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The Lake Lugano Crossing - Technical Solutions

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ABSTRACT: Sometimes the desire to reach the other side is obstructed by water, possibly deep and wide. The traditional bridge may not be a feasible solution, likewise a subsea tunnel or a submerged tunnel. And there may be constraints of a “softer” type than the pure mechanical that may count, such as noise, esthetics and energy consumption.

The Submerged Floating Tunnel (SFT) has through several concepts proved to be a competitive solution for crossings of straits and lakes. Yet the prototype is still to be built. A further step in direction of promoting the SFT as an attractive crossing solution is the development of a novel SFT concept performed by a Swiss-Norwegian project team (Grignoli Muttoni Partner/Selmer/Dr.techn.Olav Olsen). The crossing solution is unique in that existing and established technology characterizes all aspects of the concept. Design, construction and installation methods are, as well as foundation principle, based on well proven technology that adapt well to the specific site.

Emphasis is put on concept development as well as on the construction and installation techniques, which are widely gained from the offshore industry. A brief outlining of the potentials for application to other crossing sites due to the robustness and flexibility of the concept is given.

The SFT is so valuable that Aadnesen and Dr.techn.Olav Olsen formed a company (the Norwegian Submerged Floating Tunnel Co., www.nsft.no) to further develop and promote the concept.

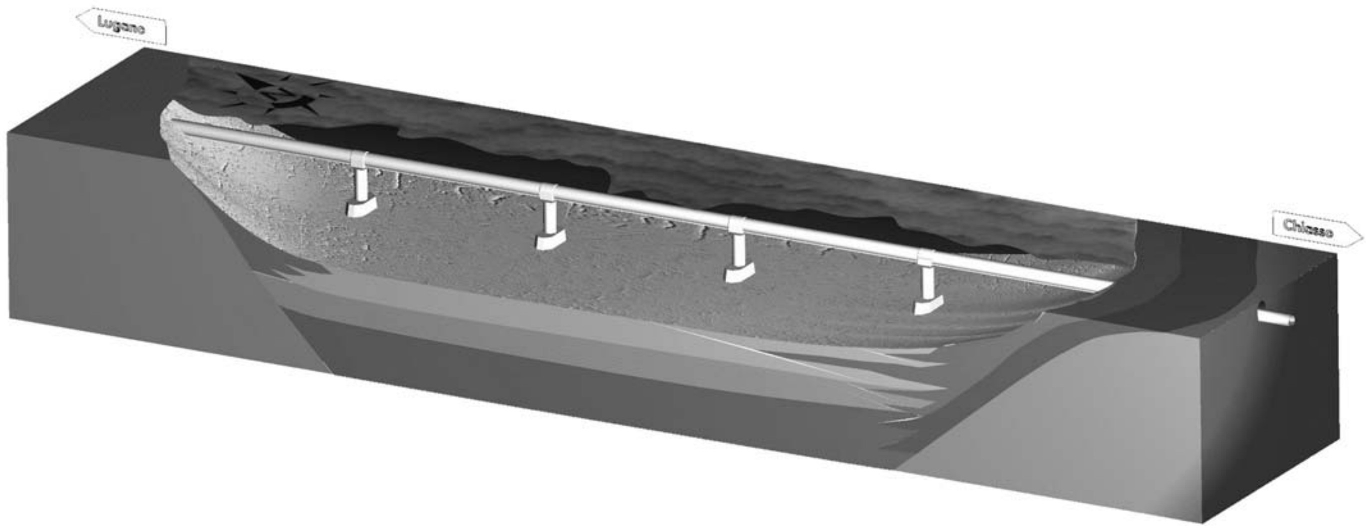

Figure1: Configuration of the submerged tunnel, located 6 m below the water surface

1 INTRODUCTION

Accommodating road and/or rail traffic the Submerged Floating Tunnel (SFT) constitutes an attractive solution for waterway crossings. Its flexibility with respect to length and water depth makes the SFT adaptable to various crossings sites such as rivers, lakes, fjords, sounds and island connections. The most salient feature inherent in the SFT concept is the compatibility with the increasing tendency to constricted tolerance regarding environmental impact. In picturesque surroundings or congested areas, the SFT can be applied without having any impact on the landscape or interference with surface traffic. It may be combined with underground parking facilities. The SFT, like tunnel crossings in general, also allows for a better control of air pollution compared to crossings in air. It is further superior to submerged or underground tunnels in energy consumption as a consequence of the smoother gradient.

