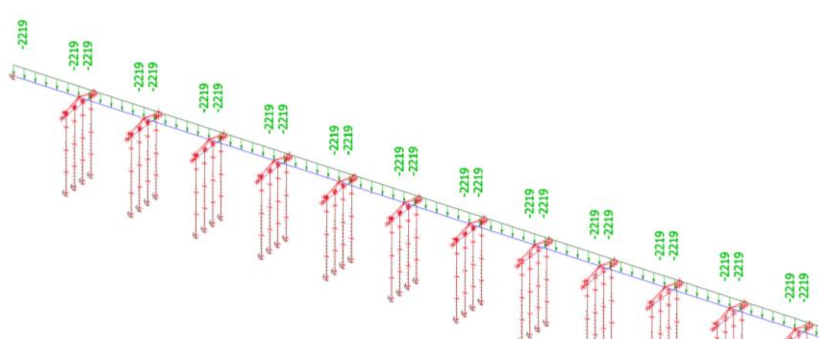

Figure 16 the load created by total flooding modelled on the pressure-bearing-poles SFT reference design

It is also possible for a SFT to be partially flooded. This can occur because a leak in the tunnel is found in time or both tunnel ends are closed to keep water from coming in during intense rainfall (because the SFT lies below the surface the water can easily flow down the SFT). In this case the generated load will be treated as hydrostatic loads with a density of 10 kN/m^3 (Barten & Ürkmez, 2016). The partial flooding will be modelled by establishing a load of the magnitude of one compartment filled with water for 25%, in the middle of the tunnel. Therefore the air area has to be divided by 4.

- This means the air in the flooded compartment will be replaced by water.
- The assumption will be made that one compartment will be 25% flooded
- And the tunnel will be filled with water, which generates a load of:
  Hydrostatic load x buoyancy area = $10\ kN/m^3 \times 0{,}25 \times 221{,}9\ m^2 = 554{,}75\ kN/m$ over an area of 50 meters.

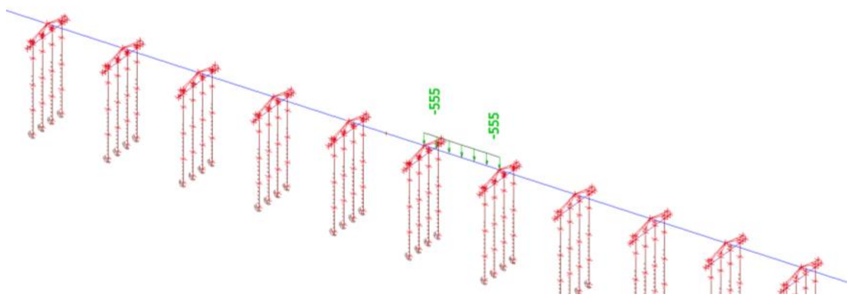

Figure 17 the load created by partial flooding modelled on the pressure-bearing-poles SFT reference design

Falling and dragging anchors

Since the tunnel is positioned in the middle of the waterway, it can be exposed to falling and dragging anchors. The load created by a falling anchor will not be able to make the construction fail. However the load can damage the tunnel, so that it needs repair or if not repaired can create a problem over time. Therefore the tunnel has a protective layer on top. This protective layer has to be designed to resist the damage created by falling anchors (Lunniss, 2013). This load will not be accounted for in the reference designs, because a protective layer on top of the tunnel will not be designed.

A dragging anchor creates a load in the horizontal direction that can generate a problem if it gets stuck behind the structure. The generated load could be calculated by considering the breaking loads of the anchor chain for all types of ships and anchors. This should not be needed, because the objective of the designer should be to design a tunnel where anchors cannot get stuck behind the structure (Lunniss, 2013). Therefore the most cross-section designs have flattened corners that prevent anchors from getting stuck.

Sunken vessel

Similar to the loads created by falling and dragging anchors, the load of a sunken vessel heavily depends on the size of the ship. Since the depth at which the tunnel is located is relatively small to the length of the ships, the load created by the sinking velocity is neglected (Barten & Ürkmez, 2016). There are several ways a ship can sink and affect the tunnel. It could sink right on top of the tunnel or partly and end up in an angle on the structure as can be seen in Figure 18.

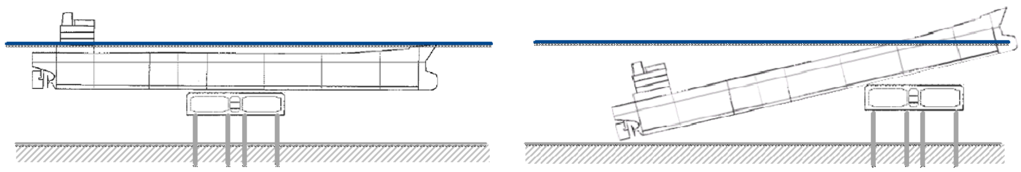

Figure 18 possible position of sunken vessels (Barten & Ürkmez, 2016)

The type of sunken vessel is very important for the amount of force created on the SFTs. In Table 4 the classifications of different Dutch vessels can be found and the weight of these vessels. With this information it is possible to calculate the amount of force a sunken vessel will generate on the structure by multiplying the mass of the vessel with the gravitational factor. To model a sunken vessel on the SFT a vessel of category Va will be chosen from Table 4. This type of ship is chosen because it is a decent sized ship that is not extremely big or small. This type of ship also resembles the load taken for the Unkapani tunnel design.

- The taken generated load by a sunken vessel will be $2.000.000\ kg \times 10\ N/kg = 20.000\ kN$

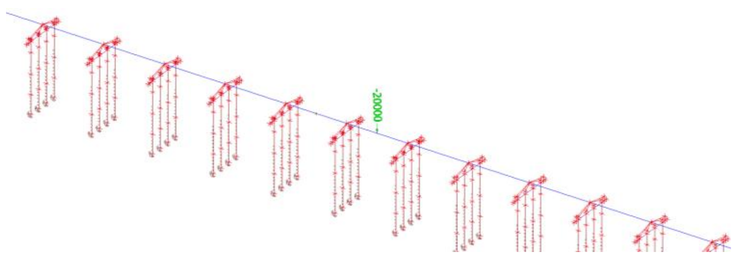

Figure 19 the load created by a sunken vessel modelled on the pressure-bearing-poles SFT reference design

Table 4 Classifications vessels (Rijkswaterstaat, 2013)

Klasse	Type	Lengte [m]	Breedte [m]	Diepgang [m]	Massa* (ton)
0	Klein/ recreatie	< 30	-	-	< 250
I	Spits	30 – 50	5,05	1,80 – 2,20	250 – 400
II	Kempenaar	50 – 60	6,60	2,50	400 – 650
III	Dortmund-Eems-kanaalschip	60 – 80	8,20	2,50	650 – 1000
IV	Rijn-Herne-kanaalschip	80 – 90	9,50	2,50	1000 -1500
Va	Groot Rijnschip	90 – 110	11,40	2,50 – 2,80	1500 – 3000
Vb	Duwvaart 2 bakken	110 – 180	11,40	2,50 – 4,50	3000 – 6000
VIa	Duwvaart 2 bakken	110 – 180	22,80	2,50 – 4,50	3000 – 6000
VIb	Duwvaart 4 bakken	110 – 190	22,80	2,50 – 4,50	6000 – 12000
VIc	Duwvaart 6 bakken	190 – 280	22,80	2,50 – 4,50	10000 – 18000
VII	Duwvaart 9 bakken	300	34,20	2,50 – 4,50	14000 – 27000

Tsunamis

Tsunami waves have very long lengths and small surface elevations in deep open waters. When the waves get closer to shore the height of the waves can enormously increase. Both waves can create loads on the SFT that can potentially generate failure of the structure. The tsunami load on the SFT can be calculated with the Morison's equation as a sum of the drag force and the inertia force(Barten & Ürkmez, 2016). Because the wave period of a tsunami is very long the inertia force can be neglected. Therefore the load on the SFTs created by tsunamis is comparable with the loads created by currents (Martire, 2010) and can be calculated by calculating the drag force. The loads created by tsunamis work in horizontal and vertical direction and are much higher than the current loads, because the water velocity is much higher. Depending on the force and distance travelled from the start of the Tsunami, the velocity of the water can differ from 0-18 m/s (Akito Tsutsumi, 2000). In every situation this flow velocity can be different and detailed research needs to be done to find the water velocity and chance of occurrence. This is still a very big range and needs to be specified. When looking at the Unkapani tunnel design a horizontal velocity of 5 m/s and a vertical velocity of 2 m/s has been taken. Therefore these values will also be taken for the reference designs. This results in:

- $The\ horizontal\ tsunami\ load = 0.5 \times 1020\ \mathrm{kg/m^3} \times 2 \times 10\ m \times (5\ m/s)^2 = 255\ kN/m$
- For the vertical load a width of 35,44 meter has to be used.
- $The\ vertical\ tsunami\ load = 0.5 \times 1020\ \mathrm{kg/m^3} \times 2 \times 35{,}44\ m \times (2\ m/s)^2 = 144{,}6\ kN/m$

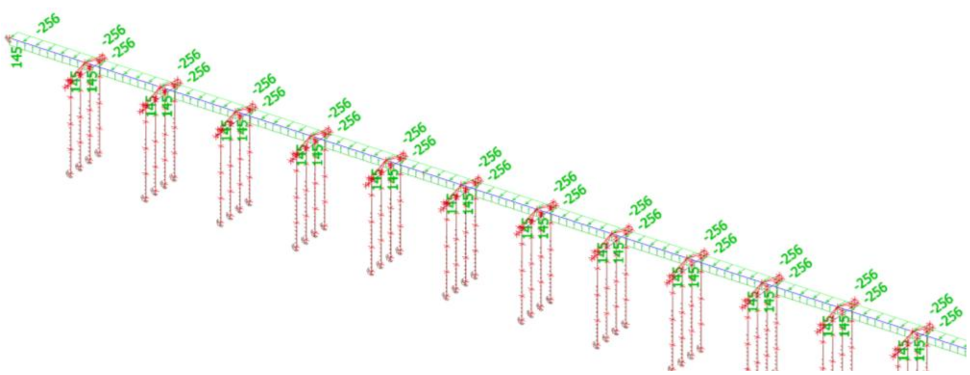

Figure 20 the load created a tsunami modelled on the pressure-bearing-poles SFT reference design

Loads modelled in SCIA engineer

The explained loads will be modelled in SCIA engineer. When looking at the permanent loads and the current load, it is clear that these loads are placed on the whole structure. The thermal load also occurs over the whole structure, but is presented differently since this load occurs inside the structure, where the other loads are external.

The traffic loads are variable and are modelled as a separate load working on each tunnel section. SCIA engineer uses load combinations, where it calculates the outcome for all possible combinations that can be made with assigned loads. In the case of traffic loads, it looks at the tunnel being totally filled with traffic to one tunnel section being filled and everything in between. Only the loads on one tunnel section are presented, because presenting all the combinations on the SFT would make the appendix unreadable. Nevertheless in the model these loads are applied on all tunnel sections.

To give a clear overview of the modelled loads they are summarized in Table 5.

Table 5 loads modelled on the reference designs

Type of load	Loads value
Self-weight	3305 kN/m
Buoyancy	3551 kN/m
Ballast concrete	459,06 kN/m
Axle load generated by a truck	1200 kN
Distributed load generated by traffic	91,5 kN/m
Brake and acceleration loads	495 kN
Current loads	2,55 kN/m
Total flooding load	2.219 kN/m
Partial flooding load	554,75 kN/m
Sunken vessel load	20.000 kN
Horizontal tsunami load	255 kN/m
Vertical tsunami load	144,6 kN/m

2.3 The requirements for the SFT reference designs

Before the reference designs can be created some requirements need to be in place for the designs. The requirements are needed so the four reference designs can be properly compared, because they were designed for the same purpose. When a construction is designed the most important requirement is that it can absorb all the loads it will be subjected to. This will be checked by designing the reference designs in SCIA engineer. With SCIA engineer all cross-sectional forces in the structural elements can be calculated and checked. All four designs will be checked for the ultimate limit state (ULS) and designed so that they comply. When the reference designs meet the requirements of the ultimate limit state, the reference designs will be checked for the accidental loads. Now the designs can be compared by checking which accidental loads they can absorb and which not.

