# An Owner's Guide to Submerged Floating Tunnels

ITA Working Group 11
for Immersed and Floating Tunnels

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# 1 >> Terms & Definitions

ALS - Accidental limit state

ALARP – As low as reasonably practicable

BWR - Buoyancy-weight Ratio

FLS - Fatigue limit state

GBS – Gravity base structure

IMT – Immersed tunnel

ITS – Intelligent Transport System

MEP – Mechanical, Electrical, Plumbing

RAMS - Reliability, availability, maintainability and safety

SFT - Submerged Floating Tunnel

SFTB – Submerged Floating Tube Bridge (Another name for Submerged Floating Tunnel)

SHM – Structural health monitoring

SLS - Serviceability Limit state

TLP – Tension Leg Platform

ULS - Ultimate limit state

Metocean – Wind, wave, currents and other marine conditions

Submersion depth – distance between the mean water level and the top of the SFT tube

# 2 >> Objective

The Guide is intended to give future Owners the information they need to consider a Submerged Floating Tunnel (SFT) as a realistic, safe, economic alternative to bridges and conventional tunnels for crossing waterways, including terms and definitions, general requirements, design, construction, operation, inspection and maintenance.

As no SFT has yet been built, the guide draws on the knowledge and experience of Owners, researchers and project engineers who have been involved in feasibility studies, planning and designing of SFT concepts. All technical solutions discussed herein are based on ideas that have been put forward in previous studies, and these studies are listed at the end of the document.

A large body of knowledge and experience exists from projects such as immersed tunnel (IMT) structures and offshore structures, and from tethers, moorings and anchors used in the oil & gas and renewable energy industries; these can assist the development of SFTs. Indeed, SFTs incorporate technology from both IMTs and offshore structures. However, the combination of technologies within an SFT is yet to be proven at full scale.

The Guide would aim at a twofold objective: to provide a brief guide for deciding when an SFT is an appropriate option for a permanent water crossing and to address the issue for understanding what being the Owner of an SFT entails. To keep the guide concise, undue discussion of topics that are not SFT-specific have been avoided to the extent possible.

As this is not a design guide, technical discussions are kept at a descriptive level. The reader is encouraged to consult the references for details.

### 3.1 SUBMERGED FLOATING TUNNEL - DEFINITION

An SFT is a tunnel through water that is not in direct contact with the bed. It may be either positively or negatively buoyant. It may be suspended from the surface or supported from or tied down to the bed. Other terminologies such as Submerged Floating Tube Bridges (SFTB) and 'Archimedes Bridge' have also been used to describe this technology. The main components of an SFT are the tube (which can have different cross-sections), the stabilising systems and the shore connections. Figure 1 gives an example of two SFTs with twin tubes configurations and different stabilising systems.

SFTs considered in this document may be assumed to accommodate rail and/or road traffic. Utilities and facilities for pedestrians and/or bicycles could also be incorporated. Unlike an IMT, which rests on the bottom, an SFT is surrounded by water. Consequently, the loads on the structure can give rise to a dynamic response.

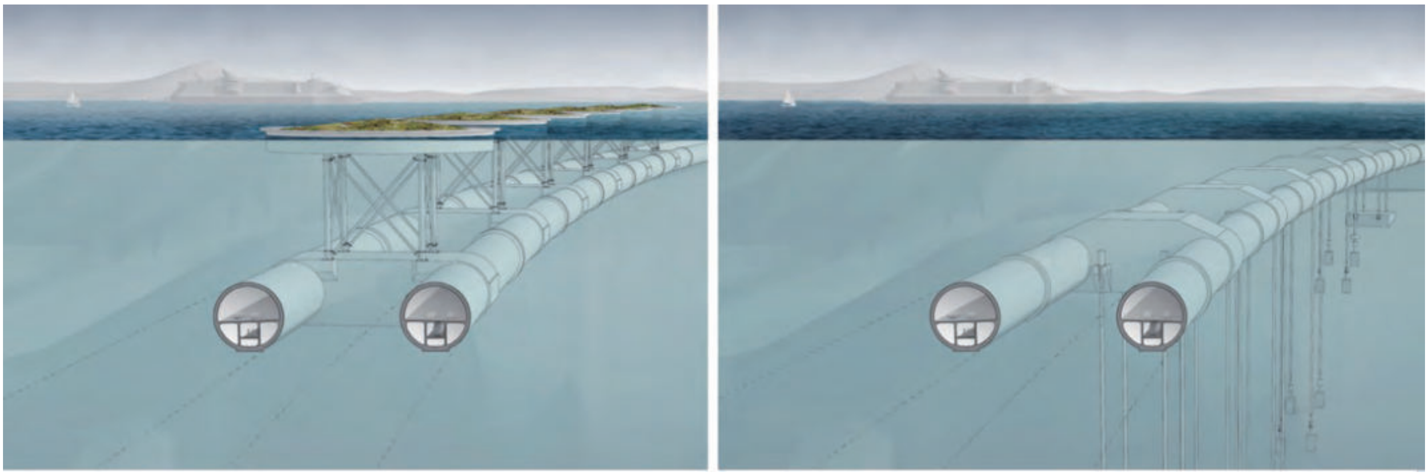

*Figure 1: Visualization of pontoon (left) and tether (right) supported SFTs (Norwegian Public Roads Administration).*

### 3.2 WHY AND WHEN TO CHOOSE A SUBMERGED FLOATING TUNNEL

SFTs can be considered as an alternative to other tunnels or bridges for a marine or inland waterway crossing.SFTs might best be suited to crossings with deep water (understood as greater than about 100m), significant marine traffic or where wind and wave conditions are harsh and immersed/ bored tunnels are not a feasible/attractive solution (ITA WG 11 Immersed tunnels in the natural environment). They also minimise the visual impact of the crossing, compared to a bridge. An SFT can be a suitable solution in seismic zones and might be applicable for any length of crossing.

The main features of an SFT crossing are:

- **Low gradient.** The submerged depth of the SFT can be set such that steep road gradients can be avoided in deeper water. Low gradients (up to 5%) can reduce the incidence of vehicle fires and result in lower fuel consumption. Further a higher elevation of the SFT might decrease the length of the shore tunnels.
- **Inclement weather.** An SFT is influenced by wind generated waves, as well as swell seas, but the submergence depth can be chosen to significantly reduce the load experienced from wind generated waves. Moreover, vehicles or trains inside the tube are protected from wind. As a result, there could be no need to close an SFT due to harsh weather.
- **Design freedom.** An SFT can be tailored to the specific needs of the site and has no length restrictions. The stabilisation system can be selected depending on the water depth, the soil properties and the metocean conditions, so that several solutions, like piers, surface pontoons or different types of mooring can be used. An SFT can be constructed as a single tube, or several tubes, for example one for each traffic direction.
- **Ship passage.** The SFT can be submerged to the depth needed to allow free passage of surface vessels. However, the risk of underwater impact from ship's anchors (dropped or snagged) and submarines on the SFT must be considered. Where surface pontoons are chosen as a stabilising system, the likelihood and consequences of ship impact should be mitigated.
- **Environmental impact.** Where freedom in the selection of its location is possible, SFTs should preferably be located where the environmental impact at the site is lowest. An SFT, being a fully submerged structure, has little or no visible impact on the local aerial environment. It can be completely hidden from view, except where surface pontoons are used as stabilising systems. An SFT does not generate surface noise pollution. The

presence of the structure can influence the local currents and the effect could be significant in shallow waters. Nevertheless, underwater noise and subsea construction works that may affect underwater flora and fauna should be evaluated.prefabrication and construction.