So far a prototype of the SFT has yet to be realized. Although the feasibility of the SFT is manifested through several envisaged concepts, their acceptances have been reserved. The modesty towards new crossing concepts can largely be traced back to cautiousness, as design for safety, service life and life time costs are important aspects for the decision makers within the transportation authorities. Spreading information addressing these aspects and disseminating a reliable base of knowledge proves to be a vital step towards gaining the necessary trust.

1.1 *The Lake Lugano Crossing*

The Swiss Federal Railway Authorities plans a new railway line from Zurich towards the Italian border. This is a vast national program (AlpTransit), and is described in more detail by Prof.A.Muttoni at this conference.

A submerged floating tunnel is a well suited concept and perhaps the only type of structures that combines the demand of minimizing the environmental impact on the scenery with the strict alignment criteria for such railways.

2 CROSSING SITE AND SPECIAL REQUIREMENTS

The tunnel site is located at the southwest arm of the Lake Lugano, between Olivella and Brusino-Arsizio. The distance between the adjacent rock tunnels is approximately 1055 m. At a horizontal distance of about 100 m from each shore, the sea bottom slopes down, reaching an approximate horizontal seabed in the middle of the lake. Maximum depth of the water at the crossing is approximately 70 m. The rather flat surface of the subsoil consists of some 10-12 m with soft deposits of mud and clay, overlaying the consolidated pre- and sub-glacial clay deposits extending down to a deep and distinct V-shaped rock profile.

Major functional requirements are that the double track line shall be designed to accommodate 450 trains per day with maximum speed of 230 km/h and 140 km/h for passenger and freight trains respectively. Vital requirements from a design point of view are the demands on the tunnel being able to resist abnormal, accidental actions like flooding of the tunnel, explosion and fire inside the tunnel. There are also strict requirements on allowable settlements of the foundations and piers.

3 THE CONCEPT

A 5-span submerged buoyant concrete tunnel characterizes the developed concept. Between the landfalls the tunnel is supported on four piled concrete piers.

Both sub and superstructure are, as well as the landfalls made of reinforced high strength concrete (C60) with a total volume of 63 000 m^3. Nearly 7 000 tons of ordinary reinforcement and 2 500 tons of prestressing tendons are used in the various structural parts.

A configuration of the tunnel with no horizontal or vertical curvature and with no dilatation support at the landfalls is considered to be a simple and thus cost efficient solution that requires a minimum of maintenance. Small environmental loading from waves and current combined with stiffness contribution from the piers laterally allows for a straight horizontal alignment. Vertically, the longitudinal axis also follows a straight line, with a depth of 12.8 m, leaving a free clearance of 6 m for marine traffic.

3.1 *Superstructure*

The tunnel, composed of five 186 m long, cylindrical tunnel modules are assembled and monolithically joined at the piers. The tunnel configuration is mainly determined by the cross-section required to accommodate the double track railway line with relevant facilities. The quasi-circular tunnel has an internal diameter of 10.6 m. The tunnel is given a general wall thickness of 85 cm, which is locally increased to 150 cm over the piers for construction purposes. The lower part of the section below the traffic plane is compartmentalized into three non-communicative compartments. The outermost compartments are dedicated to permanent ballasting, whereas the one in center will serve as access channel, passable for a small truck, for inspection and maintenance during operation.

At both ends the tunnel is monolithically joined with the landfall structure without dilatation, that is no relative movement between the tunnel and landfalls. Thus the chosen connection requires a minimum of maintenance and inspection and a high degree of durability is obtained.