The first requirement is applicable on the tunnel section. The tunnel section will be made of concrete and cannot fail. To prevent the concrete from failing a pre-tension needs to be applied such that no tensile stresses will arise in the concrete. The pre-tension will be 2 N/mm^2 and will be applied by means of prestress cables in the roof and floor. Therefore the maximum tensile stress in the SFT sections can be 2 N/mm^2.

The foundations of the SFTs will also be subjected to forces resulting in stresses. These foundations are steel cables or concrete poles enclosed by steel. The steel cables will be subject to tensile stresses which is limited to 355 N/mm2 (S355). The poles are subject to normal forces and bending moments. The combination of both result in stresses which are also limited to 355 N/mm^2.

Secondly there has to be a maximum for the displacement of the tunnel. Since there are no SFTs built yet, specific requirements cannot be found. It is possible to take a look at standards for other constructions and find their requirements for displacement. The most obvious standard to look for is the standard for building bridges, since they resemble SFTs quite a lot. The maximum displacement allowed on bridges longer than 10 meters ($L > 10m$) is the length of the bridge divided by 300 (maximum displacement = $L/300$)(Nederlands Normalisatie-instituut, 2011). Therefore this will be a requirement for the reference designs.

3 Numerical modelling

Now the loads on the SFTs and the requirements for the SFTs are determined, the reference designs can be modelled. This is a process with a lot of iteration to get to appropriate designs. To give a clear overview of the design process a flow chart can be found in Figure 21.

As mentioned before, all four references designs will be designed in SCIA engineer. Each design will be clarified in the next section. Thereafter the tension and displacement on the reference designs will be presented.

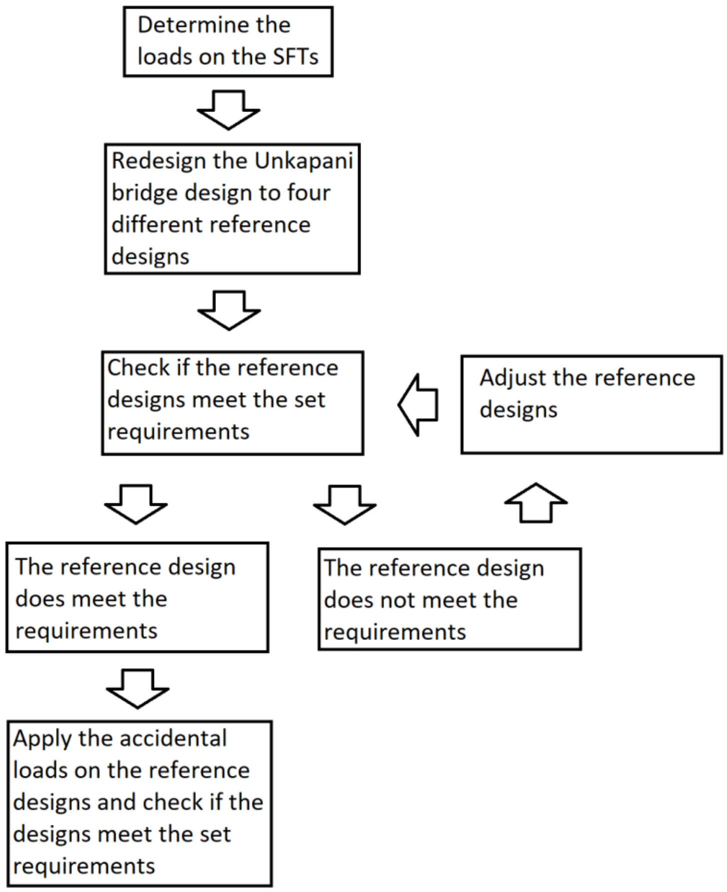

Figure 21 an overview of the design process

For the start of the four designs an existing design for the Unkapani tunnel will be used. The Unkapani tunnel is designed to be on piles has to cross a distance of 950 meters and exists of part cut-and-cover tunnel, immersed tunnel and submerged floating tunnel. The design for the Unkapani tunnel can be found in Figure 22. A more elaborate overview of the Unkapani Bridge design can be found in10.1.1 Original Unkapani bridge design.

For all reference designs the cross section will be kept as it is designed. The foundations for all reference designs will be adjusted. While the Unkapani tunnel has a slight slope in the longitudinal direction, the reference designs will be horizontal to simplify the model. The length of the foundations (poles and cables) of the different SFT types will be 20 meters.

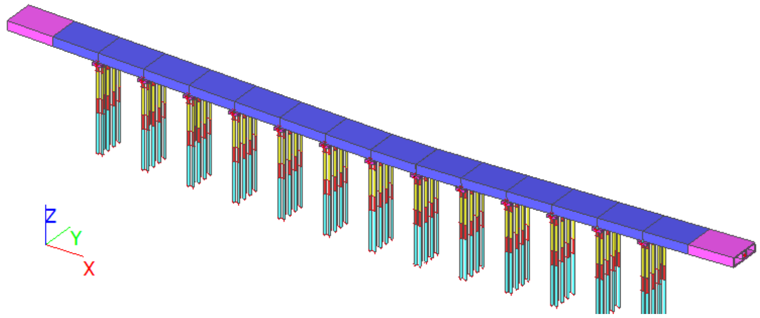

Figure 22 the Unkapani bridge design

3.1 The free submerged floating tunnel reference design

To create the free submerged floating tunnel all other elements except the cross sections have been deleted from the Unkapani design. This results in a straight line of cross sections. The literature says that the free submerged tunnel could have an estimated length of 150 meters (Østlid, 2010) and therefore the length of the first design has been chosen at 150 meters. The reference design of the free SFT is shown in Figure 23 and a more detailed overview can be found in chapter 10.1.2 Free submerged floating tunnel design.

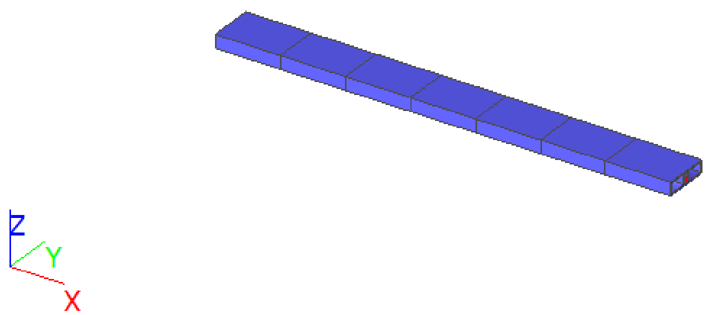

Figure 23 the Free SFT reference design

After calculating the tension and displacement in the free SFT, the tension in the cross section was too high. This was the result of the tension created by the expanding of the SFT due to the potential temperature differences. To solve this, the connection on one side of the shore was allowed to move in the x-direction. This resolved the problem and tunnel met the requirements that were set. However, this means that a special underwater joints needs to be developed to allow for the displacements at the transition between the SFT tunnel and the cut & cover tunnel section.

The biggest improvement for this model would be to increase the length of the tunnel. When the tunnel length was increased to 200 meters it did not meet the criteria of a maximum of 2 N/mm^2 tension due to the increased bending moments. This has been solved by lowering the buoyancy to balance the buoyancy and own weight of the structure. With a perfect balance only the variables loads will cause bending moment (leading to stresses) in the structure. At a span of 250 m the variables loads will causes bending moments of 2 N/mm^2. With longer spans the limit of 2 N/mm^2 will be exceeded.

3.2 The pontoon submerged floating tunnel reference design

To design the pontoon submerged floating tunnel in SCIA engineer two cables are connect to the tunnel sections that are supposed to be connected to the pontoons. The design for the pontoon SFT can be found in Figure 24 and a more detailed overview in chapter 10.1.3 Pontoon submerged floating tunnel design.

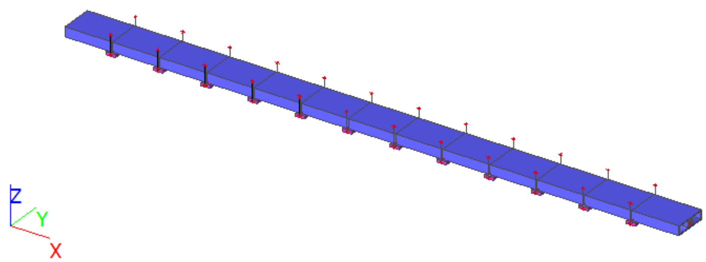

Figure 24 the pontoon SFT reference design

The pontoons have been modelled as a stiffness at the end of the cables. The stiffness occurs in the z-direction and has an amount of 2,5 MN/m. This is calculated by assuming the pontoons have an area of 50mx10m. With a volumetric density of 10 kN/m^3 it results in a stiffness of 50 m x 10m x 10 kN/m^3 = 5 MN/m generated by one pontoon. This stiffness is divided over two cables, therefore the stiffness in one cable is 2,5 MN/m.

Similar to the free SFT the pontoon SFT is not able to absorb loads from the y-direction (horizontal load perpendicular to the tunnel axis). This is why the pontoon SFT was connected at both shores with a fixed bearing. After the initial calculations were performed it was clear the thermal deformations also created too much tension in the tunnel section. Therefore one bearing needed freedom of movement in the x-direction (again requiring the special underwater joint to allow for the horizontal displacements). Thereafter the displacement in z-direction (vertical) had to be lessened because this was still exceeding the set requirements. In this case the displacement came due to the extension of the steel cables as a result of the weight of the cross section. To solve this pre-tension was applied to the steel cables that removed vertical displacements caused by permanent loads. After an iteration process of changing the pre-tension and the buoyancy the SFT met the set requirements. Only at the connection with the shore the tensile stresses in the concrete exceed the 2 N/mm^2 requirement. At those locations additional prestress is required. An overview of the used parameters can be found in Table 6.

Table 6 the used parameters for the pontoon SFT reference design

	Amount of pontoons	Size pontoons	Support direction pontoons	Length cables	Diameter cables	Type of cables	Stiffness generated by the pontoons
Pontoon SFT	12 pontoons	500 m2	Only supporting in the z direction	20 m	150 mm	S 355	5 MN/m2

3.3 The reference design for the submerged floating tunnel with pressure-bearing-piers

This reference design has the most resemblance to the Unkapani bridge design. Where the Unkapani Bridge also consisted of cut-and-cover sections, immersed sections and SFT sections, the reference design only consist of only the SFT sections. The Unkapani design used 8 poles per tunnel sections (8 per support) and the poles consisted of part concrete, concrete enclosed by steel and hollow steel sections. To make the reference design simpler only 4 poles per tunnel section are used (4 per support). Both ends of the SFT again were allowed to move in the x-direction to remove the effects due to the thermal loads, nevertheless thermal loads still affect the pile support. The reference design can be found in Figure 25 and a more detailed overview in the chapter 10.1.4 Submerged floating tunnel with pressure-bearing-poles design.