- **Seismic area.** An SFT can be an option at earthquake prone sites, being a flexible structure, connected to the ground at discrete points.
- **Cost modularity.** As the SFT is a modular structure, studies have shown that, in most cases, the cost per unit length is relatively constant. In addition, it is suitable for industrial prefabrication and construction.

### 3.3 LIST OF PREVIOUSLY PROPOSED AND ONGOING SFT-PROJECTS

Several projects have evaluated SFTs over the years, and these may be of help and inspiration to future Owners. A selection of previously proposed crossings is listed below; their main parameters are listed in Table 1.

Research into SFT technology is ongoing. Significant research efforts and centres are also listed here. The research includes simulation and model testing of a variety of proposed cross sections, but no prototype has yet been built or tested. A list of relevant papers and reports is found in the reference section.

**Proposed crossings**

- Bjørnafjord crossing (Reiso et al., 2015)
- Breisundet SFTB crossing (Dr. Techn. Olav Olsen, 1999; Fib Bull no.96)
- Daikokujima crossing (Kanie et al., 2010)
- Digernessundet crossing (Eidem et al., 2017)
- Dikket pontongbro (Trygve Olsen, 1923; Fib Bull no.96)
- Drøbaksundet hybrid bridge (Snøhetta, 1989; Fib Bull no.96)
- Eldfjord (Statens vegvesen, 1979; Fib Bull no.96)
- Funka Bay crossing (Kanie, 2010)
- Golden Horn Unkapanı Highway Tube Tunnel, Istanbul (Arcadis/IBB, 2017; Fib Bull no.96)
- Gulf of California (Faggiano et al. 2016)
- Høgsfjord crossing (Skorpa & Østlid, 2001)
- Jintang Strait (Faggiano et al., 2002)
- Karmsund tube bridge (Statens vegvesen, 1948; Fib Bull no.96)
- Lake Lugano crossing (Haugerud et al. 2001)
- Messina strait crossing (Faggiano et al., 2001)
- Oinaoshi in-port (Kanie et al., 2010)
- Osaka bay (Ahrens, 1997)
- Pont submergé dans le lac Léman (Notari, Muttoni, Moccia, 2018; Fib Bull no.96)
- Qiandao lake prototype (Mazzolani et al., 2008)
- Qiongzhou Strait, China (Jiang et al., 2018)
- Rovdefjord crossing (Statens vegvesen, 2017; Fib Bull no.96)
- Seribu archipelago (Budiman et al., 2016)
- Sognefjord crossing (Fjeld et al., 2013)
- Statpipe Shore Approach (Selmer AS, 1982; Fib Bull no.96)
- Sulafjord SFTB (Statens vegvesen, 2018; Fib Bull no.96)
- Tubolario (Gianfranco Magrini, 1984; Fib Bull no.96)
- Uchiura Bay (Ahrens, 1997)

**Research centres**

- Department of Structures for Engineering and Architecture of the University of Naples Federico II, Naples, Italy
- Delft University of Technology, Civil Engineering and Geosciences
- Institut Teknologi Sepuluh Nopember, Department of Civil Engineering, Indonesia
- Coastal Highway Route E39 Project, The Norwegian Public Roads Administration
- Research Centre for Smart Submerged Floating Tunnel Systems, KAIST, Korea
- Research Centre for Submerged Floating Tunnel, Zhejiang University, China
- Trilateral international network between KAIST, Zhejiang University and University of Naples Federico II for joined SFT studies

| CROSSING | LENGTH [km] | MAX WATER DEPTH (MAX) [m] | MAX SUBMERGENCE DEPTH [m] | STABILISATION SYSTEM | MATERIAL OF TUBES |
|---|---|---|---|---|---|
| **Bjørnafjord** | 5.5 | 580 | 30 | tension leg mooring or pontoons | concrete |
| **Breisundet SFTB crossing** | 4.2 | 450 | 35 | Inclined tethers | concrete |
| **Daikokujima crossing** | 0.1 | 12 | - | inclined mooring | reinforced concrete & steel |
| **Digernessundet** | 0.52 | 200 | 40 | Free span, shore-anchored | concrete |
| **Dikket pontongbro** | - | - | - | tension leg mooring and pontoon | - |
| **Drøbaksundet hybrid bridge** | - | - | - | mooring | - |
| **Eldfjord** | 1.2 | 250 | 16.5 | Inclined tethers | - |

| CROSSING | LENGTH [km] | MAX WATER DEPTH (MAX) [m] | MAX SUBMERGENCE DEPTH [m] | STABILISATION SYSTEM | MATERIAL OF TUBES |
|---|---|---|---|---|---|
| **Funka Bay** | 30 | 120 | 30 | inclined mooring | composite concrete steel |
| **Golden Horn Unkapanı Highway Tube Tunnel** | 0.66 | 35 | 10 | Foundations on piles halfway between river bed and water surface | concrete |
| **Gulf of California** | 150 | 213 | 25 | inclined mooring | concrete |
| **Høgsfjord** | 1.4 | 150 | 20 | tension leg mooring or pontoons | concrete or steel |
| **Jintang Strait** | 3.2 | 100 | 25 | inclined mooring | concrete |
| **Karmsund tube bridge** | 1.4 | - | 12.5 | Free span | Double steel filled with concrete |
| **Lugano Lake** | 0.93 | 70 | 6 | concrete piers | concrete |
| **Messina Strait** | 3.3 | 200 | 30 | inclined mooring | composite reinforced concrete & steel |
| **Oinaoshi in-port** | 0.3 | 15 | - | steel piles | concrete |
| **Osaka bay** | 11 | 40 | 20 | steel piles | reinforced concrete & steel |
| **Pont submergé dans le lac Léman** | 37 | 50 | 30 | pile funded columns | concrete |
| **Qiandao Lake prototype** | 0.1 | 30 | 10 | inclined mooring | composite concrete and steel and aluminium |
| **Qiongzhou Strait** | 20 | 88 | 30 | inclined mooring | concrete |
| **Rovdefjord crossing** | 0.23 | 70 | 14 | - | concrete |
| **Seribu archipelago** | 150 | 21 | 5 | inclined mooring | reinforced concrete & steel |
| **Sognefjord** | 3.7 | 1200 | 20 | pontoons | concrete |
| **Statpipe Shore Approach** | 0.67 | 30 | 30 | piers | concrete |
| **Sulafjord SFTB** | 3.64 | 440 | 58 | tethers | concrete or steel |
| **Tubolario** | 70 | 418 | 20 | tethers | - |
| **Uchiura Bay** | - | - | - | - | - |