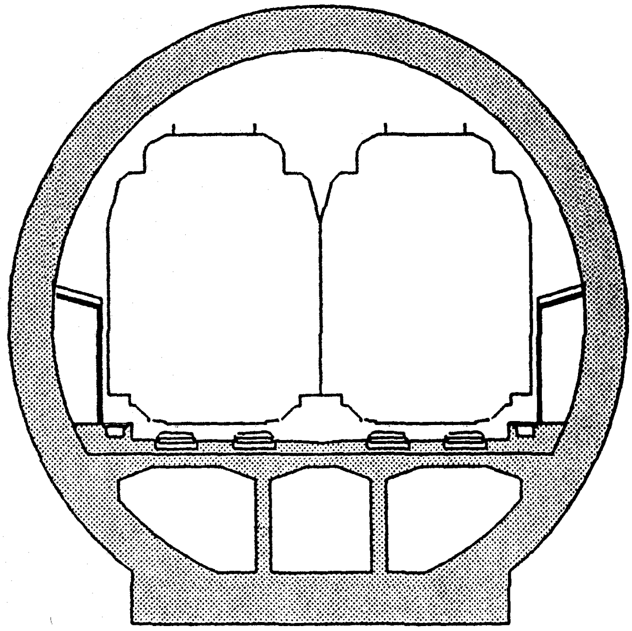

Figure 2: Cross-section of the tunnel, with SBB tunnel profile

The natural buoyancy of the tunnel is utilised to obtain an optimum structural behaviour in operation. The tunnel is trimmed with solid ballast so that the net buoyancy surplus under permanent condition approximately corresponds to half that of distributed traffic loading. Hence the moments due to the traffic load are equal to that generated by the buoyancy. The material quantities and costs are thus optimized.

Special emphasis is dedicated to structural integrity and sustained operability of the tunnel after potential severe and abnormal loading. When exposed to extreme loading conditions, which are characterized by the accidental flooding of the tunnel and explosion, the tunnel shall be capable of resisting the load without causing non-reversible plastic deformations. Re-operation of the railway line can thus be accomplished within short time without the need for extensive repairs.

3.2 *Piers*

The Substructure consists of circular columns resting on octagonal caissons. Sixteen open ended steel piles penetrating some 60 m into the seabed support the caisson. A 2.5 m deep skirt foundation secures stability in temporary phases prior to and during piling.

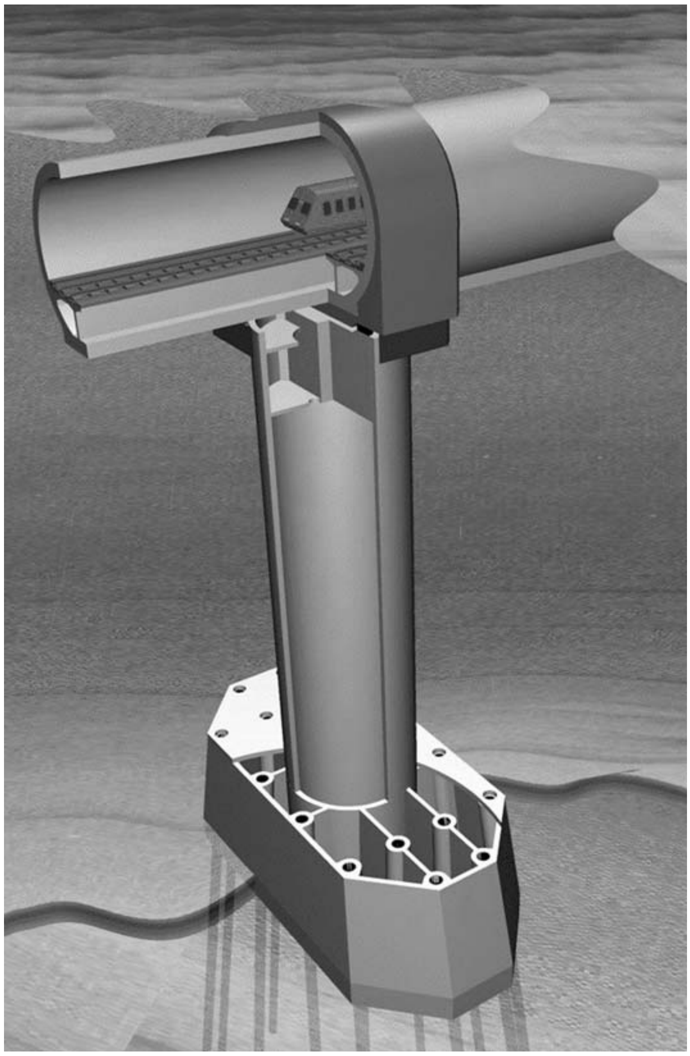

Figure 3: Substructure with pinned tunnel support

3.2.1 *Support system*

Two alternative solutions are developed for the connection of the substructure to the tunnel. This is done to improve the concept's flexibility to accommodate changes of the geotechnical parameters that form the basis of the settlement calculations.

On the first alternative will the superstructure be supported on adjustable replaceable Ø1420 mm pot bearings in order to counteract long term as well as short-term settlements. Maximum short-term settlements may be caused by an accidental event that causes flooding of the tunnel.

