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Design of the Submerged Floating Tunnel operating under various conditions

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Abstract

In Norway there has been identified several crossings with a variety of different conditions under which a Submerged Floating Tunnel, SFT or Archimedes Bridge, may be used. In the Høgsfjord project whose feasibility was well documented before the project was stopped for local political reasons the length was some 1400 m, the water depth about 150 m and the site was well protected from large sea waves. However, swell, vortex shedding and slowly varying internal waves due to layers of different salinity presented a hazard of significant dynamic oscillations. In the wake of the Høgsfjord project feasibility studies have been undertaken in Norway for sites at the very inlet of a fiord directly exposed to the big North Sea waves, in an inland lake with ice infested waters, in fiords threatened by large waves induced by huge, falling rock masses, and most recently the largest fiord in the country, the Sognefjorden which at the identified crossing site is 3700 m wide and 1250 m deep. In addition to the challenge of these various conditions some common accidental situations have to be solved for all applications including fire, sinking ships, falling anchors as well as sudden massive water ingress into the tube.

The paper discusses the design challenges presented by the various conditions and pros and cons for alternative technical solutions for these various applications and summarizes some of the experiences learned by the Norwegian studies.

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Keywords: SFT; design challenges; width and depth of crossing site; wave and current loads; dynamic response; accidental scenarios

1. The Norwegian history of SFT Design

The Submerged Floating Tunnel (SFT) was patented in UK in 1886, and the first Norwegian patent on the subject was issued in 1923. In the late 1960's a small group of highly recognized Norwegian engineers was established to evaluate the potentials for the SFT concept. They concluded that the concept was worthwhile pursuing and made sketches for tentative design for spans up to some 1500 m.

In the 1980's a comprehensive development work was embarked upon to cross the Høgsfjord, a 1400 m wide and 150 m deep fiord southeast of Stavanger on the west coast of Norway. The work made under the Høgsfjord-umbrella was very wide in scope and very diversified: Four of the largest and most well-known Norwegian

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contractors established their own design groups and developed their own concepts based on criteria specified by the Norwegian Public Roads Administration, NPRA. NPRA on their side awarded several contracts to both Marintek to perform comprehensive model tests in their large scale sea model basin in Trondheim as well as to Det norske Veritas to verify the tests. In the mid 1990's a reference group of four professors at the Norwegian Technical University of Trondheim was established to scrutinize the model tests and their results as well as all other work done on sea loading and their effects on an SFT for conditions relevant for the Høgsfjord-crossing. To be even more certain that no significant effects or phenomena had been overlooked some internationally well-known scientists were engaged to make their independent evaluation of these issues.

A group of Norwegian and international experts on heavy construction and marine works were also established to verify the feasibility of the construction aspects and the marine operations involved in installation of the SFT.

At the end of this period a group of three professors at the university in Trondheim evaluated the safety aspects of the SFT concept, and based on their report and all the other work that had been done the NPRA announced that they were ready to go for an SFT as a pilot project in Høgsfjorden.

Unfortunately, before the project came to the detail design stage, it was for political reasons decided to move the roadway route much further to the north, and the development has since then concentrated on a subsea rock tunnel. An ideal opportunity to launch a full-scale prototype SFT-project in a relatively protected area thus seems to have got lost.

About at the same time NPRA made a survey of all prospective crossings in the country and concluded that for some 10 to15 locations an SFT would be the best or even the only realistic crossing alternative. Even so, since the Høgsfjord-project there has been made relatively little systematic development work in Norway to further improve the concept. Some feasibility studies have been made, but these have largely been based on the technology and methods developed for the Høgsfjord project.

Only recently however some work has been launched to identify methods to cross the wide and extremely deep Sognefjord, see the paper by Mr. L. Skorpa presented at this symposium. This work has the potential to take the SFT concept some significant steps further towards realization.