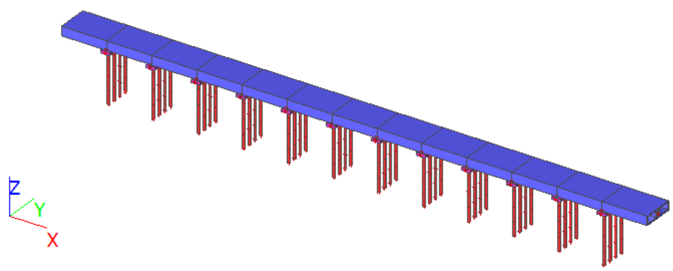

Figure 25 the SFT with pressure-bearing-poles reference design

This system is very stable and after calculation the reference design met the requirements fairly easy. Only the tension in the poles exceeded the requirements. To solve this, the Unkapani poles were replaced by poles of concrete enclosed by steel. The concrete is taking part of the normal force and bending resulting in lowering of the steel stress. This made the reference design meet the requirements. The used parameters for the reference design can be found in Table 7.

Table 7 an overview of the used parameters for the pressure-bearing-poles SFT reference design

	Foundation	Amount of poles	Length of the poles	Support direction poles	Diameter of the poles	Type of poles	Stiffness on poles due to the ground
Pressure-bearing-poles SFT	4 poles connected to a supporting beam	12 x 4 poles	20 meters above the seabed and 36,5 meters in the ground	Only supporting in the z direction, support in x and y direction generated by the stiffness of the ground	2,5 m	Steel poles filled with concrete	2 MN/m2

3.4 The tethered type of submerged floating tunnel reference design.

The tethered type SFT has a higher buoyancy than its own weight. This was accomplished by removing the ballast concrete from the structure. It is very important that no pressure will occur in the tethers, because this would mean that the tunnel would sink. The literature suggests that the use of inclined tethers would give the most preferable result, since this would allow the cables to absorb the loads in the y-direction (Yan, Zhang, & Yu, 2016)(Lin, Mengjun, Guangdi, & Peng, 2016). Therefore the first reference design was designed with inclined tethers in the y-direction. After simulating the forces on the structure it was clear that there was not enough resistance in the x-direction, which made the structure fail. To solve this, the tethers were also inclined in the x-direction which solved the problem. To limit the amount of foundations used, two tethers were connected to one foundation. The reference design can be found in Figure 26 and a more detailed view in chapter 10.1.5 Tethered type of submerged floating tunnel design.

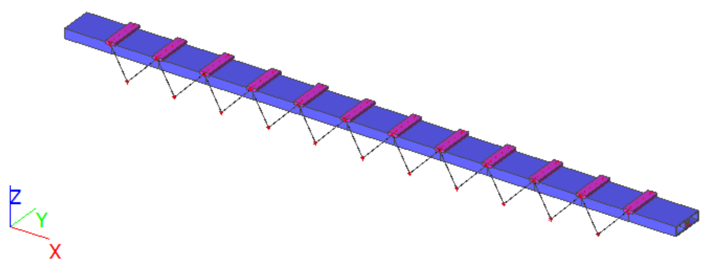

Figure 26 the tethered type of SFT reference design

Thereafter the tension in the steel cables was too high to use the regular S355 steel cables, at 705 N/mm^2. For this reason the diameter of the cables were doubled. This resulted in cables also having a displacement in the negative z-direction. This means the structure would sink. Through a lot of iteration it has been tried to vary the buoyancy and diameter, to get the desired tension and displacement in the steel cables and tunnel sections. This could only be solved by allowing more tension in the steel cables. Therefore steel cables have to be used that can absorb 550 N/mm^2. Also the tension in the tunnel section is still slightly too high. This has to be solved by applying more pre-tension in the tunnel sections. In Table 8 the parameters used for the reference design are shown.

Table 8 an overview of the used parameters for the tethered SFT reference design

	Foundation	Amount of tethers	length of tethers	Support direction tethers	Diameter of the cables	Type of cable
Tethered type of SFT	4 tethers connected to a supporting beam	44 tethers	37,846 m	Support in the x, y and z direction	200 mm	Resistance to at least 550 N/mm2

3.5 The resulting forces of the reference designs

The created reference designs differ from each other in several ways. To get a clear view of the parameters used for the final reference designs and the resulting forces on the designs Table 9 shows them for every type of SFT. In chapter 10.2 Resulting forces, the resulting forces on the SFTs are presented visually and more extensively. In the table it can be seen that the buoyancy for the free SFT is lowest and the tethered type of SFT has the highest buoyancy. As explained before, the pontoon and tethered type of SFT have a higher tension in de outer cross-sections. This has to be solved by adding extra pre-tension in those cross section. In Table 9 the biggest displacement in either direction is shown. Some designs have a positive and negative displacement. This can be seen in chapter 10.2 Resulting forces. The displacement in x-direction determines the maximum span for the pressure-bearing-pole SFT. Expansion joints have to be used to allow the tunnel to move in the x-direction and would make the impact of the displacement negligible. The more displacement occurs, the more complex expansion joints have to be used, but theoretical the use of expansion joints makes the pressure-bearing-pole SFT able to cross any distance.

Table 9 the used parameters and resulting forces for the SFT reference designs

	Self-weight (kN)	**Buoyancy (kN)**	**Ballast concrete (kN)**	**Tension cross-section (N/mm^2)**	**Displacement cross-section (mm)**	**Tension foundation (N/mm^2)**	**Displacement foundation (mm)**
Free SFT	3305	3349,75	-	1,48	ux = 55,2 uy = 0,2 uz = 35,7	-	-
Pontoon type SFT	3305	3551	459,06	Both outer cross-sections 3,32. The other cross-sections have a maximum of 1,92	ux = 102,4 uy = 2,4 uz = 260,6	129,84	ux = 260,8 uy = 3,2 uz = 105,4
Pressure-bearing-poles SFT	3305	3551	459,06	0,31	ux = 53,4 uy = 5,1 uz = - 1,8	9,61	ux = 1,4 uy = 5,1 uz = 46,0
Tethered type of SFT	3305	3794,68	-	Both outer cross-sections 2,64. The other cross-sections have a maximum of 1,74	ux = 51,0 uy = 4,9 uz = 107,1	519,78	ux = 92,9 uy = 18,8 uz = 94,2

Since the reference designs are now optimized for the ultimate limit state, it has to be investigated which accidental loads the four types of SFTs can withstand. This is done by modelling the accidental loads in SCIA engineer and calculate the tension and displacement created by the accidental loads. The results can be found in Table 10.

Table 10 the resulting forces of the accidental loads

	Total tunnel flooding	Partial tunnel flooding	Sunken vessel	Current velocity	Tsunami
Free SFT	Fail. Maximum tension = 60,65 N/mm^2	Fail. Maximum tension = 3,93 N/mm^2	Maximum of a vessel of 1000 ton	Maximum current velocity of 2,0 m/s	Fail. maximum tension = 7,54 N/mm^2
Pontoon type SFT	Fail. Maximum tension = 138,05 N/mm^2 and maximum displacement = - 9555,1 mm	Fail. Maximum tension = 13,09 N/mm^2	Fail. The SFT cannot absorb any load of a sunken vessel	Maximum current velocity 0,5 m/s	Fail. Maximum tension = 17,79 N/mm^2
Pressure-bearing-poles SFT	Satisfy Maximum tension = 1,54 N/mm^2	Satisfy. Maximum tension and displacement meet requirements	Maximum of a vessel of 7.500 ton	Maximum current velocity 2,5 m/s	Fail. Maximum tension = 6,50 N/mm^2
Tethered type of SFT	Fail. Downward displacements of 191.3 mm in tethers	Satisfy. Maximum tension and displacement meet requirements	Maximum of a vessel of 3.500 ton	Maximum current velocity 1,5 m/s	Fail. Downward displacements of 143.7 mm in tethers

As suspected none of the reference designs can withstand a total flooding of the tunnel, although the pressure-bearing-poles SFT has a tension that is just 0,34 N/mm^2 higher than the set requirements. This SFT would be able to withstand full flooding if a little more pre-tension would be applied. Partial flooding of the SFT would make the free and pontoon SFT fail, while the pressure-bearing-poles and tethered type of SFT would comply the requirements. To find the maximum weight of a sunken vessel each SFT type could withstand, some iteration has been done. The pressure-bearing-pole SFT can withstand the largest sunken vessel, while the pontoon SFT cannot withstand any sunken vessel. The force generated by a tsunami is too extreme for all of the SFT types to absorb. Table 10 shows that the pressure-bearing-poles SFT is strongest type of SFT, while the pontoon type SFT is the weakest. It should be noted that the free SFT is only stronger because the length of the free SFT is significantly shorter than the other SFT types. After finding the accidental loads each SFT can absorb, there might also be a difference in the current velocity each reference design can withstand. As stated before, the used current velocity in the ultimate limit state was 0,5 m/s. Through an iteration process it has been found what maximum current velocity each reference design could withstand. The results can be found in Table 10.

4 The decision support matrix

The decision support matrix that will be made is meant to help designers in the first stage of the design process. During the first stage the designer will think about solutions that are based on gained knowledge from previous project. However a designer might not have all the knowledge available to choose the best design. That is where the decision support matrix will come in play. It will give a clear overview of the four SFT types and in what circumstances they can be used. This should limit the time needed to research all four SFT types and leave more time to research a specific SFT type to create the best design. The best SFT type depends mostly on the location the SFT needs to be built, since the parameters distinguishing the SFT types are almost all location specific. The first parameters that have to be taken into account are geographical like the distance and depth of the waterway the SFT needs to cross. Thereafter the loads that the SFT is subjected to determine what SFT type can be used.

The decision support matrix is created with the found results of the literature study and the numerical modelling. The distance and depth of the SFTs as well as the advantages and limitations of the SFT types have been found with the help of the literature study. Expect maximum distance of the pressure-bearing-pole SFT, this was done with numerical modelling. The decision support matrix can be found in Table 11.

Table 11 the decision support matrix

	Distance (m)	**Depth (m)**	**Max. current velocity**	**Sunken vessel load**	**Total flooding load**	**Partial flooding load**	**Tsunami load**	**Advantages and limitations of the SFT types**
Free SFT	0-250	∞	2 m/s	1000 ton	Unable	Unable	Unable	Simple design, but difficult construction process.
Pontoon type SFT	0-2000	∞	0,5 m/s	Unable	Unable	Unable	Unable	Cannot be used in areas with waves and limits the space for marine traffic.
Pressure-bearing-poles SFT	∞	60	2,5 m/s	7.500 ton	Able, with more pre-tension	Able	Unable	Lot of knowledge available, construction comes with high costs, might be difficult to maintain.
Tethered type of SFT	0-4500	450	1,5 m/s	2000 ton	Unable	Able	Unable	Flexible form, large buoyancy is required, tethers can fail due to fatigue.

The literature study showed that a rectangular cross section made of reinforced concrete can be a good cross section for SFTs. The possible distance and length for the pontoon and tethered SFT are taken from the literature should be used as benchmarks. These SFT types might be able to cross even longer distances and depth using other designs. Likewise some advantages and limitations found during the literature study are shown in Table 11. In the second part of this research four reference designs were modelled. Since the reference designs were modelled to absorb the same permanent and variable loads, the decisions support matrix is based on what accidental loads the different SFT types can absorb. Firstly the predetermined accidental loads in chapter 2.2 The loads affecting the submerged floating tunnels were checked. Thereafter it was clear the decision support matrix could be expanded by finding the limit for each SFT type of the variable and accidental loads. These found variable and accidental loads were added to the decision support matrix.

Some clear difference between the SFT types can be seen in Table 11. The decision support matrix shows that the free SFT can only be used for short crossings and cannot handle a heavy sunken vessel. Additionally the free SFT cannot absorb any of the other accidental loads. This makes the free SFT not useable for long crossings, active waterways and in regions with chances of flooding or tsunamis. The construction of the free SFT uses the least amount of materials, because the SFT is not supported by any type of foundation. Nevertheless this could result in construction problems, since the tunnel sections need to be kept in place until all of them are connected.

The pontoon SFT looks to be the most unstable SFT type. It cannot handle any of the accidental loads and only a low current velocity of 0,5 m/s. It is also restricting the areas it can be used in, because it cannot absorb loads generated by big waves and restricts the passage of certain marine traffic. However the pontoon SFT is suitable for crossing long distances.