*Table 1: Main parameters of previously proposed SFTs.*

# 4 >> SFT Layout & Construction

## 4.1 SFT LAYOUT ALTERNATIVES

In terms of layout and arrangement, SFTs consist of three main elements: a section of one or more tubes, the joints between the inner modules and shores and the stabilising system. The tube(s) may be straight or curved in the horizontal and/or vertical planes, not only to suit alignment criteria but also to increase stability and reduce motions.

The relationship between the buoyancy and the weight of the structure is important for SFTs. It is described as the buoyancy-weight ratio (BWR), which is a key design parameter. A structure is defined as neutrally-buoyant if its buoyancy equals its weight (BWR=1). If its weight exceeds its buoyancy, the structure is defined as negatively-buoyant (BWR<1). Likewise, if its weight is less than its buoyancy, the structure is defined as positively-buoyant (BWR>1).

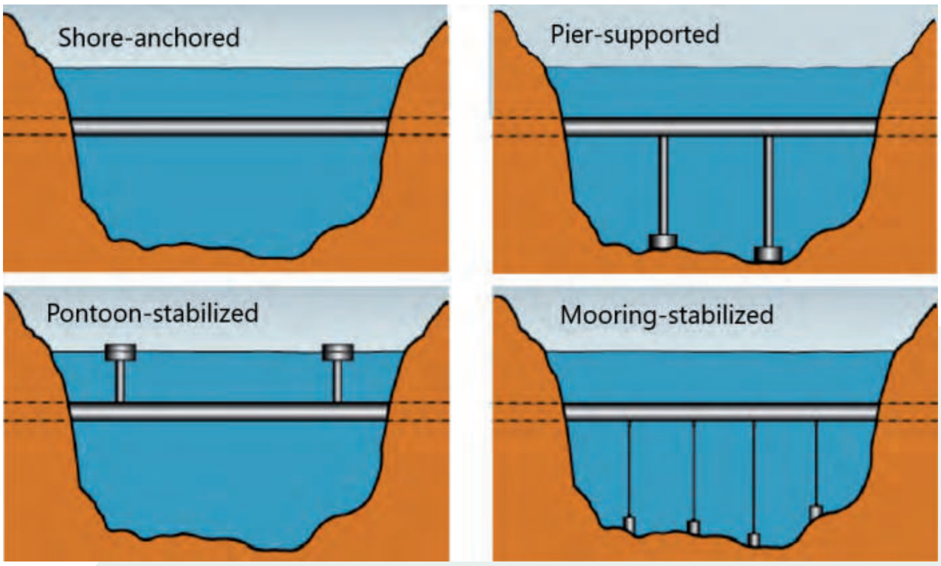


*Figure 2: Different types of SFTs, adapted from (Østlid, 2010): shore-anchored, pier-supported, pontoon-stabilised, and mooring-stabilised.*

Potential SFT layouts, in terms of the stabilising system, include shore-anchored, pier-supported, pontoon-stabilised and mooring-stabilised. In some studies, combinations have been evaluated. Additional lateral load carrying capacity may be desirable to increase the SFT's ability to resist horizontal forces and thermal deformations. This can be achieved using various measures, such as prestressing, adding support structures, or changing the geometrical stiffness by modifying the cross section or introducing axial curvature of the tubes.

Examples of different SFT layouts are shown in Figure 2.

- **Shore anchored.** The tunnel is fixed at its landfall ends without additional stabilising system. Therefore, it is sometimes called free. The tunnel behaves as a clamped beam supported at the ends and the tube is likely to be neutrally-buoyant.
- **Pier supported.** The SFT is held in position by piers, which act as fixed supports. In this case, the SFT is equivalent to an underwater multi-span continuous bridge. The SFT is likely to be neutrally or negatively-buoyant.
- **Pontoon-stabilised.** The SFT is stabilised against vertical motion by pontoons. The tube should be neutrally-buoyant throughout, or the BWR can be optimised at the pontoons so that internal forces are minimized. Structures connecting the pontoons to the tube may be designed with a sacrificial connection to limit the transmission of accidental ship impact forces. Pontoon-stabilised SFTs are sensitive to forces due to wind, waves, current and near the shoreline to water level changes. This solution can be used when the environmental conditions are favourable and the horizontal loads are small.
- **Mooring-stabilised.** The SFT is stabilised against vertical and/ or horizontal motion by vertical and/or inclined moorings. For vertical moorings, the tube is likely to be positively-buoyant, as moorings cannot sustain compression loads. It is possible to combine both stabilising methods within one project.

## 4.2 CROSS-SECTION

The internal space requirements of an SFT are governed by the same requirements as other types of tunnel to meet national codes and regulations:

1. Number of road lanes, including clearance, possible emergency lane, and/ or rail tracks
2. Possible lay-bys and/ or shoulders, hard strips and crash barriers
3. Escape and emergency access ways
4. Possible pedestrian and bicycle access
5. Mechanical, Electrical, Plumbing (MEP) including ventilation, transformers, pump sumps and other provisions
6. Possible gallery for ducts and cables
7. Intelligent Transport Systems (ITS) including road traffic signage
8. Possible provisions for utilities

In addition, space is required within the cross section for permanent and for temporary ballast.

The external shape of an SFT tube is likely to be circular, elliptical or polygonal, either in a single-tube or multi-tube configuration, as shown in Figure 3. However, the external shape is still topic of ongoing research. The shape can also be influenced by the wave and current conditions, as explained in section 5.6.