2. The SFT concept

Typically an SFT consists of the following elements, see Fig. 1:

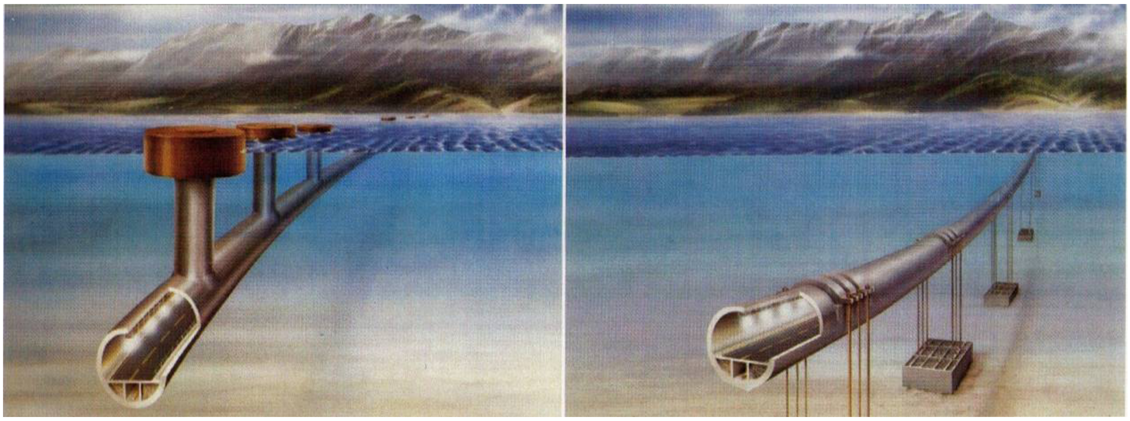
- The tunnel tube which provides space for the road and/or railway traffic
- Tethers, vertical or inclined fixing the tube to the seabed at certain spacing
- Pontoons mounted on top of the tunnel and "anchoring" it to the sea surface
- Gravity anchors on the seabed providing support for the tethers
- Shore connections at the ends of the tunnel

The tubes may be constructed of steel, concrete or a combination of the two. In Norway, the tube has up till now mostly been designed with circular cross-sections, primarily from hydrodynamic reasons. Other shapes as elliptical, rectangular or multiple-sided may also be of relevance.

Tethers and pontoons are alternative ways of controlling the vertical position and motions of the tube. They may also be used in combination. Typically, the tube is a long and very slender structure thus requiring special measures to provide sufficient horizontal stiffness to the system. Up till now, this has normally been done by forming the tube as a horizontal arch or by inclining the tethers.

If the crossing is wide and there for some reasons may be difficult or too costly to use inclined tethers due to e.g. very deep waters the horizontal stiffness may be significantly increased by using a horizontal arch comprised of two more or less parallel tubes being connected at certain intervals by rigid riegels, see Fig. 2. Each tube may then give space to traffic in one direction and provide escape possibilities in case of fire and alike in the other tunnel.

As an alternative to the double tube increased horizontal stiffness may be provided by some kind of horizontal stiffening tendon system, a simple and promising system of which is shown on Fig. 3. Major elements of such systems would have to be pretensioned, and it will be necessary to develop reliable anchorages at the shore which in Norway normally would be of good rock quality. The two concepts shown in Figs. 2 and 3 have been conceived in the recent study to cross the 1250 m deep Sognefjorden and will be further developed in the time to come.