The bearing type and configuration create a pinned support system of the tunnel that resists lateral movements. The size of the bearings is governed by the stresses in the rubber disc inside the bearings at the ultimate limit state. The bearings may be replaced.

An alternative to the column / tunnel intersection with adjustable bearings is to join the two structural parts together as a monolithic structure. This will create a fixed support of the tunnel. A more accurate determination of the vertical displacements at all limit states is required for this solution, as the possibility of counteracting the displacement does not exist. To determine the vertical displacements more accurately require an increased confidence in the geotechnical parameters of which they are based. This configuration would require less maintenance and operation costs than the other solution with bearings; there are no bearings or prestressing tendons that need to be inspected and replaced. The initial cost of a monolithic joint will also be less.

The frame analysis reveals that the foundations with ample margins can resist the maximum horizontal reaction at the seabed.

3.3 *Column*

The column has a circular cross section over the entire height with a constant wall thickness. A uniform cross section over the total height will facilitate simple construction and is thus cost efficient. A circular cross section is an optimal shape regarding the ability to resist external water pressure imposed on the column during installation. The outer radius is 5.7 m. There are three criteria for selecting the diameter of the column:

- Provide sufficient load bearing capacity at the base during earthquake generated loading,
- Ease the intersection between super and sub structure,
- Provide sufficient buoyancy in the floating phases.

There is no prestressing in the columns, as the ordinary reinforcement is sufficient to limit the crack widths.

3.3.1 *Caisson*

The geometry of the caisson is governed partly by the hydrostatic stability and partly by the load transfer capacity through the shear walls in a PLS flooding situation. The caisson's height of 10.5 m is required to obtain satisfactory floating stability of the structure during installation.

During operation, the 2.5m deep skirt will act as ties while they contribute to the pier's stability before and during piling. The skirt foundations are capable of resisting a vertical force of approximately 10 MN, prior to and during piling.

The caisson supports 16 Ø1100 mm piles (t = 25 mm), of which 12 are inclined. Inclination of the piles increases the horizontal resistance of the foundations and reduces the settlements of the structure as the vertical loading is spread over a larger area. With the chosen pile configuration, the average intermediate settlement is estimated to 35 mm, while the average long-term settlement due to consolidation is estimated to 55 mm. The additional settlement due to the accidental loading, flooding of the tunnel, is predicted to be less than 0.1 m.

3.4 *Landfalls*

The landfall structures at both ends create a fixed end of the tunnel.

Longitudinal walls anchored by rock anchors secure flexural resistance during operation and act as watertight plates for the dry dock during construction. The landfalls are founded on a line of drilled concrete piles transverse to the tunnel at one end, and directly on the rock at the other end. The tunnel is equipped with external access at each of the two landfalls.

3.5 *Analysis and design aspects*

In addition to a linear elastic static FE analysis, a dynamic analysis is used to verify the structure's structural integrity when subjected to earthquake loading. The structure is represented as a linear elastic frame model, composed of straight beam elements rigidly connected at the nodal points. The models are fully fixed at the abutments, and supported by linear elastic translational and rotational springs at the foundations.

Flooding of the tunnel is the governing load case for ordinary reinforcement, while tightness criteria of the tunnel govern the amount of longitudinal prestressing. Uniformly distributed post-tensioned tendons in the hoop direction counteract the pressure generated from an explosion in the tunnel. In order to meet the tightness criteria for such a structure, there are no principal membrane tensile stresses at the serviceability limit state. Furthermore, a strain limitation of 2.5‰ is applied to both stirrups and longitudinal reinforcement at ULS and PLS, to prevent plastic deformations.

The main design challenge regarding foundations is to obtain sufficiently small settlements. A piled foundation is thus inevitable. Site specific soil data are mainly based on geological and seismic interpretations. Data from borings are limited to the upper 12 m below the seabed. The design of the piled foundation is based on conservative predictions for the soil shear strength, assuming the soil to be normally consolidated. An accidental flooding of the tunnel is governing for the bearing capacity of the foundation, resulting in 56 m long OD = 1.1 m open ended steel piles.

The analysis and design performed is very similar to the analysis and design of offshore platforms. Due consideration has been paid to the construction phases, which include marine operations.

Each pier is like a little platform. Ballasting systems must be included, of course, and the subsea piling is well known to the industry. Installation of the tunnel elements is also well known, from the submerged tunnels constructed in great number in many parts of the world.