The pressure-bearing-pole SFT is the most robust type of SFT. It can absorb the most accidental loads and can be built in waterways with a current velocity of 2,5 m/s. The biggest restriction for this SFT type comes from the economic cost that results from the construction and maintenance of this SFT might be difficult. Although the available amounts of knowledge about construction types like the pressure-bearing-pole SFT can be an important upside. The pressure-bearing-poles could be fabricated to be longer, but the cost of making them would not be worth it. The possible length of the structure would be unlimited, but normally a longer crossing, means a deeper crossing. When the depth of 60 meters is crossed, this SFT won’t be the optimal solution.

The tethered type of SFT can be used in the deepest water and for long crossings. This SFT is also able to withstand more accidental loads than the free and pontoon SFT. The construction method of this type of SFT is a new one and it has to be prevented that the tethers can fail due to fatigue. Nevertheless the tethered type of SFT can be an excellent way of crossing long and deep waters.

Two important parameters for the SFTs types that are not yet discussed are the environmental and economical parameters. In the literature study was found that SFTs in general have a smaller impact on the environment than other current water crossing solutions. Nevertheless the difference between the four SFT types is not investigated. It is clear though that the free and pontoon SFT types are better for the environment than the pressure-bearing-poles and tethered SFT, since they are in no way connected to the bottom of the water crossing.

The economical value of the SFT types is a very important one, because this will be the decisive parameter for choosing one of the SFT types. Calculating the construction cost of a SFT is a difficult process, because the reference designs are in the beginning stage of the designing process. The best way to calculate the construction cost of the different SFT types would be to find the amount of used materials for each reference design and find the cost of the materials. The cost of these materials should also include the installation cost of the materials to get the best overview of the total cost of a SFT type.

Overall the decision support matrix gives a good overview of some advantages and limitation of each SFT type. With the decision support matrix it is possible to shorten the preliminary research before the design process can start.

5 The Unkapani Bridge case study

5.1 Description of the Unkapani tunnel project

This case study will be used to authenticate if the created decision support matrix can be a good tool in the early design stages of a SFT. The Unkapani Bridge project has been chosen for this case study, since the project is still in the design stage and will be the first ever built SFT. Firstly the situation of this case study will be clarified and thereafter the decision support matrix will be used to make an assessment of the best SFT type in the situation.

In Istanbul the Unkapani Bridge will be replaced with a tunnel, because it will clean up the view of the city and enhance the water flow (Hurriyet daily news, 2017). The tunnel will cross the Golden Horn, a side river of the Bosporus and connect the Fatih and Beyoglu districts in Istanbul. The crossing will be around 950 meters long, with a steep slope on both sides of the river (Witteveen+Bos, 2016). The bedrock of the Golden Horn consists of a layer of clay from 30 to 70 meters below the water and the maximum depth is 41 meters. Thereafter the bottom consists of stone. Figure 27 gives a good overview of the cross section of the Golden Horn at the place the SFT has to be placed.

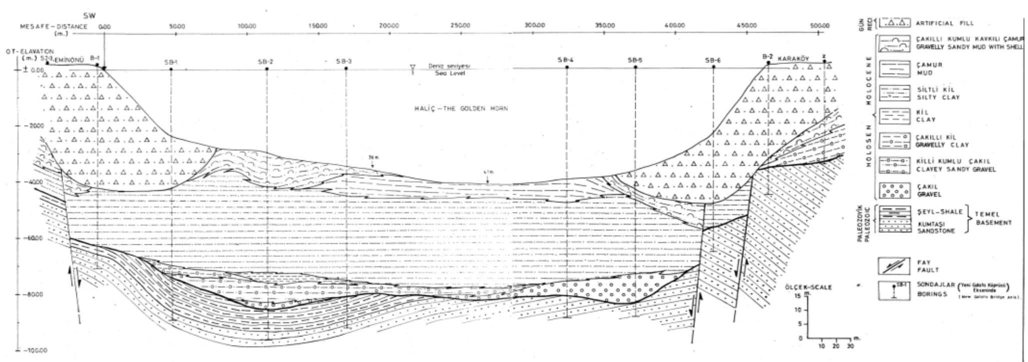

Figure 27 the geographical profile of the bedrock of the cross section of the Golden Horn

To allow marine traffic to cross uninterrupted, the tunnel has to be 8,5 meters below the water for 100 meters and 5 meters below the water for 300 meters.

Finally the tunnel has to bear all permanent loads as well as the following variable loads:

- The self weight of the structure
- A current velocity of 0,5 m/s
- The tunnel should be able to absorb the load of a sunken vessel with a weight of 5.000 ton.
- The loads caused by falling and dragging anchors.
- The Golden Horn is affected by tsunamis and the tunnel needs to resists these forces. As stated before the current velocity of a tsunami can differ from 1 to 18 m/s. For this case study a current velocity of 5 m/s will be taken, because TEC also used this value.
- In the area of the Golden Horn seismic activities occur, which the tunnel needs to be able to handle. In this report no research about seismic activities is done, so additional research would have to be done to know what SFT types can absorb seismic loads.

5.2 Application of the decision support matrix

To make the use of the decision support matrix easier it is shown again in Table 12, but now the requirements for the Unkapani tunnel project are showed in the last row.

Table 12 the decision support matrix for the Unkapani tunnel project

	Distance (m)	Depth (m)	Max. current velocity	Sunken vessel load	Total flooding load	Partial flooding load	Tsunami load	Advantages and limitations of the SFT types
Unkapani tunnel project	950 meters	41	0,5	5.000 ton	Does not need to absorb this load	Needs to absorb this load	Needs to absorb this load	There should be space for marine traffic to pass and the SFT needs to be able to absorb seismic loads.
Free SFT	0-250	∞	2 m/s	1000 ton	Unable	Unable	Unable	Simple design, but difficult construction process.
Pontoon type SFT	0-2000	∞	0,5 m/s	Unable	Unable	Unable	Unable	Cannot be used in areas with waves and limits the space for marine traffic.
Pressure-bearing-poles SFT	∞	60	2,5 m/s	7.500 ton	Able, with more pre-tension	Able	Unable	Lot of knowledge available, construction comes with high costs, might be difficult to maintain.
Tethered type of SFT	0-4500	450	1,5 m/s	2000 ton	Unable	Able	Unable	Flexible form, large buoyancy is required, tethers can fail due to fatigue.

The first thing to do is look at the length needed for the crossing. In this case it is 950 meters and means the free SFT is not an option that can be used. When looking at the depth it is clear that all options would suffice, since the depth of the river has a maximum of 41 meters. The pontoon SFT will not be a suitable solution because it limits the space for marine traffic and is not able to absorb a load of a 2.000 ton sinking vessel.

Both the pressure-bearing-pole and tethered SFT are not able to absorb the tsunami load and most likely will not be able to absorb the seismic load. Therefore none of the current reference designs qualify as a solution for the Unkapani tunnel project and the designs should be improved. Depending on the time the choice can be made to improve one or both designs. If one design will be improved it would be pressure-bearing-pole SFT, since this seems to be de strongest SFT. If there is time to improve the tethered SFT it is possible it would also be able to absorb a higher load of a sinking vessel and therefore satisfy to all requirements. Thereafter the construction costs of each SFT type can be calculated and the best SFT type can be chosen.

With the help of the decision support matrix the pressure-bearing-pole SFT seems to be the most adequate solution, because it looks to be the strongest SFT type. Therefore the design for the Unkapani tunnel should be focused on this SFT type. If the client wants two different designs the tethered SFT should also be investigated.

6 Discussion

During the research some problems have been encountered that should be noted. The reference designs could have been modelled in many different ways. The designs were modelled to be comparable and resemble a simplified version of the SFTs. Nevertheless the reference designs could take many different forms, where different parameters could be varied:

- The cross sections could have a different shape;
- The length of the SFTs could be longer or smaller;
- The amount of foundations could be altered;
- The depth of the structure could be adjusted.

These are examples which could make the models work differently, however the differences between the four reference designs should not experience big changes when adjusting the parameters.

In this research project, calculations are done with several loads, however there are even more loads that affect the reference designs. These loads have not been applied to simplify the models and there was not enough time for applying all the loads. Nevertheless these loads will be discussed so they can be used in further research.

- There are a few more permanent loads that have not been specified in this report. For the real designs this means the structure will have more weight. This increased weight can be countered by increasing the buoyancy. The permanent loads are:
    - The protection layer around the tunnel: A layer to prevent damage and erosion to the outside of the cross sections;
    - The tunnel interior: for example the asphalt, barriers, fire protection, etc.;
    - The installations: all mechanical and electrical installations needed in the tunnel.
- There are also some variable loads that have been elected to disregard during my project. Simply because there was not enough time to investigate all variable loads. The loads that were not investigated, but could play an important role are:
    - The wave load: This load is very important to the pontoon SFT and finding how waves affect the pontoons could be important to find where the pontoon SFT can be used.
    - Loads generated by creep and shrinkage. These loads could have a impact on the structure and should be taken into account when designing a real SFT. Nevertheless these loads are comparable to the thermal loads, only smaller.

- At last there are some accidental loads that still can be investigated. Just as the variable loads, the accidental loads were not investigated due to the time limit.
    - Collision with a vessel: The SFT should be constructed far enough below the water so the passing marine traffic on the water cannot hit the SFT. However there is the possibility of underwater marine traffic like submarines to hit the SFT. This is a load that the SFT should be designed for, since it could lead to a big disaster if the SFT is not designed for it.
    - Also seismic loads on the SFT have not been investigated. To improve upon the decision support matrix, the response of the SFTs to seismic activities can be added. This would make the matrix also useable in areas like the Golden Horn, since there are possibilities of seismic activities.

The investigation of the remaining accidental loads would be the biggest addition to this research, since it would increase the effectiveness of the decision support matrix. All four SFTs should be designed so they can absorb the remaining permanent and variable loads. This could mean that the reference designs have to be stronger and therefore are able to absorb more of the accidental loads. This is something that could be investigated in other studies.

7 Conclusion

In this report the four different SFT types have been analyzed and compared. This has been done with the help of literature and modelled reference designs. The reactions of different loads have been investigated for these reference designs. Thereafter a decision support matrix has been constructed that shows load limitations of each SFT type and under what circumstances they can be built. Finally the decision support matrix has been used to assess the Unkapani tunnel project.

The created decision support system is the output of the literature study and performed numerical modelling for four SFT types. It can be used to select the best solution in the preliminary design stage, using the advantages and limitations for every reference design and therefore give an idea what the advantages and limitations are for all four SFT types. The decision support matrix can be found in Table 11. This project was limited to technical parameters of the SFT design project, namely it didn't include the research on economic and environmental aspects.

The most notable observations from the decision support matrix are:

- The free SFT can be built till a length of 250 meters before the ratio between the self weight and the buoyancy becomes too small and the loads cannot properly be absorbed anymore.
- The pontoon SFT seems to be the most unstable design. It will be affected by waves that can have enormous impact. Also the pontoon SFT is able to absorb only the loads it is designed for and none of the accidental loads, this makes the pontoon SFT reference design the most unstable reference design.
- The pressure-bearing-pole SFT seems to be the most stable design. It can handle the highest amount of accidental loads, which makes it a suitable solution when more extreme circumstances occur.
- The tethered SFT can be used in case of the more extreme depths, while also being able to absorb big loads. It is almost as stable as the pressure-bearing-pole SFT, but the tethers allow it to be used in much deeper waters. The ideal tether combination seems to have the tethers connected under an angle in the x, y and z direction.