(a) SFT with pontoons (b) SFT with tethers

Fig. 1. SFT's developed in the Høgsfjord-project

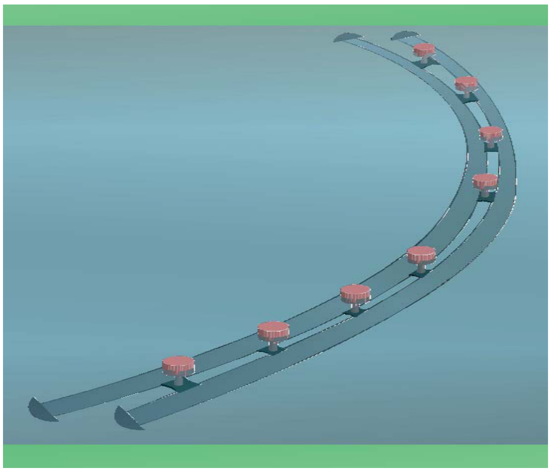


Fig. 2. SFT as a horizontal arch made up of twin-tubes

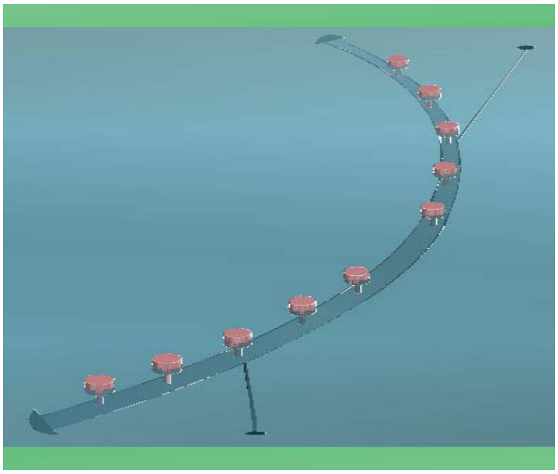


Fig. 3. SFT with horizontal stiffening tendon system

3. Design issues

For design of an SFT the following basic considerations should be taken into account:

- The cross-section must give sufficient space for traffic, evacuation, ventilation, ballast, inspection, maintenance and repair work
- The alignment must be such that there is no interference with ship traffic passing above
- The tunnel must have a simple and well defined static system which can be properly represented in the design calculations
- The joints should have no less strength or integrity than the tube between the joints
- The structure must have a ductile behaviour in the potential failure modes
- The anchoring system should be redundant

- The tunnel must not be unduly susceptible to local damage
- The structural details must be simple and designed to avoid undue stress concentrations
- The structure must be robust against changes in the static system, variations in the material properties and corrosion
- The tunnel must behave in a satisfactory manner with regard to deformations, settlements and vibration
- The tunnel must have a satisfactory safety against fatigue
- The tunnel should be designed such that the water inflow rate is so limited that people have time to safe evacuation in case of massive water ingress
- Tether lengths must be adjustable to compensate for e.g. possible settlements
- Slack and snapping of the tethers must be avoided
- It must be possible to repair or replace parts of the structure that are considered to have a shorter service life than the tunnel tube itself. Such parts can be tethers and other anchoring systems, bearings and moveable joints
- For the first SFT's and until sufficient experience has been gained with the concept, they should be designed and prepared such that steps could be taken to improve their behaviour, if proved necessary

4. Dynamic effects and their challenges

4.1. Wave loads

Waves in a fiord basin may have different origins. Firstly, the wind induced waves generated in the basin itself will depend on several factors, for instance the fetch length. In Norwegian fiords significant wave heights of a 100 year storm would typically be in the range of H_s = 1.5-2.5 m with spectral peak periods of T_p= 4-6 seconds.

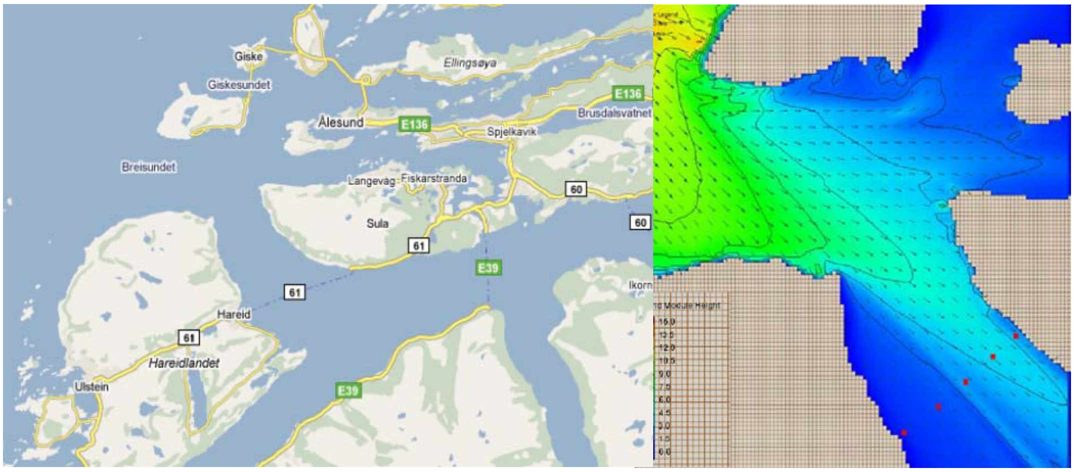
If the crossing is located not too far from the inlet of the fiord and the fiord is not well protected from the storm waves coming from the open sea by islands and alike, large, long-periodic waves can hit the structure. In a case on the north-west coast of Norway between Hareid and Sulasundet, see Fig. 4, waves with significant wave heights of H_s = 5.7 m with a spectral peak period of T_p= 15.5 s were analytically estimated at the crossing site for a 100 year storm situation out in the nearby North Sea of H_s= 15.0 m and T_p = 15.8 s.