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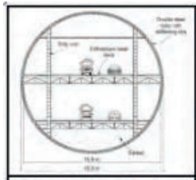
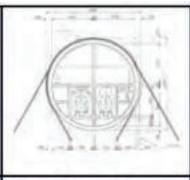
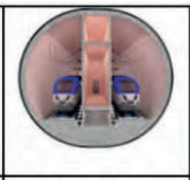
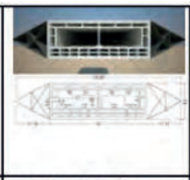
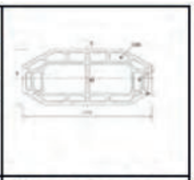
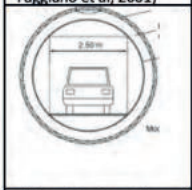
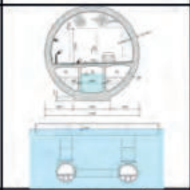
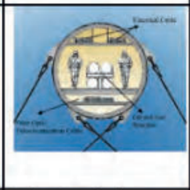
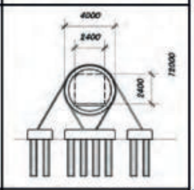
|  |  |  |  |  |
| Italy – Messina Strait (Martire et al, 2009; Faggiano et al, 2001) | Japan - Funka Bay (Kanie, 2010) | South Korea (Seo et al, 2015) | Mexico - Gulf of California (Faggiano et al., 2016) | China - Jintang strait (Faggiano et al, 2002), |
|  |  |  |  |  |
| China - Qiandao Lake (Mazzolani et al, 2001, 2007, 2008; Faggiano et al, 2009, 2018) | Norway - Sognefjord (Fjeld et al, 2012) | Indonesia - Seribu archipelago (Budiman et al, 2016) | Japan - Oinaoshi in-port (Kanie 2010) | Japan - Daikokujima crossing (Kanie 2010) |

Bulkheads and floodgates or inflatable plugs to compartmentalize tunnel sections can be incorporated to control the BWR in case of accidental flooding (see section 3). These must be considered in the conception and design of the cross-section. A secondary barrier, such as a double hull, can also be used as a measure against the water ingress in the main ways, due to accidental impact.

### 4.3 SHORE CONNECTIONS

To handle transverse and longitudinal forces and displacements, shore connections are needed at each end of the SFT. Depending upon site conditions, the SFT tunnel may connect directly to bored, mined or cut-and-cover tunnels, or may connect to an intermediate transition caisson or immersed tunnel.

The shore connection is an essential structural link between the SFT and the adjacent tunnels, which will be much stiffer than the SFT. Provision may be required for potential axial and transverse relative movements, particularly if the crossing is in a seismic zone where short transition sections may be needed to handle larger relative transverse movements.

### 4.4 MATERIALS

Concrete, steel, aluminium and composite materials have been considered in the studies. High performance materials complying with the requirements of durability and for resisting the water environment are also available. Experience of material performance is available from existing immersed tunnels, offshore structures and floating bridges. Materials for joints, mooring lines, anchors, and shore connections should also be evaluated.

### 4.5 CONSTRUCTION AND INSTALLATION

#### 4.5.1 Tubes

Several strategies are possible with regards to construction and installation of the tubes. In most of the previously proposed solutions, the tubes are constructed using a modular system, later assembled. The construction method depends on the geometry, chosen material, site conditions and the production facilities available. Efficiencies can be realised through prefab- methods.

The construction facility for the tube elements may be located close to the site or more remotely. Like IMTs, they can be constructed in various ways. In each case before the tubes are floated out, the ends are sealed with temporary bulkheads and equipment for marine operations installed. Typical construction locations include:

- In a dry dock.
- In a factory yard onshore where the elements are constructed in an indoor environment and from where they are pushed through a lock system.
- Construction onboard a submersible vessel, barge or floating dock.
- For a steel-concrete composite tunnel, construction can be completed in the above locations. Alternatively, the steel structure with enough keel concrete for stability may be constructed onshore, then floated out or launched from a slipway or transferred to water by a crane. The remaining concrete can be placed at a convenient location while the element is afloat.

Once the elements are complete and afloat, they would be ballasted such that they have only a small freeboard. The elements would be towed to a location where they could be assembled into longer sections of tunnel. Depending on site conditions, assembly of tube elements can either be on-site or elsewhere. Assembly is likely to be easier while the elements are still floating.

**Modular assembly on site.** At the crossing site, elements or preferably previously joined sections would be temporarily supported, then submerged using additional ballast, pontoon supports attached (if used), then joined to previously installed elements, supporting systems or terminal joints. Supporting systems would then be finalised, following which the ballast would be adjusted to the required final BWR according to the type of SFT. Assembly could be done from both shores simultaneously. Where there is a risk associated with potential motion of the unfinished sections of tunnel, temporary support should be provided. This is less likely to be needed for pier-supported and mooring-stabilised solutions SFTs after each element or section is installed. Installation operations need favourable weather conditions.

**Off-site assembly and transport to site.** The elements are towed to a sheltered location off-site, where they are joined together into longer sections or even the entire length. The main risk associated with off-site assembly is the complicated towing of a long flexible structure, which may require the coordination of several towing vessels. Unlike IMTs, which are designed for movements in the element joints, the joints between the SFT elements must be designed and constructed to form a monolithic structure to ensure structural continuity.

Because an SFT is a modular structure, it may be possible for the tube elements to be completed in the yard, including part of permanent internal infrastructure; this will depend upon the type of SFT and the final BWR. If elements or sections are installed sequentially out from the shore completed with their final support systems, installation of equipment inside can proceed whilst the next element or section is being installed. This can represent a substantial optimisation and a reduction of construction time, leading to cost savings.

#### 4.5.2 Pontoons

The pontoons and their connections could either be produced on-site, or off-site and towed to the crossing to be attached to previously submerged elements.

#### 4.5.3 Mooring and mooring foundations

Moorings are commonly used in the offshore industry, for which there are established production facilities around the world. Therefore, these will typically be produced off-site and transported to the crossing. After being connected to their foundations and the submerged tunnel tubes.

Depending on the local ground conditions, the type of foundation may vary, also along the length of the structure. Common types of foundation include driven piles, rock socket piles, suction piles, dead weight blocks and other. Drag anchors may be applied for semi-taut moorings if anchor drag and embedment can be controlled.

Due to possible settlement, it is recommended that the foundations be installed well in advance of the installation of the tubes.

#### 4.5.4 Shore connections

The shore connections may be constructed by several different methods (see 4.3); the SFT installation procedure will vary accordingly.

#### 4.5.5 Piers

Piers can be constructed using traditional bridge construction methods. The pier foundations could use existing developed methods, for example traditional bridge piers, solutions from the oil and gas industry, or a gravity base structure (GBS).

# 5 >> Site Conditions

### 5.1 ENVIRONMENTAL IMPACT

The crossing location must be assessed for ecological, societal, archaeological and environmental constraints. Stakeholders that may be affected by the crossing should be consulted.

A comprehensive environmental impact assessment will be required for the chosen site according to national and local laws and regulations. Local environmental impact may be a major consideration in the choice of the layout and alignment. As with any large infrastructure project, approval of the project may require habitat compensation to negate any adverse impacts of the crossing itself.