In the end the created decision support matrix seems like a good tool to get a first impression of the characteristics from the four SFT types and give a clear overview what SFT type could be a preferable for a certain project. Although the matrix could be expanded more by also compare the SFT types in case of a submarine collision or a seismic event. After the decision support matrix has been used to determine what SFT type should be used, the specific SFT should be designed from scratch, since the reference designs' only goal was to compare the four SFT types.

8 Recommendation

Based on the outputs from my research project, some recommendations can be done. Since there are no prevailing designs for the four SFT types, some aspects that will need further investigation on this matter are:

- It should be further analysed if the cross sections should be best built in a straight line or under a small downward incline until halfway of the structure, where after it has the same incline upward. The Unkapani bridge design in Figure 22 shows an example of the inclined version, while the SFT reference designs show the horizontal built cross sections.
- Some literature has proposed to build the pontoon design not straight across the water, but built with an arc (Jakobsen, 2010). An example is shown in Figure 28. This would make the structure more resistant to loads created by currents. More research could tell if this is the best way to build the pontoon SFT and if it also might be better for the other SFT types.
- The shape for the cross sections in the SFT reference designs have been made polygonal, because this seems to be the most economical solution. Although there has been no extensive research to the economical value of the other cross section shapes and more research could change the results of what shape should be used.
- In the performed research the characteristics of the pontoons and the foundation of the tethers have not been investigated. Further examination will be necessary to find the limitation of the pontoons and the foundation of the tethers.

Furthermore some investigation has to be done to the seismic and collision with underwater vessels. This will expand the decision support matrix and improve the usability of the matrix.

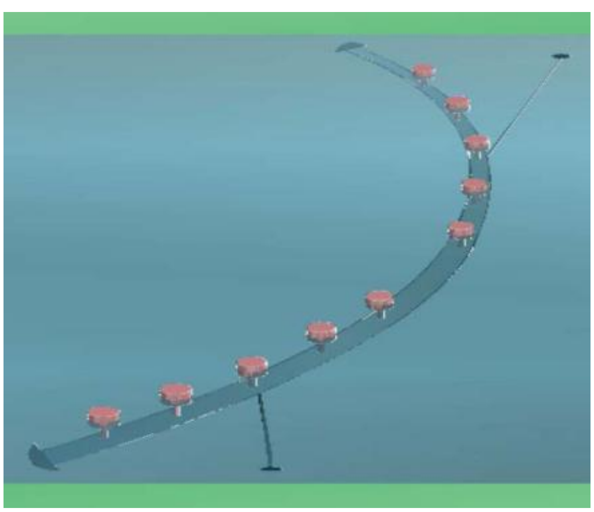

Figure 28 an example of an arced pontoon SFT (Jakobsen, 2010)

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10 Appendix

10.1 Appendix numerical modelling

10.1.1 Original Unkapani bridge design

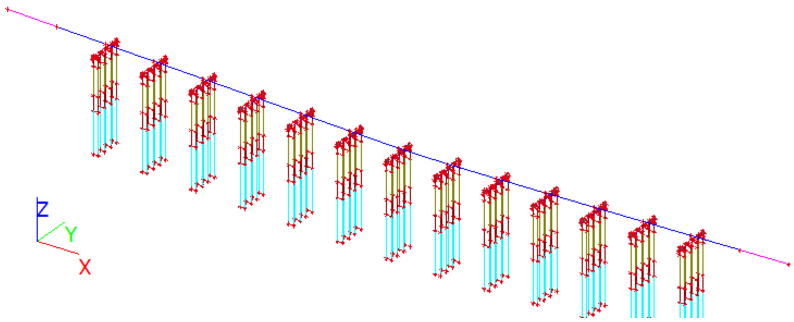

Figure 29 Overview Unkapani bridge model

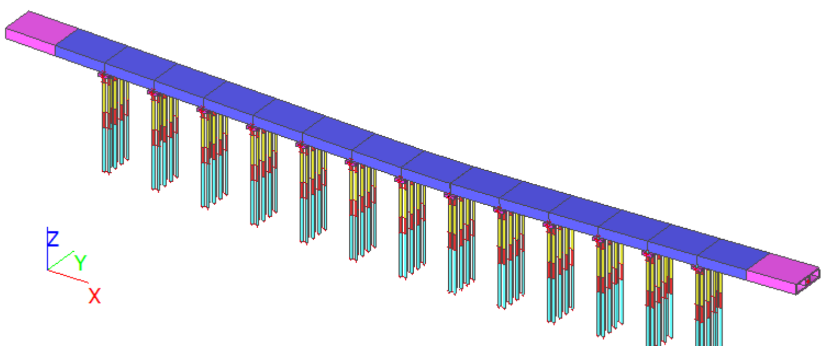

Figure 30 Overview Unkapani bridge design

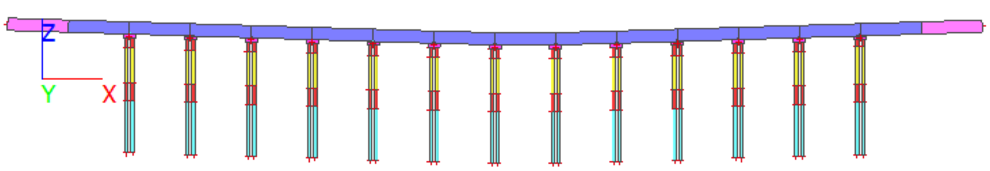

Figure 31 Side view Unkapani bridge design

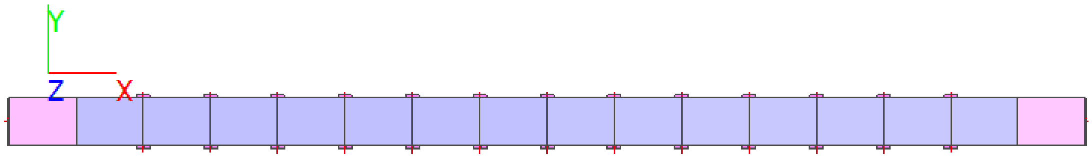

Figure 32 Unkapani bridge design from above

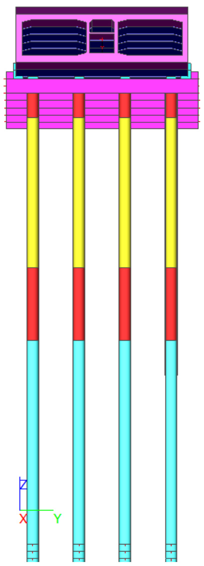

Figure 33 Cross section of the Unkapani bridge design

10.1.2 Free submerged floating tunnel design

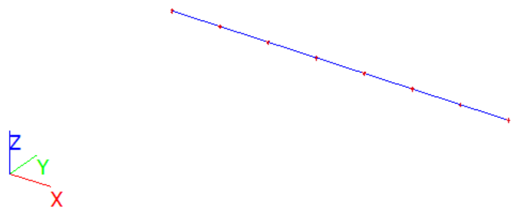

Figure 34 Overview of the free submerged floating tunnel model

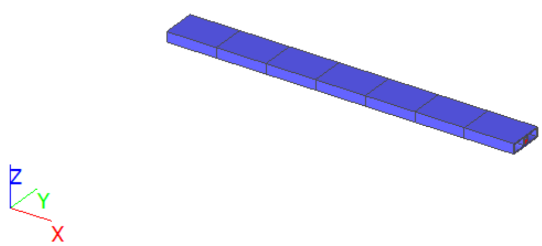

Figure 35 Overview of the free submerged floating tunnel design

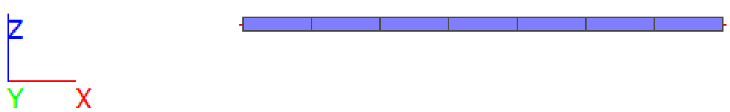

Figure 36 Side view of the free submerged floating tunnel design

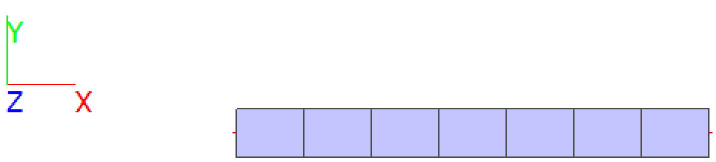

Figure 37 view from above of the free submerged floating tunnel design

10.1.3 Pontoon submerged floating tunnel design

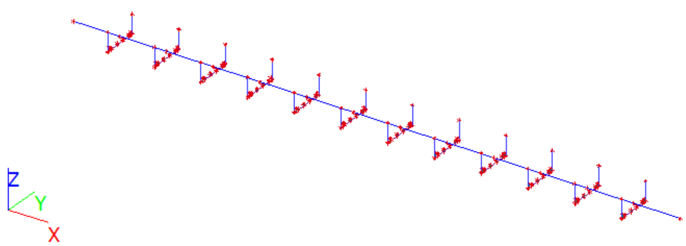

Figure 38 Overview of the pontoon submerged floating tunnel model

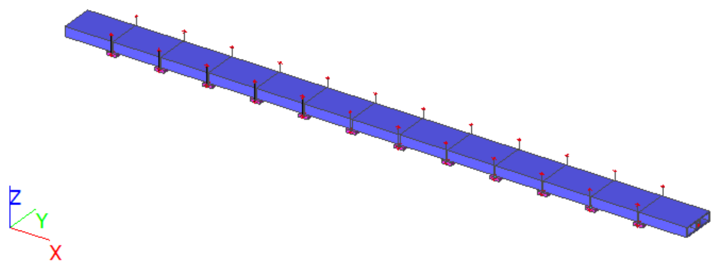

Figure 39 Overview of the pontoon submerged floating tunnel design

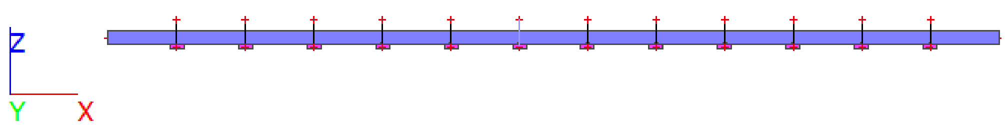

Figure 40 Side view the pontoon submerged floating tunnel design

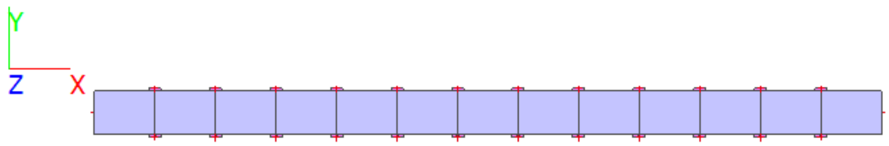

Figure 41 View from above the pontoon submerged floating tunnel design

10.1.4 Submerged floating tunnel with pressure-bearing-poles design

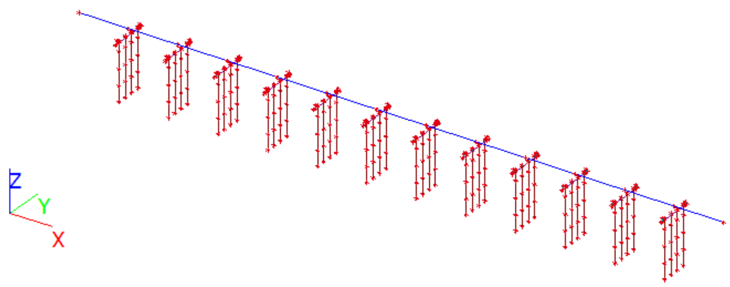

Figure 42 Overview of the submerged floating tunnel with pressure-bearing-poles model