It is not so much the difference in wave heights that causes higher wave loads on the structure from the sea waves, but more the difference in wave periods. Fig. 5 illustrates the effect of different wave periods on the wave force as a function of the depth at which the tube is located. The effect of the "fiord-waves" can effectively be reduced by locating the crossing on a larger depth. As seen, to achieve the same effect for the sea waves the crossing must be located at very large depths. This is even more so if very long-periodic swell waves, say with periods of some 20-30 seconds can penetrate in to the site. In the Hareid-Sula-crossing the tube had to be located at a water depth of 80 m to reduce the wave forces to manageable forces.

It is not likely that swell waves have amplitudes higher than some few decimeters in a fiord, so the wave loading as such would be very moderate. However, since the SFT system is generally very flexible it consequently also has very high dynamic eigenperiods. One thus has to be aware that detrimental resonance for such long-periodic waves should be avoided.

Non-linear effects in the waves create small unbalanced wave drift forces of which the so-called difference frequency loads will be long-periodic and may also cause resonances for the lower eigenmodes.

Another source for such possible long-periodic resonances are the so-called internal waves. These are effects that generate from potential layering of water with different densities due to salinity variations. In fiords with significant supply of fresh water, a lighter layer of breakwater can exist on top of a more dense layer of sea water with higher salinity. The most important effect of this layering is the free internal waves which can give rise to wave forces on an object in the vicinity of a boundary between two layers. It has been estimated that such waves can occur at periods higher than 40 seconds. These phenomena were subject to serious investigations during the Høgsfjord-project, but it was never confirmed that they occurred in reality. However, until it has been verified that they are not real phenomena and since they can cause dangerous resonances, they have to be taken seriously and be designed for.



(a) Map of the area with the North Sea to the north-west Crossing at Highway no. 61 between Hareid and Sula

(b) Detail of the sound with estimated wave heights

Fig. 4. Crossing site at the inlet of an exposed fiord

4.2. Current loads

A maximum current speed at the surface of a Norwegian fiord is typically up to1.5 m/s. It can vary very much across the fiord, so both symmetrical as well as antimetrical current profiles have to be considered in the design. On the tube the current gives rise to a constant in-line force which is proportional to the square of the current velocity. For a horizontal arch-shaped tube the symmetrical current profile is very well resisted by the axial forces in the arch, and the capacity of the arch is largely governed by its buckling capacity. An antimetrical current profile will not create significant axial forces in the arch, and the current forces have to be resisted by the bending moment capacity of the tube unless some supporting tendon systems or similar are introduced.

The current speed may also have some slowly varying velocity components, which should be kept in mind when evaluating the potential for resonance phenomena induced by slowly varying forces.