### 5.2 BATHYMETRY, TOPOGRAPHY AND GROUND CONDITIONS

In order to decide at an early stage whether an SFT is a potential alternative for the proposed crossing location, basic knowledge of the bathymetry, topography and ground conditions is needed. The detailed design will require refinement of this data as well as accurate site surveys.

In seismic-prone zones, the seismicity of the site should be characterised and considered in the design of the SFT structure.

Knowledge of the geology, ground conditions, seismic hazards, metocean, tide and local hazards is required for the choice and design of the stabilisation system and foundation type.

### 5.3 METOCEAN CONDITIONS

Metocean conditions include water levels, current, wind, waves, temperature, salinity and density variations.

During a feasibility study, simulations may be sufficient to decide whether to proceed with an SFT alternative, but detailed knowledge must be gained through measurements as the project progresses. Measurements of the metocean conditions should be taken for an adequate period to have a sound statistical basis.

Regardless of the chosen installation procedure, operations on water are very dependent on forecasting weather and metocean data, for which computer modelling may be needed. Weather statistics should be used to create an initial timetable for the various installation stages, including weather windows for critical operations. It is of vital importance that this is considered early in the design of the structure and installation procedures.

- **Water level.** Water levels change due to tides, but seiches and storm surges can also contribute to extreme water level variations. Tidal ranges can be several metres, which affects the free depth above the tube. This is significant for ship traffic on the surface, but it also changes the wave loads as these vary with the water depth. Moreover, water level may influence the stability of a pontoon solution. Water level variations may introduce additional loads on the shore connections. The contribution of the tidal variation to the currents should be considered.
- **Current.** The current velocity and profile along the proposed alignment must be measured and considered in the design loading. SFTs may be challenging options when the current speed is high, such as in narrow straits between large bodies of water.
- **Wind.** The wind characteristics at the site should be measured. These form the basis for wave prediction, for the loading on any pontoons and for setting suitable weather windows for the installation phase.
- **Waves.** Wave fields should be characterised by measurements and simulations in order to determine the hydrodynamic load on the SFT structure. The possibility of propagation of ocean generated swell waves to the site should be considered, as these may penetrate to a greater depth than locally generated wind driven waves.
- **Tsunami.** If the occurrence of a tsunami is probable, for instance as the result of an earthquake or landslide, the loading on the SFT from such an event must be evaluated.
- **Landslide** An (underwater) landslide as a result of an earthquake can threat both a tether foundation as well as a shore connection.
- **Earthquake** dynamic loading due earthquakes introduced to the tunnel at the shore connections. In seismic areas the effect of earthquakes must be evaluated.
- **Density variations.** Variations in water density could cause internal waves that may influence the dynamic response of the SFT. The possible occurrence of such waves must be investigated for the site.

### 5.4 SHIP TRAFFIC

Marine growth. The maximum thickness of marine growth through the water depth should be established as this can add significant weight to the SFT and increase the drag forces.

The types, sizes and frequencies and related transit speeds of vessels passing through the crossing site should be established and forecast over the lifetime of the crossing. This will form the basis for the determination of design loads by probabilistic methods as well as for understanding precautions to be taken during construction.

This information could be significant in determining whether to use a pontoon supported system, considering the risk of accidental vessel impact. An SFT may also be subject to accidental submarine impact.

### 5.5 ROAD AND RAIL TRAFFIC

The expected annual traffic, including both people and goods, should be estimated over the lifetime of the structure. An estimate of the volume and type of dangerous goods is needed to evaluate design criteria for fire and explosion and whether there is any need to impose traffic restrictions.

### 5.6 INFLUENCE OF SITE CONDITIONS ON SFT DESIGN

- **SFT stabilisation.** The selected stabilisation systems are heavily influenced by the site conditions such as the metocean environment, soil characteristics, bathymetry and other geological and geotechnical parameters, including the risk of slides and earthquakes. Moreover, the geometrical constraints, like water depth and the length of the crossing are also important.

  A shore anchored SFT is probably most suitable for shorter crossings, for example up to a few hundred metres. Previous studies have proposed this solution for crossings up to

*Likely to be greater than one year for recording of normal conditions and modelling of extreme conditions. Should also continue throughout the project period and for the final structure to support detailed monitoring of the SFT behaviour, noting its novel nature.*

approximately 700 m (Xiang, et al., 2017), but longer crossings may require additional stabilisation systems. For very long crossings, a system relying solely on pontoons may not provide sufficient stabilisation.

For relatively shallow water, pier supports may be appropriate. For medium to deep water, the two main alternatives for stabilisation are surface pontoons or moorings, both of which are widely used in the offshore industry. For example, tension leg tethers are in use in depths up to around 1600 m on some existing tension leg platforms (TLPs). In deep water, it may be desirable to minimize the number of moorings and their foundations (without compromising the reliability of the SFT system),, or to consider pontoon stabilisation, in order to reduce the cost associated with installation, inspection and possible replacements. At sites with unfavourable ground conditions, pontoons may be the best option, provided that the metocean conditions are favourable.

As pontoons are influenced by wind and wind-generated waves, moorings maybe a better option if the weather conditions are harsh.

Where pontoon stabilisation is used, the location of the pontoons must take into account surface ship traffic and ensure enough room for safe navigation.

The suitability of the main stabilisation systems for various site conditions is summarised in Table 2. Combinations of stabilisation systems can also be considered where conditions are suitable, such as a pier-supported and a pontoon-stabilised system for an SFT crossing which crosses both shallow and deep water.

| PARAMETER | STABILIZATION SYSTEM | | | |
|---|---|---|---|---|
| **Crossing lengh** | **Shore-anchored** | **Pier-supported** | **Pontoon-stabilized** | **Mooring-stabilized** |
| Short | Suitable | Suitable | Suitable | Suitable |
| Medium | Less suitable | Suitable | Suitable | Suitable |
| Long | Unsuitable | Suitable | Suitable | Suitable |
| | | | | |
| **Water depth** | | | | |
| Shallow | Suitable | Suitable | Suitable | Suitable |
| Medium depth | Suitable | Unsuitable | Suitable | Suitable |
| Deep | Suitable | Unsuitable | Suitable | Less suitable |
| | | | | |
| **Weather conditions** | | | | |
| Favorable | Suitable | Suitable | Suitable | Suitable |
| Moderate | Suitable | Suitable | Less suitable | Suitable |
| Harsh | Suitable | Suitable | Unsuitable | Suitable |
| | | | | |
| **Ship traffic** | | | | |
| High number of vessels | Suitable | Suitable | Less suitable | Suitable |
| Vessels with deep draft | Suitable | Suitable | Less suitable | Suitable |
| | | | | |
| **Ground conditions** | | | | |
| Unfavorable soil conditions | Suitable | Less suitable | Suitable | Less suitable |
| Seismic hazard | Suitable | Less suitable | Suitable | Suitable |
| Probability of underwater sllides | Suitable | Less suitable | Suitable | Less suitable |