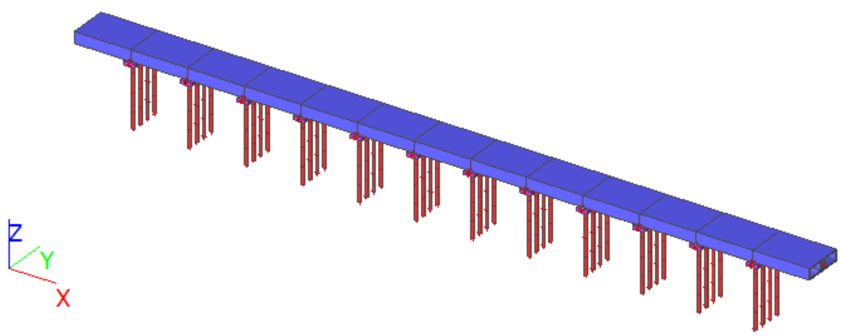

Figure 43 Overview of the submerged floating tunnel with pressure-bearing-poles design

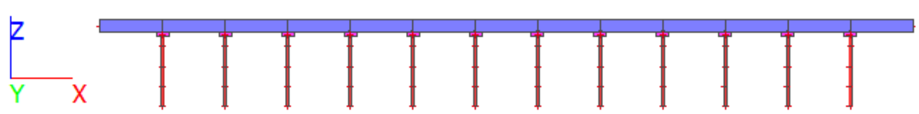

Figure 44 Side view of the submerged floating tunnel with pressure-bearing-poles design

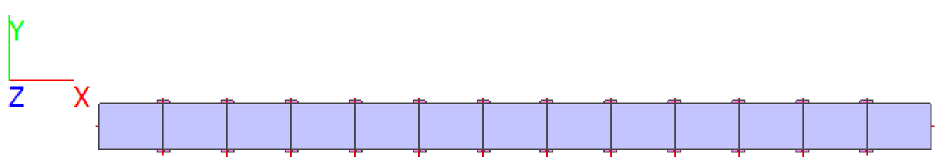

Figure 45 View from above of the submerged floating tunnel with pressure-bearing-poles design