Current will give rise to vortex shedding when passing an obstacle. When passing a cylinder the vortex shedding occurs at a frequency that is proportional to the current velocity. When this frequency approaches the natural frequencies of the cylinder Vortex Induced Vibrations (VIV) occur. For a circular cylinder in-line vibrations typically start at a reduced velocity of U_r = 1-2 ($U_r = U_c/(f_n \cdot D)$ where U_C is the current speed, f_n the natural frequency of the tube and D is its diameter) and cross-flow oscillations at a reduced velocity of typically 3-4. These oscillations are self-limiting in the sense that the in-line oscillations stabilize at an amplitude of some 0.15D while the cross-flow oscillations stabilize at amplitudes up to about 1.3D. It is interesting to note that simultaneous wave loading tend to reduce the amplitudes of vortex induced motions. These phenomena are closer discussed in a paper by Professor T. Søreide at this symposium.

For the tube such cross-flow oscillations should be avoided. With an outer diameter of a tube of some 16 m and a maximum current velocity of 1.5 m/s the fundamental period of the vertical vibration modes should then be lower than about 30 seconds. In-line vibrations are relatively small and present mostly a fatigue issue.

For the tethers and tendon stiffening systems, however, it may be difficult to avoid cross-flow vibrations. Say the diameter of these members is 1m, then their fundamental period has to be lower than 3-4 seconds to avoid cross-flow vibrations when assuming that the governing current velocity is reduced to 1 m/s at the relevant water depth. Helical strakes may be a device used to suppress such vortex induced oscillations, if they do not have too severe negative side-effects such as increased current and wave loads.

Galloping is an instability phenomenon that may occur in current at significantly higher current velocities than vortex induced vibration, typically at reduced velocities $U_R \geq 10$. Fortunately, galloping does not occur for cylinders with a circular cross-section.

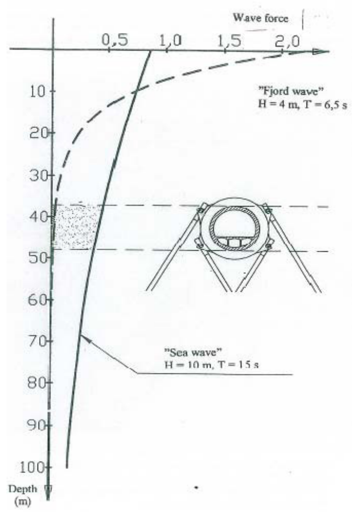


Fig. 5. Wave force as a function of wave period and depth

4.3. Artificial damping

As discussed above, there are many various sources of slowly varying environmental forces of low magnitude. As such, they would normally not do any harm to the SFT and its components if it had not been for the danger of resonance with major vibration modes of the tunnel tube.

One safe way of dealing with this challenge is to design the tube and its supports such that the lower fundamental eigenperiods are safely below the periods of these forces. In the more recent studies in Norway the first eigen-period has thus been kept below 5-6 seconds to also limit the dynamic effects of the larger first order wave forces. This however may have a big cost penalty since it generally would require a relatively large number of anchoring points, either through tethers or as pontoons. For recent Norwegian case studies with two-lane traffic and an outer diameter of the tube of some 12 m this has called for anchoring points every 250 m.

If it had been possible to design reliable artificial damping systems that could limit the resonance phenomena to tolerable levels, the number of such anchoring points and then also the cost could probably be significantly reduced. For the 4200 m long and 450 m deep Hareid-Sula crossing the cost associated with the tethers and their foundation was estimated to approximately 30% of the total cost. There are thus significant saving potentials by reducing the number of anchoring points.

Such damping systems could be in the form of tuned mechanical dampers; i.e. internal mechanical systems that have eigenperiods tuned to the frequencies that should be damped out. The space below the roadway could be utilized for this matter. Also, heavy concrete blocks hanging in e.g. chains underneath the tunnel might have the same effect. This latter system could furthermore increase the hydrodynamic damping.

Another possibility is, still under the roadway, to install water basins on each side of the cross-section and connect these basins with a tube. Water flow from one basin to the other induced by the motions of the tube could then create viscous damping.

To our knowledge the challenge with these tuned damper systems is that they have not yet been designed for periods above some 20 seconds. Due to the long periodic movements in question and the limitations on the acceptable amplitudes imposed by the psychological reactions of the passing drivers the accelerations that would activate these systems are very low.