*Unsuitable* *Less suitable* *Suitable*

*Table 2 Suitability of stabilisation systems for different site conditions.*

- **Foundation.** The type of foundation and the position of the individual foundations in case of mooring systems are influenced by ground conditions. Where there is a significant risk of underwater slides during the lifetime of the SFT, this must be taken into account in the design.
- **SFT submergence depth.** The main factors that influence the SFT submergence depth are the draft and required under-keel clearance of passing ships. In addition, swell is one of the most important factors for defining environmental loads on the SFT and may be decisive for choice of depth. Moreover, there may be a maximum feasible depth with regards to installation. If an SFT is planned for a crossing in relatively shallow water, the bathymetry may influence the submergence depth. In this case, the proximity effect between the tube and the bottom should be evaluated.
- **Cross section shape.** The shape of the SFT cross section influences the hydrodynamic behaviour of the structure and must be designed according to the metocean conditions, in particular the loads from waves and currents. The choice of outer shape may also be influenced by considerations of vessel impact or sinking objects. It may be possible to incorporate sacrificial layers or cross section extension to absorb such impacts. Also water pressure increase with depth and geometrical shape of the structure becomes more important.
- **Shore connections.** Design of the shore connections must be based on surveys of the geological and geotechnical properties of the ground, as well as on the expected response from environmental loading, including tidal range. For steep rock slopes, the SFT may connect to a rock tunnel, whereas in shallow coastal bathymetry and sedimentary soils, the SFT may connect to an immersed or cut & cover tunnel.

## 6.1 RISK ASSESMENT FOR A NOVEL DESIGN

All infrastructure projects are associated with a certain risk for the Owner. An SFT is a novel structure that has not yet been built at full-scale. Traditional structures rely reliability requirements on guidelines and standards and set target reliabilities for structural safety. These guidelines are validated by large numbers of structures of the same type and are not developed with SFT's in mind. To define acceptable risk criteria can be set focussing on individual or societal risk of tunnel users. Individual risk concerns the annual probability of death of a person, while societal risk concerns the probability of an event with many fatalities. Next to these risk, economical risk can also be considered, in which (additional) costs of mitigation matters are related to the reduction of monetary risk of failure. Acceptable risk criteria can set the requirement on the target reliability.

Risks can be identified by a risk assessment, in accordance with local rules and international standards, i.e. ISO 31000, and mitigation strategies should be adopted accordingly, using the as-low-as-reasonably-practicable (ALARP) principle. The procedure is the same for an SFT as for any other type of structure. The process can be divided into different phases: planning, feasibility study, design, construction tendering, construction, operation, and final decommissioning. The type of hazards that must be considered are largely like any other type of structure, although some are specific to SFTs.

- **Frameworks and guidelines.** A technology qualification framework can be used to assess the maturity of a design and to manage the risk related to adoption of new technology. Qualification is defined as a process of providing evidence that a technology will function within specified operational limits with an acceptable level of confidence (DNVGL-RP-A203, July 2019). Within this framework, a system consisting of previously proven technologies assembled in a novel way is considered new technology. The same is true for proven technology used in a novel environment. Both these statements apply to SFTs to some degree: Concrete and steel tunnels, various types of tethers and concrete and steel pontoons are all well-known technologies, but their combination and application to a freely floating system is new.

  The technology qualification process described in DNVGL-RP-A203 is essentially a reduction approach, where the system is broken down into subsystems that are assessed with respect to novelty and risk. The DNV process must therefore be extended to address system-level uncertainties and phenomena that arise from the interaction between subsystems (Minoretti, Johansen, Xiang, & Eidem, 2019).

  The RAMS (reliability, availability, maintainability, and safety) methodology, for example described in European Standard EN 50126 for railway tunnels, may be useful to ensure adequate safety and availability of the SFT system in a life cycle perspective. At present, there is no similar standard for road tunnels, but the World Road Association has published an introduction to RAMS for road tunnel purposes (World Road Association (PIARC), 2019). In the report, it is emphasized that RAMS is more relevant for the technical systems in the tunnel, such as electrical or mechanical systems and safety equipment, than the road tunnel structure itself.

- **Public opinion.** For novel designs, the risk, as perceived by the public, could be quite large. This is first and foremost a communication issue because the public are not yet familiar with an SFT, but important nonetheless, since public opinion influences decision makers. The perceived risk is related to issues like the fear of driving in tunnels in general, accidents that might lead to flooding or the fear of feeling movement while within the structure.

  Mitigation strategies to tackle the concerns of the public might be measures like lighting design in the tube, information posters and brochures and design criteria for motion and acceleration that ensure little or no movement is perceived by drivers.

  Economic risk, in public opinion, is related to the likelihood of exceeding the budget during the construction phase of an already costly project, but can also include the repair cost in case of non-availability. In most cases, funding for infrastructure comes from taxes and the taxpayers will demand that the cost be kept within acceptable limits. For the Owner, this means balancing acceptable risk with acceptable cost from both a political and a societal point of view.

## 6.2 RISK FROM PLANNING TO START OF CONSTRUCTION

From the start of the planning phase until the tendering process, the risks that can be considered as SFT-specific are related to the SFT being a novel structure and the safety and economic consequences of these uncertainties.

Due to the need for research and development associated with designing a novel structure, the Owner can expect a longer, more costly planning phase for an SFT than for a traditional structure. This may represent a risk to the project itself, in terms of political processes and funding. Model and prototype testing may be required. As experience of SFTs grows, the development phase can become shorter and costs associated with uncertainty may reduce.
Acceptable risk is a cost driver for the design. Achieving risk levels that are as-low-as-reasonably-practicable (ALARP) requires a balance to be struck between the cost of mitigating the risks and the overall safety level that is being targeted.

## 6.3 CONSTRUCTION RISK

In terms of SFT-specific issues, construction risk is mainly related to production and installation operations on water. This includes weather-related incidents, passing vessels and incidents caused by human error or mechanical failure that may lead to accidental flooding and possible damage to, or even loss of, structural elements. Ballasting operations require particular attention in this respect. Additionally, health and safety for the workforce need to be taken care of and requirements set by regulations must be followed. Similar experience and risk management exists from the renewables and offshore industry such as the installation of Gravity Based Structures (GBS) and floating renewables.

The construction risks may to a large extent be delegated to a contractor, depending on the contract, but the costs will nevertheless end up with the Owner in the form of contingencies in tendered prices.