The analysis and design of offshore concrete structures is described in detail in a number of publications, for example the symposia on High strength/High performance concrete.

Special here is the principle of "hiding" the construction site, in respect of the beauty of the area. This is in line with the principle of hiding the entire crossing.

4 CONSTRUCTION AND INSTALLATION

A major characteristic of the concept is the construction method that minimizes the intrusion of the environment during construction. Vital for the construction and installation principle is the two-piece dry dock integrated in the eastern landfall excavation. Both the tunnel and the foundation units will be prefabricated in the dry dock. Excavation of the landfall will be executed behind a steel sheet wall, which also serves as a 110m part of the dry dock. Additional dry-dock length is obtained by using the adjacent rock tunnel. To accommodate construction work, the cross-section of the rock-tunnel is locally increased. Two separate dock gates in the 240m dry-dock allow separate construction of the components in parallel, and independent launching of the caissons and tunnel elements into the lake.

The foundation caissons with the skirts will be completed in the dry dock prior to tow out. About three meters of the column will be constructed prior to tow out of the dock. The column will be slipformed while afloat while gradually increasing the draft. After completing the slipforming, the draft is about 50 m, and the caisson is fully flooded, leaving only the column as buoyancy volume. Equipped with a steel cofferdam at top of the shaft, the piers will be water-ballasted and submerged to the seabed. The skirts will be penetrated into the soil by applying suction in the various skirt compartments. The suction system enables application of different suction in the compartments accounting for different soil reaction forces in order to obtain correct vertical alignment of the pier. Steel piles running through sleeves in the caisson, using a hydraulic piling hammer will pile the foundation. The piles will be cut off at the top of the caisson and grouted to the sleeves in the foundation. At the top of the piles, soil will be removed and the piles will be concreted to 10 m below the mudline.

The tunnel is constructed in segments of 186 m, which is equal to the span length, behind the innermost dock gate. The casting will be performed in sections. The lower part including the slab and walls will be constructed in sections of about 10 m. Formwork for the slab and walls will be moved in the longitudinal direction of the tunnel. The remaining part of the cross-section will be constructed using moveable tunnel-formwork, in sections of 20 m. The inner face of the formwork will first be put in position, followed by placing of reinforcement. The outer face of the formwork will then be put in position, and the 20m concrete section will be poured.

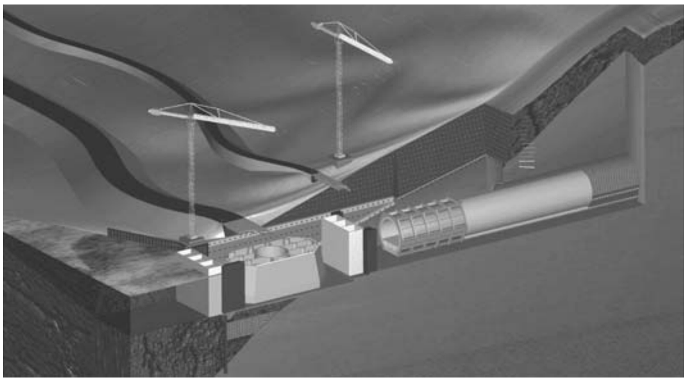

Figure 4: Simultaneous construction of foundation caisson and tunnel element in the dry dock