10.1.5 Tethered type of submerged floating tunnel design

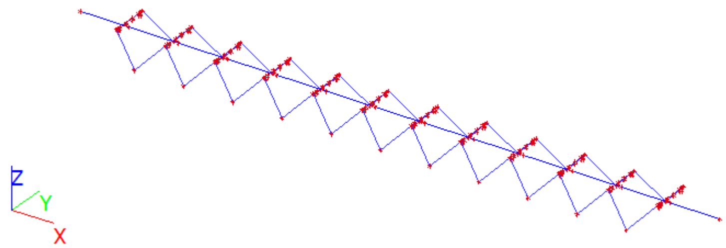

Figure 46 Overview of the tethered type of submerged floating tunnel model

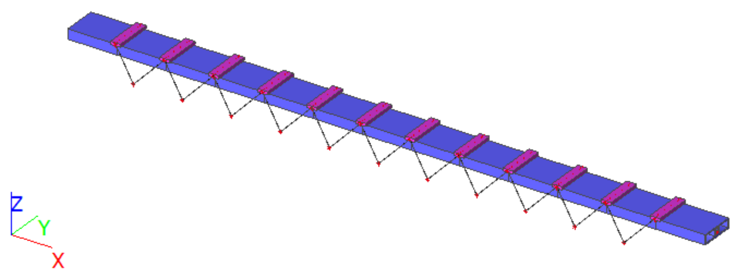

Figure 47 Overview of the tethered type of submerged floating tunnel design

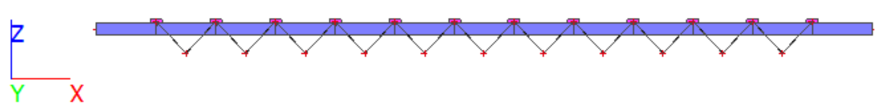

Figure 48 Side view of the tethered type of submerged floating tunnel design

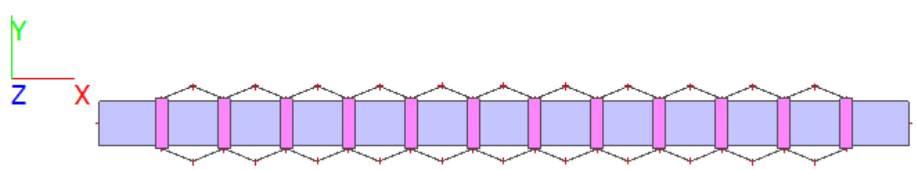

Figure 49 View from above the tethered type of submerged floating tunnel design

10.2 Resulting forces

10.2.1 Resulting force ULS loads

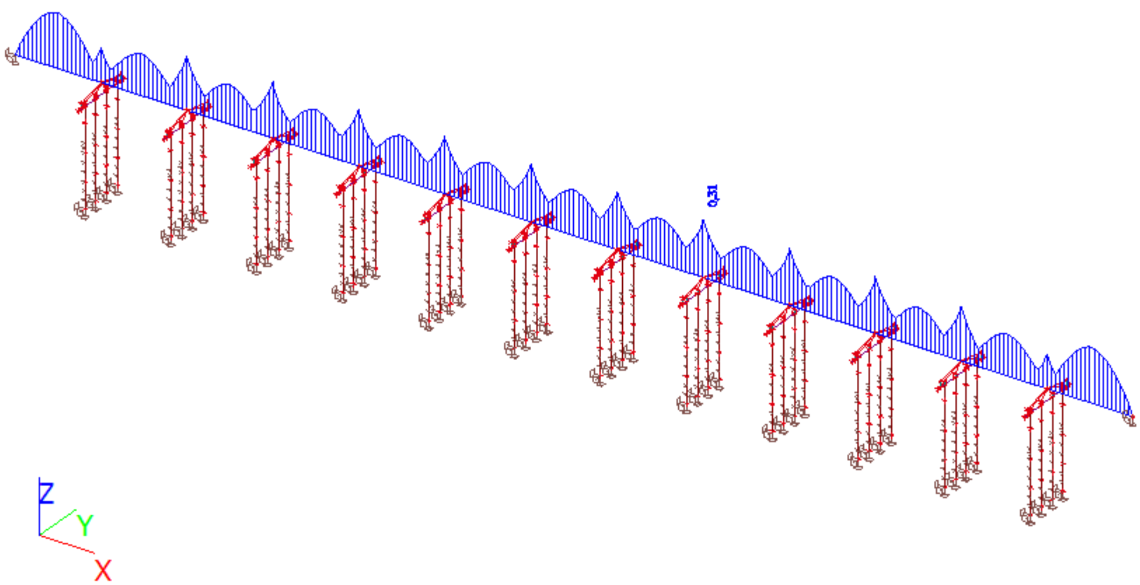

Figure 50 Resulting stress on the tunnel cross section with ULS loads

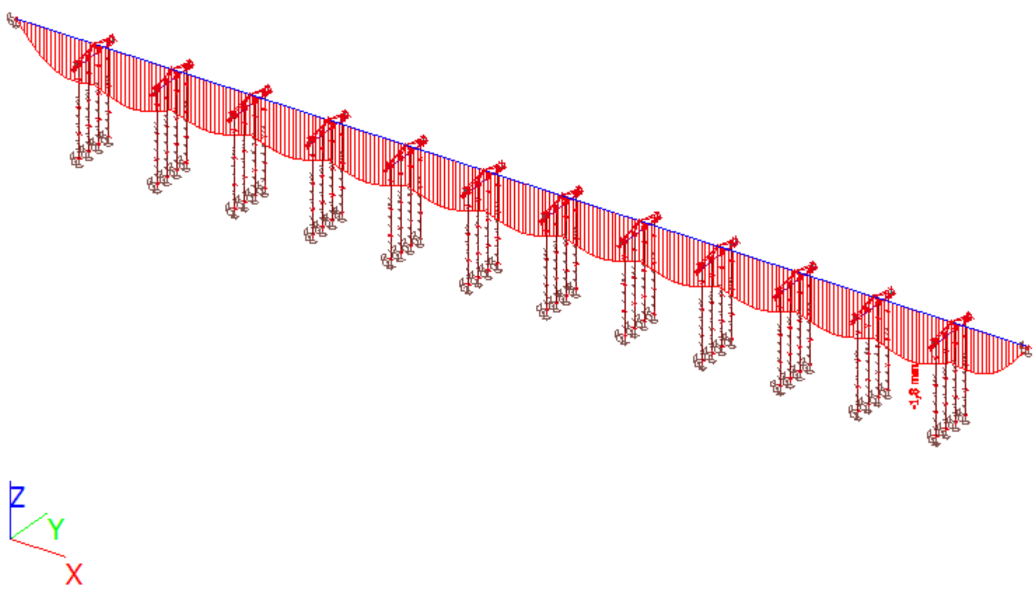

Figure 51 Resulting displacement on the cross section with ULS loads

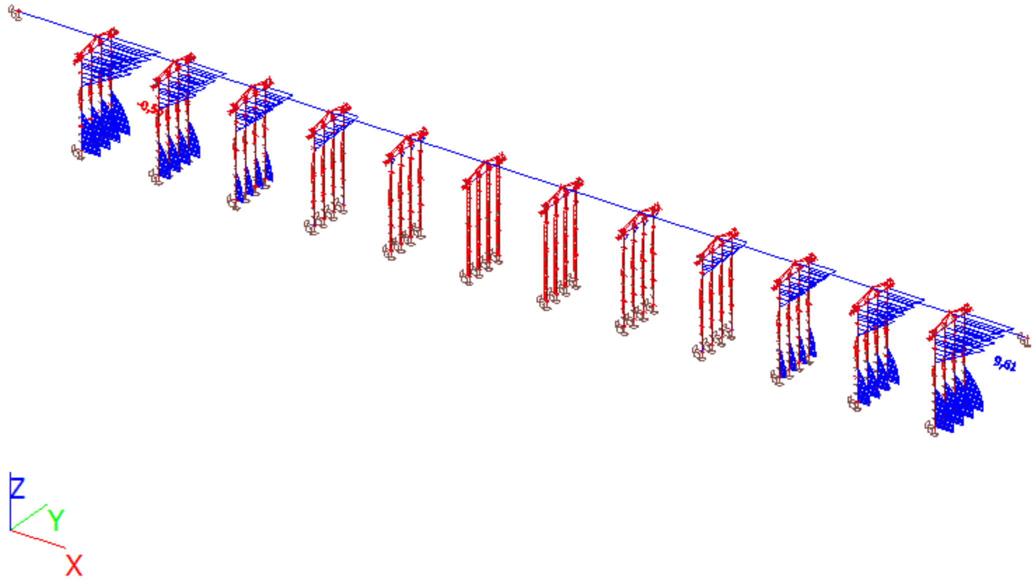

Figure 52 Resulting stress on the poles with the ULS loads

10.2.2 Resulting forces sunken vessel loads

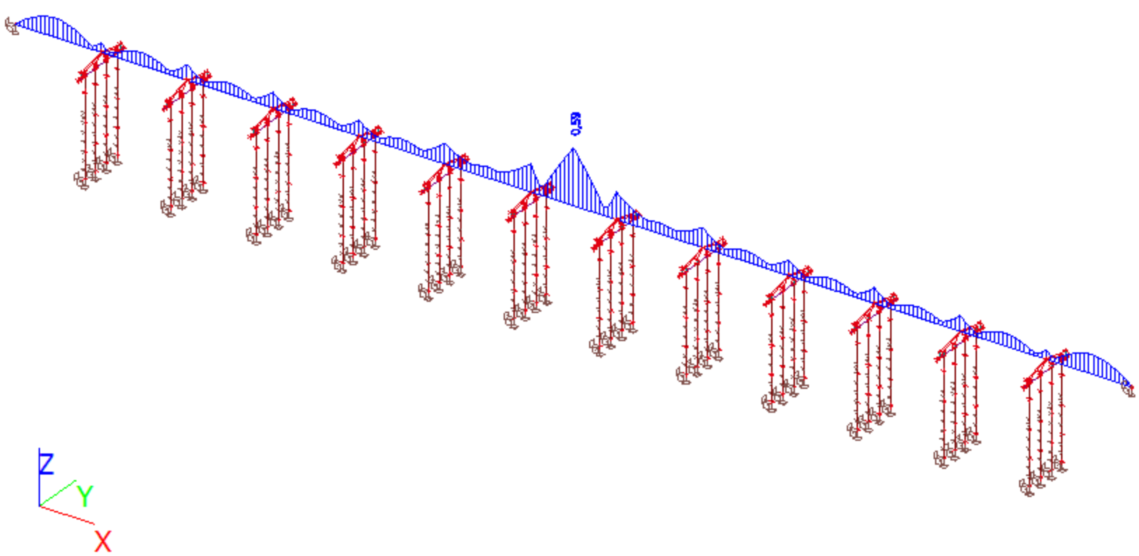

Figure 53 Resulting stress on the tunnel cross section with sunken vessel loads

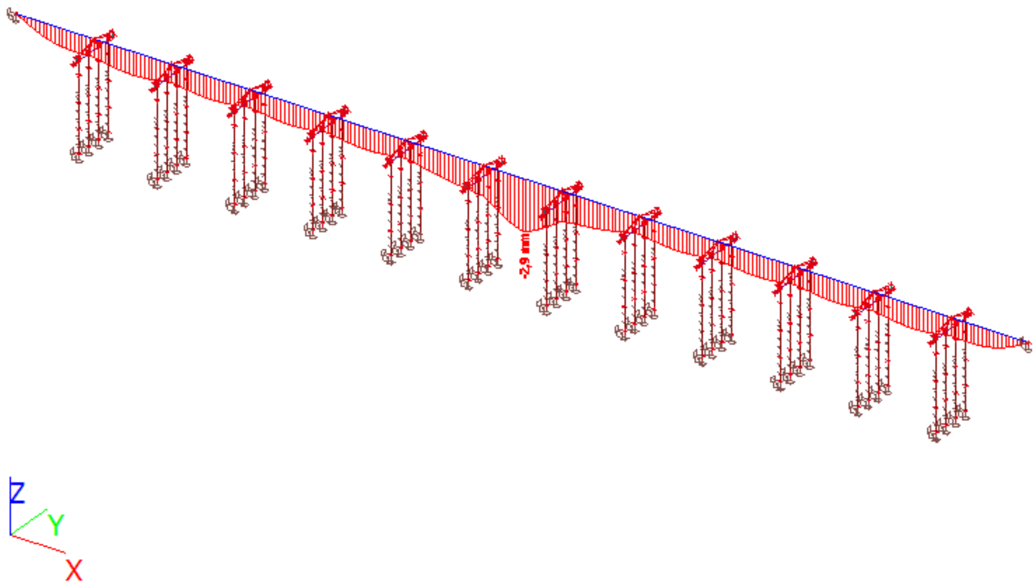

Figure 54 Resulting displacement on the tunnel cross section with sunken vessel loads