### 6.4 OPERATIONAL RISK

Operational risk can generally be separated into risk related to wear and tear, accidental events and intentional actions, namely sabotage and terrorism. Some examples of hazards and possible mitigation strategies are given in Table 3, highlighting that the SFT design should comply with robustness requirements. For example, progressive collapse of the structure must be avoided. In addition to the mitigation strategies presented, which concentrate mainly on structural design, strategies should be in place to reduce the consequences of hazards, in terms of loss of life, loss of asset and downtime. This could be achieved through contingency plans, warning systems and other measures.

Risk related to wear and tear is something that must be considered in the maintenance, inspection and structural health monitoring (SHM) plan, as well as in structural design and choice of materials etc. Experience regarding maintenance and replacement of underwater components, especially in deep water, can be taken from the offshore industry. As an SFT is likely to have a longer design life (i.e. 120 years) than an floating production system (i.e. 30 years), the reliability of critical elements such as moorings or pontoon connections needs careful consideration.

Accidental hazards particular to SFTs include submarine impact on tubes or stabilisation systems, dragging or dropping anchors, underwater slides affecting stabilisation systems and foundations, sinking ships impacting the SFT etc. The risk assessment will determine the probability and consequences of such events with respect to prevailing acceptance criteria, in order to decide whether they must be considered in the design and/or mitigated by other risk reducing measures.

Acts of sabotage and terrorism are challenging to include in the design, due to the absence of a statistical basis to support a probabilistic design approach. The decision on whether to take this into consideration by additional structural robustness or special surveillance measures rests with local and national authorities.

Apart from the need to address novel effects and phenomena, all accidental events must be considered with respect to water tightness. Hazardous events to which the SFT can be subjected must not lead to violation of this requirement. For example, fire and explosion events must not compromise structural integrity and allow water ingress into the SFT, since this could lead to uncontrolled flooding and progressive collapse, with the possible consequential loss of the entire asset. In terms of rules and regulations, fire safety provisions for SFTs are the same as traditional tunnels for example on escape routes, evacuation and access for emergency services.

In addition to reducing the risk due to accidental events to a minimum, the design should consider additional mitigating measures in case of major water inflow, such as sectioned closing of a tube by floodgates or inflatable plugs similar to those used at tunnel portals.

| ELEMENT/COMPONENT | HAZARD | POSSIBLE MITIGATION |
|---|---|---|
| **Tube(s)** | Fire and explosion | Fire Protection; restrictions on hazardous goods transport; limitation on connecting tunnel slope; escape routes and shelters; structural design |
| | Submarine impact | Structural design; restrictions on military activity |
| | Sinking ship, dragged or dropped anchor/cargo | Ship channels; traffic restrictions; structural design |
| | Landslides at shore connections | Geological Survey; structural design; dredging/reshaping |
| **Pontoons** | Ship impact | Ship channels; traffic restrictions; structural design of pontoon to resist the impact or of the SFT to survive the accidental damage/loss of a pontoon |
| | Fatigue in pontoon connections due to wind and waves | Structural design; monitoring/inspection and maintenance |
| **Moorings** | Fatigue | Structural design; monitoring/inspection and maintenance; design of the SFT to resist the loss of a mooring ; replaceable moorings |
| | Dragged or dropped anchor | Design of mooring systems |
| | Failure of tethers/pontoon connection | Redundant design |
| **Mooring foundations** | Landslides | Geological Survey; structural design |

# 7 >> DESIGN RULES & REGULATIONS

### 7.1 RULES AND REGULATIONS

There is no specific set of rules that governs all aspects of the design of an SFT. Some aspects will be governed by the regulations for traditional road and rail tunnels and some by local regulations for bridges and floating structures.

Leading international standards can be adapted to form a project specific Design Basis that address SFT-particular aspects. It is recommended that a single principal code or standard is used for developing the Design Basis, such as the structural Eurocodes. The target reliability and the design lifetime for the SFT must be selected, based on the chosen code or standard. Risk based design criteria will be derived from the safety studies and must be stated in the project Design Basis. Information required to supplement the chosen code can be incorporated from other codes and standards, or from research and studies. When combining codes, care must be taken to ensure that the required safety and target reliability are met in the overall solution.

Recently, the International Federation on Structural Concrete has published a design guideline for concrete Submerged Floating Tube Bridges – SFTBs - (Fib bull no 96 Guidelines for Submerged Floating Tube Bridges).

### 7.2 DESIGN CRITERIA

The criteria for the design will vary according to local regulations and are to be found in several international standards., but should include as a minimum:

**1. Safety and functionality**
The design must provide a safe and functional structure, according to the national and international codes. Among the different requirements, some special specification must be guaranteed:

***a. Water tightness.***
The water tightness is a strict requirement that all the elements subjected to permanent or potential water pressure difference must respect during operation and temporary conditions. A robust design and monitoring of the structure must be considered to prevent any problem caused by water entering the (sub) structures.

***b. Deflections, accelerations and vibrations***
A limit to horizontal and vertical deflection and to vertical and horizontal accelerations must be set, according to local regulations and considering the different possible users of the structure (road/rail traffic, bicycles and pedestrians), to ensure user comfort and to meet requirements of rail traffic, especially high speed trains.

**2. Robustness and risk evaluation**
The SFT must be able to withstand unexpected situations without undergoing total collapse or disproportionate damage. To provide a robust design, sensitivity studies must be performed (a normal procedure for structures). For more information see chapter 6.
The owner should consider the required levels of damage acceptance, for every part of the structure, substructure and installations, define a timeframe for the repair and manage the consequent service of the structure.

**3. Cost effectiveness**
The design should consider cost optimisation for every part of the structure, regarding the construction, the entire operational life including the repair and maintenance costs and the costs associated with the end of life of the structure.

### 7.3 DESIGN LOADS

The loads (or actions) adopted in the design of SFT are divided into three categories: permanent, variable and accidental. Some examples are given in Appendix A, but a more complete list will be provided in the fib design guideline. Figure 4 illustrates some of the loads on an SFT.

As with any novel design, measures should be taken to identify new or unexpected loads and phenomena. The technology qualification process mentioned in section 6.1 can be used for this purpose. Model testing should be used to confirm or define loads, but the Owner must be made aware that there are limitations to model testing of complex structures. Prototypes of a few modular elements installed may be considered in advance of main construction. The SFT structure or components should be designed in terms of the loads that may occur simultaneously in the construction and operation stages and must cover Serviceability Limit State (SLS), Ultimate Limit State (ULS), Accidental Limit State (ALS) and Fatigue Limit State (FLS). Care should be taken when factoring the loads, because factoring buoyancy and self-weight separately may lead to artificially high design loads. The factor should be applied to the difference between buoyancy and self-weight.