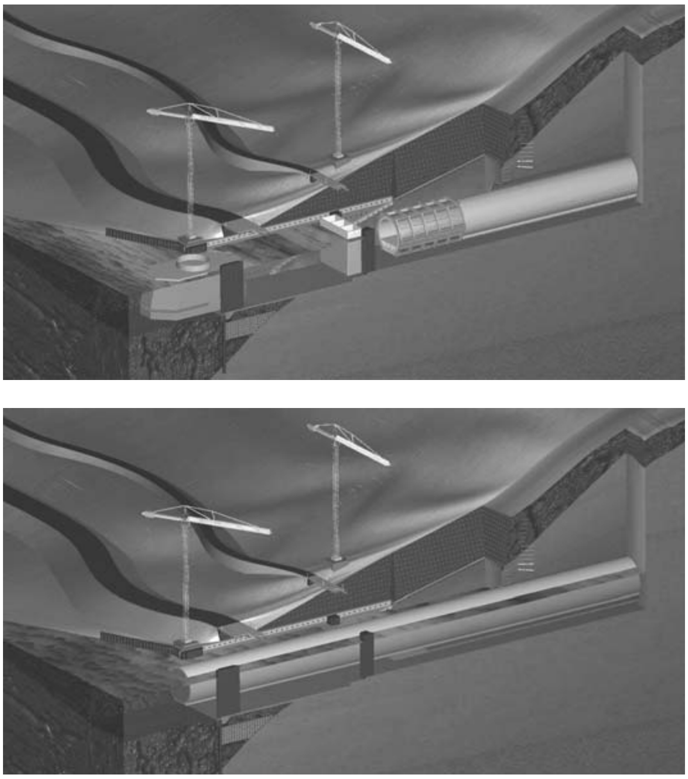

Figure 5: Launching of caisson and tunnel element

Prior to towing out of the dock, the tunnel segments are prestressed and in each end equipped with a temporary watertight bulkhead. With a freeboard of about 2.5m, the tunnel segments are towed to the site, and positioned above the piers. At both ends of the tunnel elements, the tunnel is equipped with two temporary shafts with 8 m length and a diameter of 6 m. These shafts will provide additional buoyancy in the submergence phase. Using the shaft as access, the segment will be water-ballasted and submerged to the piers. Installed on the piers, the tunnel segments will be monolithically connected in dry environment, the bulkheads removed and the sections finally de-ballasted. The dry environment will be secured by means of a temporary steel cofferdam surrounding the joint region.

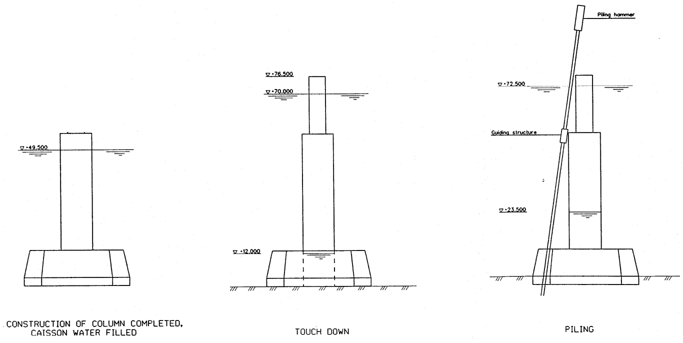

Figure 6: Installation sequence of the substructure

5 COST ESTIMATE AND SCHEDULE

A specified cost estimate for the concept predicts the overall costs to be 180 mill. SFR (per 1994) yielding a unit cost per meter of 197 000,- SFR.

Included in this cost is all technical installations required for operation of the railway line, general installations, engineering and management costs, owner's administration costs and expropriation costs. The estimate is based on a rather detailed quantity calculation as well as evaluation of construction procedures and local conditions in the Lake Lugano area.

6 CONCLUSIONS

The technology inherent in the Lake Lugano Crossing is widely gained through experience from the offshore industry. A technology put to the test in harsh environment for several decades.

Emphasis is throughout the project put on the necessity of using well proven technology for all design and construction aspects of the concept. For many proposed concepts, the realization is encumbered with risk elements related to their often-insufficient ability to cope with and resist catastrophically impacts and the incorporation of technology exceeding current standards. The viability of SFT concepts is thus conditional on the use of existing and well-proven technology - in design, construction and installation.

The major criterion of minimizing environmental impact with respect to intrusion of the scenery is fulfilled with the Lake Lugano concept. A vital aspect to avoid depreciation of the surroundings is the construction principle with a dry dock partly integrated in the rock tunnel hiding almost all construction work. Only a minimum of expropriation around the landfalls is therefore necessary.

Furthermore, the concept is considered robust, as it is flexible with respect to the boundary conditions that forms the basis of the concept. Hence the concept can easily adapt to other sites with other characteristics and requirements such as crossing length and tunnel profile. The authors foresee the concept adapted to sites, which requires tunnels of several kilometers, and to projects with other service requirements for instance combined railway and road crossing.

Vital for the realization of SFT is besides robustness also the economic efficiency. The over all realization cost is site and functional dependent. Compared to other conventional water crossing solutions, the SFT may result in substantial economy for sites with crossing lengths in excess of 1000m, and where the water depth exceeds 50m. Notably the investment cost per unit length is more or less constant for the SFT, whereas for bridges it is significantly increasing with the span length. The unit cost per meter for the presented concept is about 197000 SFR per meter, including all installations and ready for use. This cost is, however, not directly comparable with other sites as some elements of the cost estimate are site specific.

ACKNOWLEDGEMENTS

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