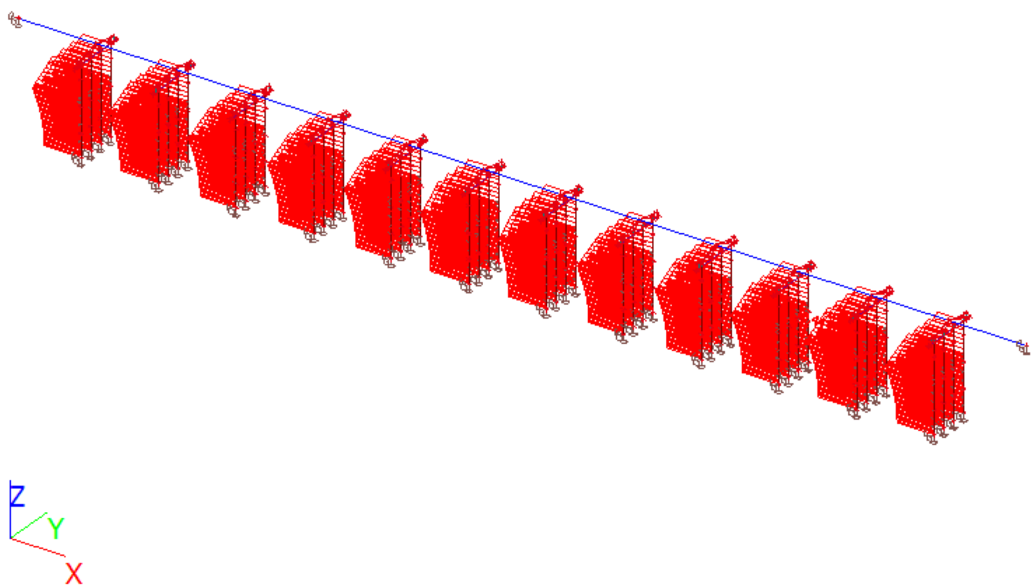

Figure 55 Resulting stress on the poles with the sunken vessel loads

10.2.3 Resulting forces Tsunami loads

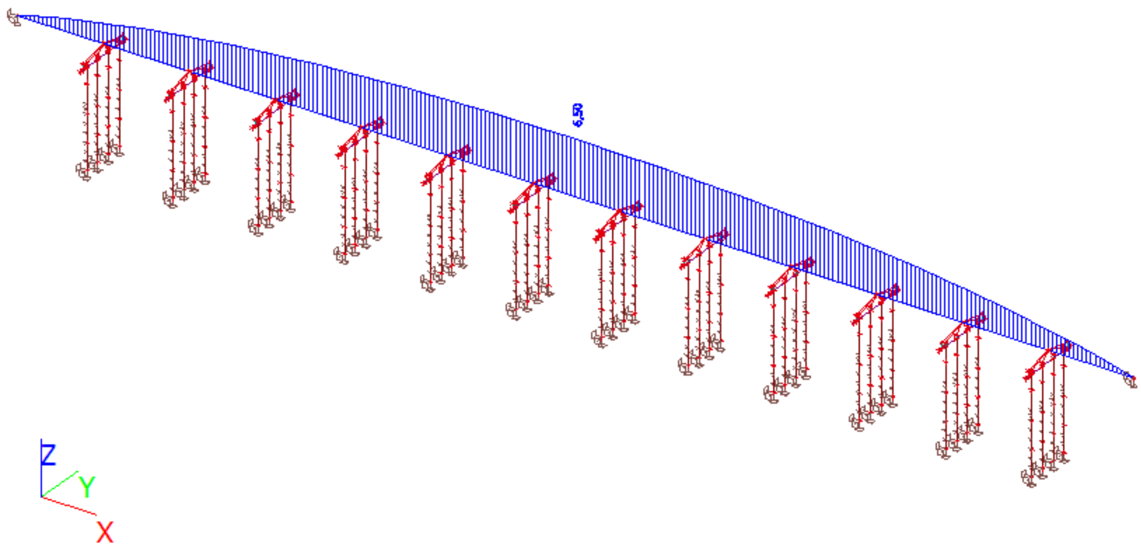

Figure 56 Resulting stress on the tunnel cross section with tsunami loads

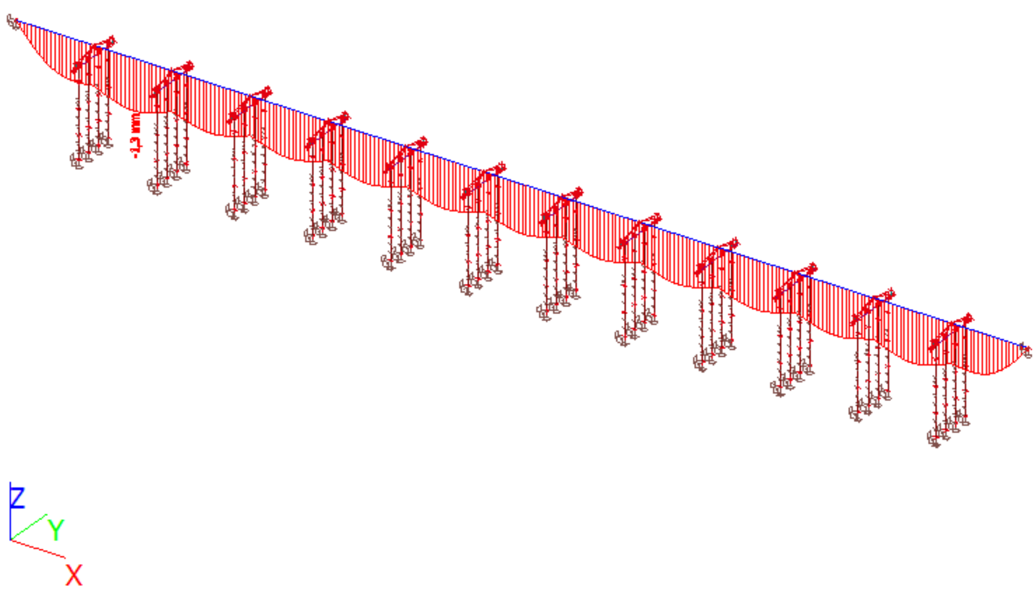

Figure 57 Resulting displacement on the tunnel cross section with tsunami loads

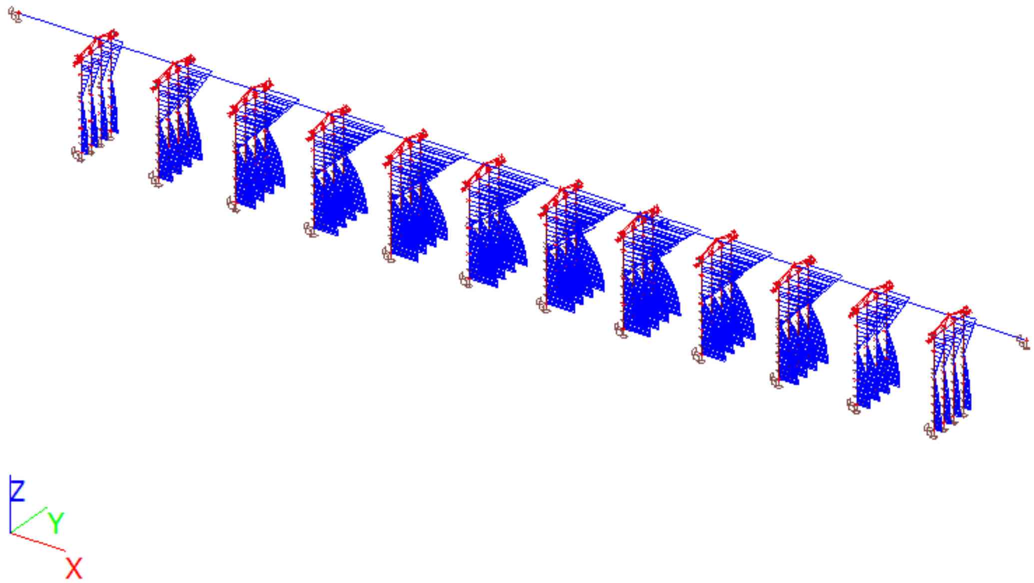

Figure 58 Resulting stress on the poles with tsunami loads

10.2.4 Resulting forces fully flooded

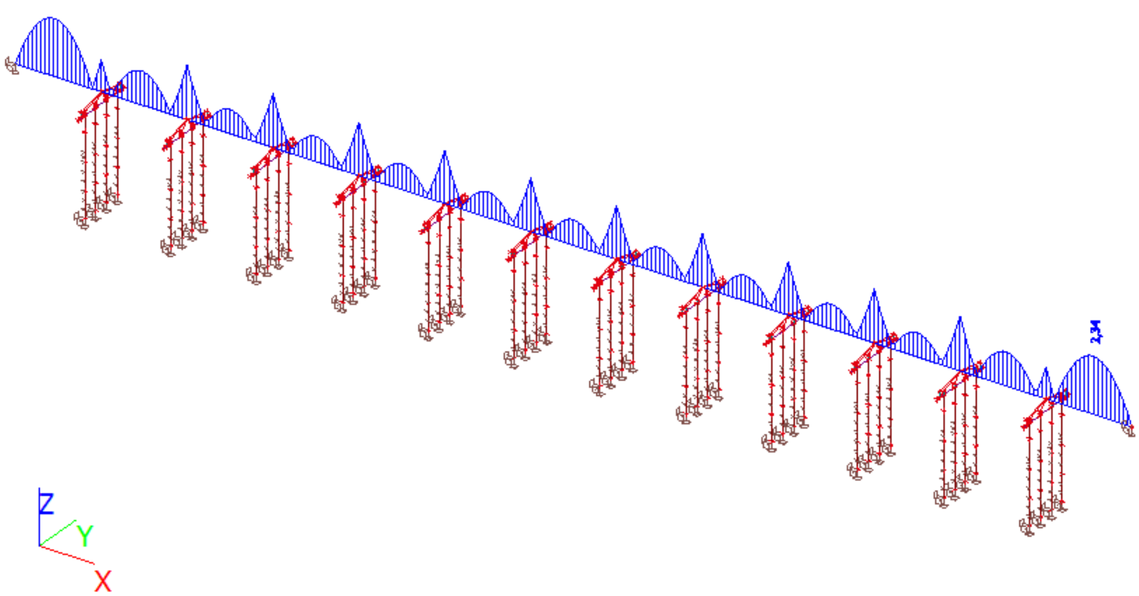

Figure 59 Resulting stress on the tunnel cross section with fully flooded loads

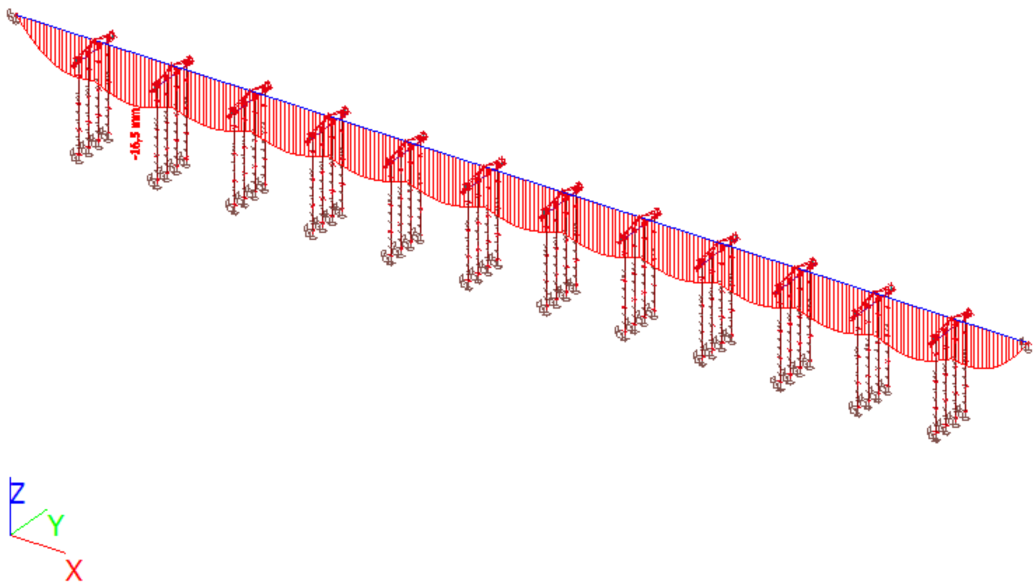

Figure 60 Resulting displacement on the tunnel cross section with fully flooded loads

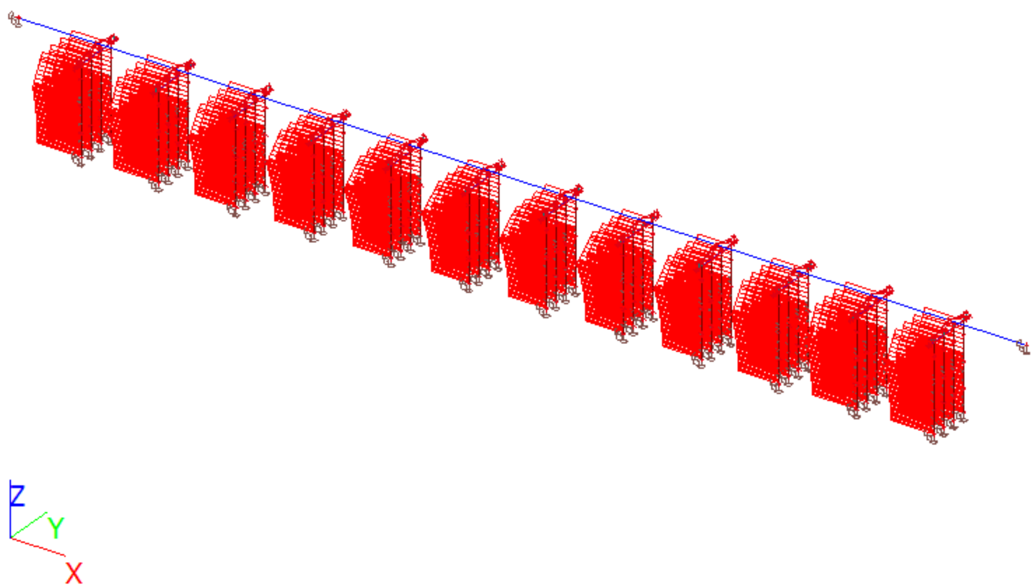

Figure 61 Resulting stress on the poles with fully flooded loads

10.2.5 Resulting forces partially flooded

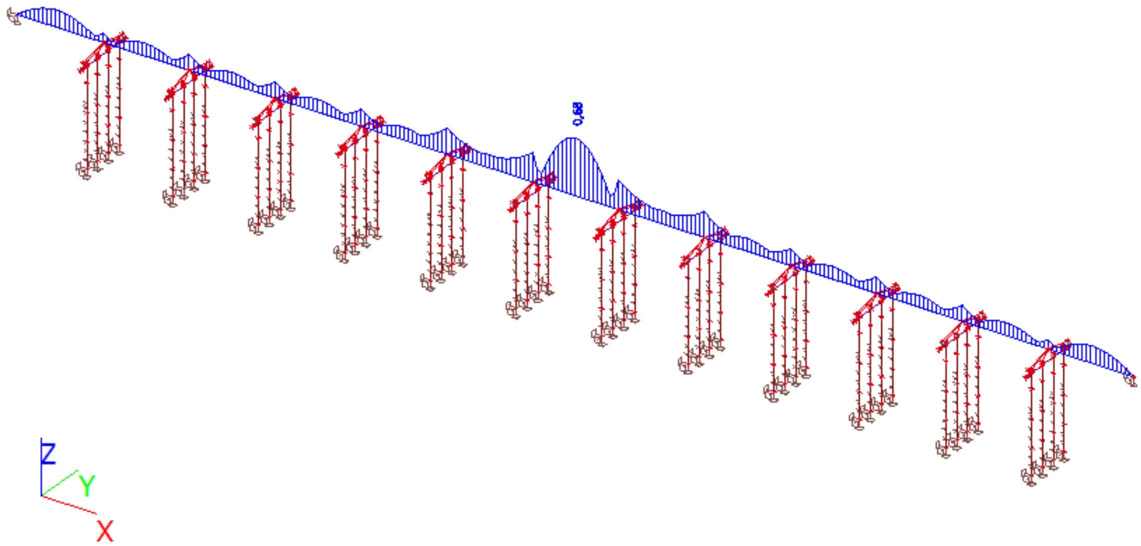

Figure 62 Resulting stress on the tunnel cross section with partially flooded loads

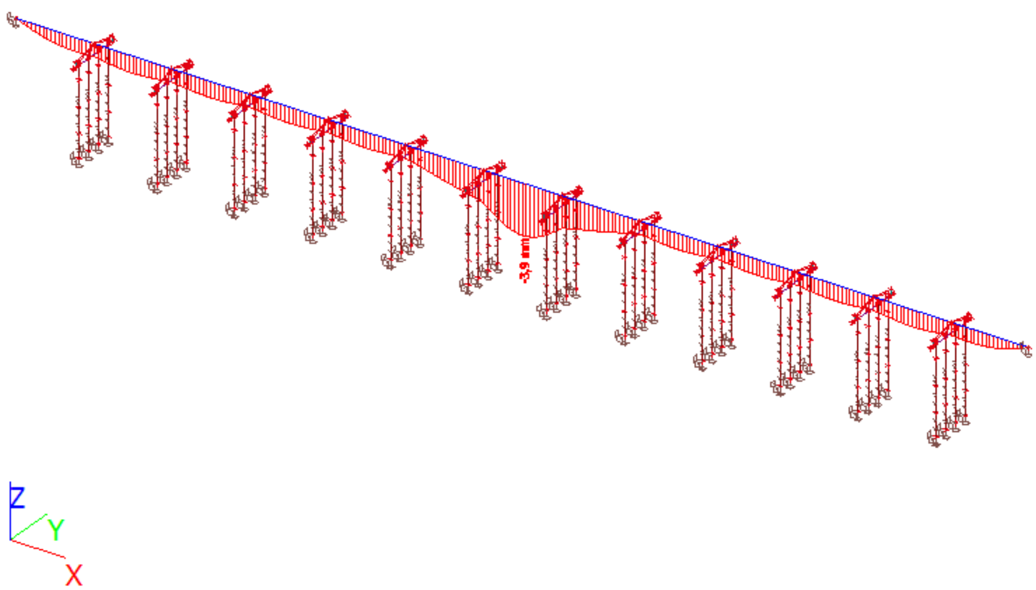

Figure 63 Resulting displacement on the tunnel cross section with partially flooded loads

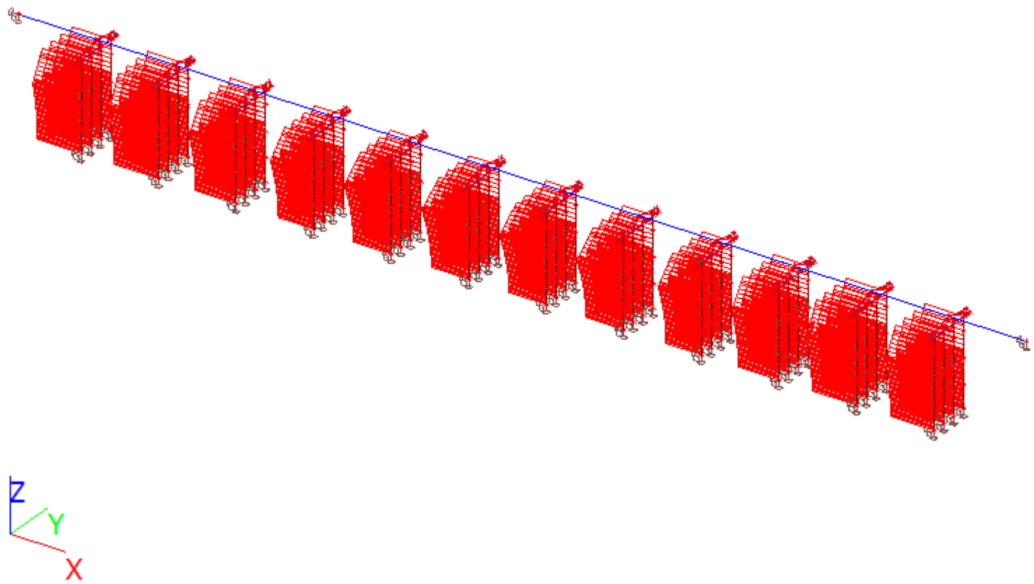

Figure 64 Resulting stress on the poles with partially flooded loads