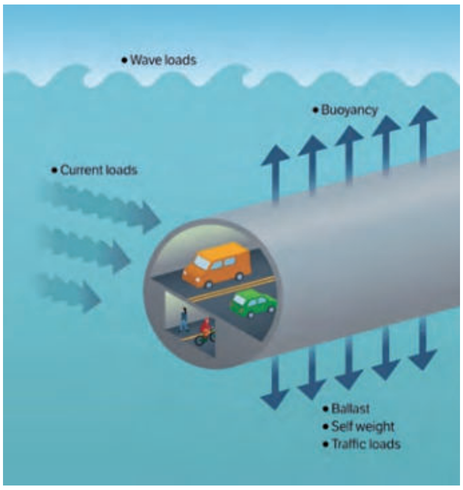



*Figure 4: Illustration of selected design loads for an SFT.*

# 8 >> Development & Execution of the Project

## 8.1 PLANNING

There is additional uncertainty related to the fact that no SFT has yet been built; this must be addressed in the planning process. A quality assurance system must be established which takes the novelty of the design into consideration and the Owner must expect a longer planning and quality assurance period than for a conventional project. The information required to make decisions at the different stages in the project should be established: these include the feasibility of a SFT for a given crossing, the design of different SFT alternatives for that crossing and the criteria to be set to compare SFTs against other structural alternatives (assuming several designs are developed in parallel). Planning of site investigations, measurements and research and development follow from these requirements.

Different contract strategies are used for infrastructure projects and these will be similar for SFT projects. However, the challenges and uncertainties that are specific to SFTs should be included in the contract.

## 8.2 PERSONNEL AND SKILLS

Whether the design work is outsourced or carried out in-house, it is of vital importance that a project organisation is established that includes the key required skills related to SFTs. A recruitment plan should be implemented to ensure this, paying special attention to disciplines related to floating structures; these skills may not exist in an organisation that usually deals with road or rail projects on land.

## 8.3 RESEARCH AND DEVELOPMENT

The novelty of the SFT increases the need for research and development, compared to alternatives that share more similarities with traditional crossing solutions. This means an Owner can expect a longer time frame and larger budget for this purpose. Nevertheless, the large experience gained in the offshore field and in the immersed tunnels can be beneficial for this scope.

A list of published literature on SFTs is provided at the end of this guide.

## 8.4 MONITORING AND DOCUMENTATION

Detailed documentation of all aspects of the SFT is needed, from the planning stage through the lifetime of the structure. It is of vital importance that the documentation is kept alive and accessible, in order to ensure transfer of knowledge. A digital twin can be considered for this purpose.
The documentation should include measurements of key parameters, such as metocean data in the planning phases and structural behaviour in the later phases. However, the monitoring must have a clear objective and the amount of data gathered must be kept at a manageable level. Measurements are useless unless there is a well-defined procedure for processing them and including them in the updated documentation.

The type of information needed is different in the different phases of the project:

- **Planning phase.** During this phase site specific factors that influence design, construction and installation methods must be determined and documented. These include road alignment, environmental conditions, geology and ground conditions and ship traffic, as well as any ecology considerations. Future traffic on the road, volume, speed, quantities of dangerous goods etc., must be assessed.
- **Construction phase.** The design should consider situations occurring during construction. For example, construction loads will differ from the operational phase. During the construction, some of the loads must be monitored carefully, in particular the parameters directly related to the buoyancy of the structure, like weight control of the elements and water tightness.
- **Installation phase.** Depending on the chosen method of installation, various types of monitoring will be required, such as measurement of stresses and strains in the structure during towing phases or monitoring of the ballast condition during submergence. The detailed design should include a plan for system monitoring during the various stages of the installation phase.
- **Operation phase.** It is important to monitor the actual condition of the structure and to check the measurements against limits set in the design phase, to assess required maintenance, inspection, SHM and repair. On-site inspection must also be performed. The documentation must also include an updated maintenance schedule.

## 8.5 THIRD PARTY VERIFICATION

Additional control mechanisms in the design process are of vital importance. Therefore, third party verification of the design is highly recommended, regardless of whether this is required by the national rules and guidelines.

# 9 >> Maintenance & End of Life Situation

Maintenance is important for any structure. The structure must be designed to minimise the maintenance cost and this assessment must include possible replacement of parts. It should be possible to inspect all the vital parts of the structure. Any critical part not accessible for inspection, maintenance or replacement must be designed for higher reliability.

There should be a plan for removal of the structure at end of its life. Depending on the chosen construction material, it may be possible to recycle part of the structure for other purposes.

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DNV-RP-F105 Free spanning pipelines, Recommended practice; Edition 2017-06 - Amended 2021-09

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Fib bull no 96 Guidelines for Submerged Floating Tube Bridges. Guide to good practice (119 pages, ISBN 978-2-88394-144-1, October 2020)


### TECHNICAL DOCUMENTS


Fib bull no 96 Guidelines for Submerged Floating Tube Bridges. Guide to good practice (119 pages, ISBN 978-2-88394-144-1, October 2020).

## Appendix A Loads and load classifications

| N$^{O}$ | LOAD CLASSIFICATION | LOAD |
|---|---|---|
| 0 | Temporary loads | Loads during construction, installation and maintenance |
| 1 | Permanent load | Permanent self-weight:<br>• Weight of main structure<br>• Weight of stabilisation structures<br>• Permanent ballast<br>• Permanent asphalt<br>• Permanent equipment |
| 2 | | Buoyancy |
| 3 | | External water pressure |
| 5 | | Prestressing |
| 6 | | Anchor foundation earth pressure |
| 7 | | Foundation heavy load |
| 8 | Variable load | Variable bounded self-weight:<br>• Marine growth<br>• Water-absorption of structural concrete<br>• Water-absorption of solid ballast |
| 9 | | Variable free self-weight:<br>• Dust-collection<br>• Relocatable ballast<br>• Variable asphalt<br>• Variable equipment |
| 10 | | Current:<br>• wind driven<br>• tidal<br>• stratification, and so on |
| 11 | | Waves:<br>• wind driven<br>• swell |
| 12 | | Wind loads (in the case of pontoons) |
| 13 | | Temperature loads |
| 14 | | Water level loads |
| 15 | | Water density (salinity and water temperature) |
| 16 | | Temporary construction load |
| 17 | | Traffic loads:<br>• Lane load and vehicle load<br>• Automobile centrifugal force<br>• Automobile braking force |
| 19 | | Loads from passing ships |
| 20 | Accidental load | Seismic action |
| 21 | | Slide or earthquake generated waves (Tsunami) |
| 22 | | Internal waves and surface seiches |
| 23 | | Ship and submarine impact, or impact from sinking vessel |
| 24 | | Dragging anchor, accidentally dropped anchor or other object eg. container |
| 25 | | Explosion |
| 26 | | Fire |
| 27 | | Vehicle impact force (inner wall) |
| 28 | | Landslides |
| 29 | | Flooding |
| 30 | | Loss of support system |

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