In Norway up till now, there has not been made any development work on this issue, and it may be a challenge for the international community interested in SFT’s to develop such systems.

5. Accidental scenarios

Irrespective of how the SFT is designed possible accidental scenarios have to be identified and dealt with to minimize or possibly to eliminate their consequences. Pontoons may be subject to both local and more overall damage due to ship collision. Dividing the pontoons into compartments and introduction of weak links between pontoon and tube may be the answer to such threats.

The tunnel tube may be subjected to scenarios such as sinking ships, impact from submarines, hooking of trawling gears and anchor lines, internal fire and explosion and water filling due to rupture of possible internal water mains. The ultimate consequence of these scenarios is massive water filling of the tube. The tunnel should be designed so that all potential failure modes be ductile. Other safety enhancing measures may be to use double hull, steel lining in case of concrete tubes and also to shape the tube so it has the apex at midspan such that possible incoming water flows towards the ends of the tube.

Tethers and tendon systems may be subjected to impact from submarines, impact from trawling gears and anchor lines and also from sinking ships. These systems thus have to be redundant so that their individual elements may be repaired or replaced while the remaining system is fully operable.

6. Pontoons vs. tethers

As described above, pontoons penetrating the water surface will add vertical stiffness to the system, but they will not add anything to the horizontal stiffness. For long and slender tubes other measures then have to be added to give sufficient horizontal strength and stiffness. This will be necessary to resist forces from wind, waves and current, and possibly also to prevent resonance with long-periodic sea loading.

Vertical tethers down to the sea bottom will also give vertical stiffness, but virtually no horizontal stiffness. In order to also get horizontal stiffness the tethers have to be inclined. Then, the tethers should be neutrally buoyant in order to avoid reduced stiffness due to geometry deviating significantly from straight lines.

Three of the four contractors in the Høgsfjord-work used pontoons in their proposals, while the fourth used vertical tethers. The latter was based on their experience from offshore tension leg platforms.

At the end of the Høgsfjord-project, NPRA evaluated the two anchoring principles, the following points were advocated in favour of the tether alternative:

- No restrictions to ship traffic and represents no collision risk for ships
- No visible parts above water
- Easier installation of additional measures to cope with possible unforeseen behaviour
- Eliminates slowly varying dynamic response
- Less excited by first order wave forces
- Less excited by wind and current
- Probably less complicated dynamic response including less torsional excitations
- Less vulnerable for possible closing of roadway in case of accidental loss of one anchoring element
- Safer and less costly installation of tube since tethers can be used as mooring systems during installation
- May have both straight and curved horizontal alignment

In disfavour of the tether alternative, the following were emphasized:

- They may be subjected to collision by submarines
- They can require large net buoyancy of the tube in order to prevent slack in tethers
- Tethers are subjected to dynamic loading both from current, waves, and possibly earthquake and may also be subjected to Mathieu-instability phenomena due to varying stiffness caused by varying axial tension
- Foundations are dependent on soil conditions on sea bottom and may be vulnerable to underwater land-slides

For the brief studies that have been made in Norway since the Høgsfjord-project, tethers have been used as the preferred alternative. Fig. 6 shows the proposed SFT for the 4500 m long and 450 m deep Hareid-Sula crossing, the location of which is shown on Fig. 4. Apart from the deeply located tube this is typical of the more recent Norwegian SFT-design proposals.

For deep waters, such as for the very deep Sognefjorden, other concepts have been proposed, see Figs. 2 and 3, since it is believed that tethers down to the seabed in such cases would be very technically challenging and above all extremely costly.

The ultimate solution for an SFT-crossing might be the one depicted in Fig. 7. This is a single tube stabilized by its own net weight and where both pontoons and tethers are eliminated. By having it curved the other way than shown on Fig. 7 and having the apex at midspan and the tube stabilized by its net buoyancy, massive water ingress can be made less dangerous since water then will flow towards prepared water basins in the rock sides at each end of the tube. Before realizing such a challenging proposal in full scale, however, large-scale model-tests and perhaps also some full-scale experience from other SFT's or from crossings with the concept of shorter lengths, say a few hundred meters, should be available and confirming the principles of the concept. This solution has been proposed since many years by Dr. Per Tveit, and is closer described in e.g. Ref.[1].

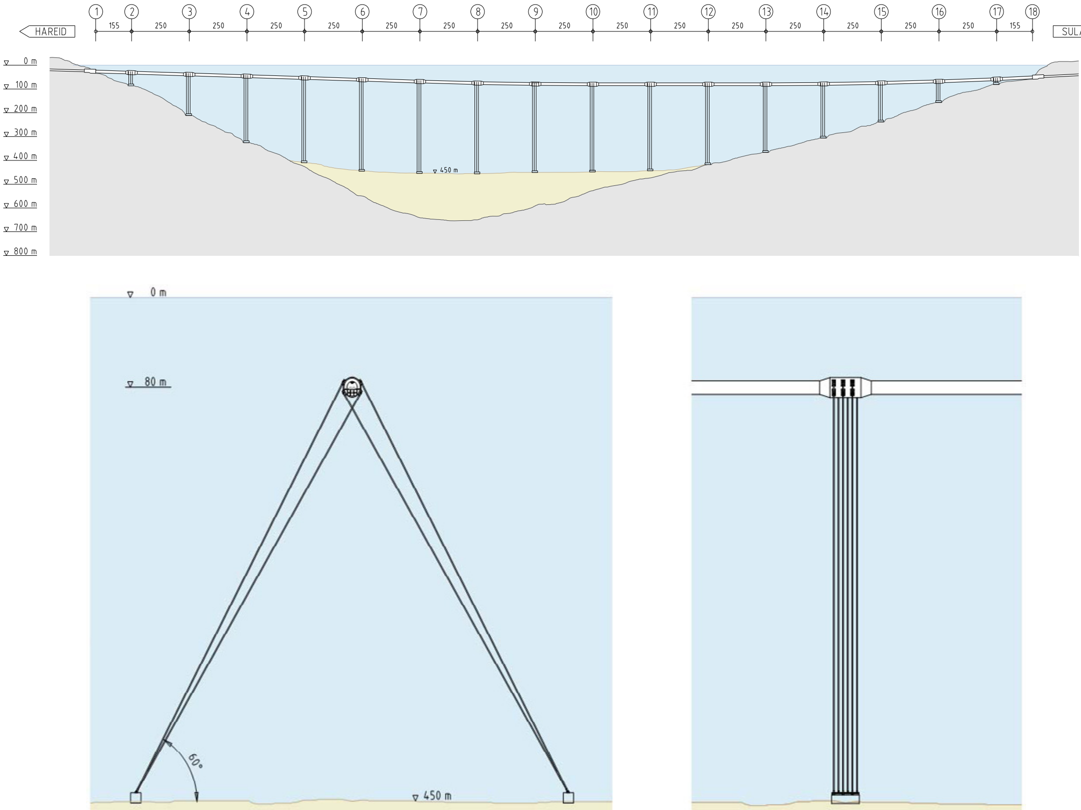


Fig. 6. Typical Norwegian design for an SFT crossing

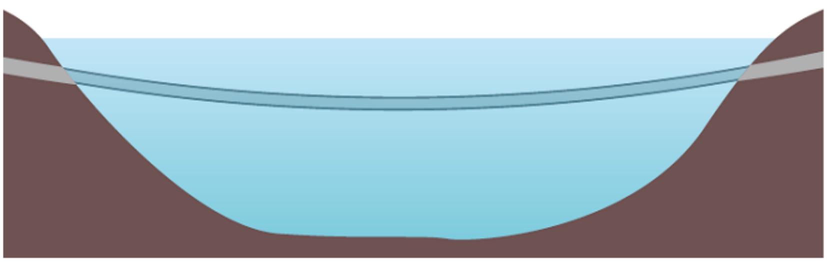


Fig. 7. The ultimate SFT-solution

Acknowledgements

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