Conceptual study for a deep water, long span, Submerged Floating Tunnel (SFT) crossing

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Abstract

With a background of some 50 years of experience in the immersed tunnel industry, most recently having been in charge of inspection during the construction of the Bosporus Rail Tunnel, and having the privilege of working with engineers in Norway on various aspects of their SFT projects for a basis, the author presents some concepts for the design and construction of a long submerged floating tunnel in deep water. These concepts are presented as sketchy ideas only supported by rudimentary calculations and assumptions. It is hoped however, that some of these ideas might at be useful in the future development of viable, long crossings in deep water. Such crossings are the challenges often faced by engineers in a country like Norway with its deep, wide fjords.

An SFT design premise that has been written about by the author over the years (most recently at the Fifth Strait Crossing Symposium 2009 held in Trondheim, Norway [1]) is that an SFT should be designed to float and remain stable even if its roadway or track ducts were to be completely flooded. There is no doubt this requirement would be considerably more costly than the SFTs presently being considered. The author feels very strongly however, that an owner, either governmental or private (as in a toll road), would never finance a water crossing that could be completely destroyed in the event of a single flood. If a flood were to occur that would slacken the tethers of an SFT as presently conceived, the whole tunnel crossing would quickly become unstable and collapse in ruin at the bottom of the waterway. Floods have occurred in many tunnels as a result of carelessness, water mains breaking, or even the failure of a bulkhead. Such floods, ranging from minor to major, would have destroyed an SFT.

This paper touches on methods to provide stability against flooding, construction methods and equipment that could be used to cast and install anchor blocks attached to braced “tether towers”, a sequence of construction with methods to lower, join and align, modular tunnel elements, how to attach the tether towers and equalize the tensile loadings, and a method to stabilize the completed SFT laterally while providing for elongation or contraction due to temperature changes. The methods described are felt to incorporate doable construction techniques.

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1. Introduction

The Archimedes Bridge, more generally known as the Submerged Floating Tunnel (SFT) can be developed in three basic configurations: (1) Supported from surface pontoons, (2) as an underwater bridge on underwater piers, and (3) as a tethered floating tunnel where tethers anchored into the bottom hold the tunnel vertically and laterally stable utilizing its positive flotation forces.

Over the years the writer has given considerable thought to concepts that might be useful for the design and construction of the tethered SFT. He has considered how proven, conventional, immersed tunnel techniques might be used to construct a SFT of significant length and the special considerations inherent in such an exposed structure. Building any structure in a marine environment becomes more and more difficult as the depth increases. The development of accurately placed, stable anchorages requires careful geotechnical design and unusual marine construction techniques. Tethers should be at least neutrally buoyant as sagging would complicate underwater attachment and adjustment to the tunnel structure. Measures must be taken to provide lateral stability for the SFT and allow for temperature variation affecting tunnel length.

If geotechnical conditions are such that significant differential settlements cannot be avoided, then tether tension monitoring and re-adjustment may be necessary. This could be done in this example in the lower flotation ducts by using hydraulic jacks with locking devices holding extensions of the individual tethers. These extensions would have to penetrate the lower hull. Penetrations into the hull are never desirable but using watertight packers, seepage would be minimal and easily controlled. In this example however, it is assumed that differential settlements will not be a long-term problem so the tether loads are shown carried directly into the tunnel wall structure.

A tethered submerged floating tunnel is particularly vulnerable to total destruction by flooding. SFT vertical alignment could be planned to drain outward from the tunnel midpoint to interceptor drains on shore. Even with minimum drainage slope of ½ percent this method of flood prevention would drive the tunnel profile deeper with increasing length of the water crossing (the deeper grades at the shorelines making the overall tunnel longer). Also, such a system would only work for small leaks and seepages but would not protect against a severe breach of the tunnel envelope. This could occur if its buoyancy were to be overwhelmed as a result of a breach of its “hull” due to an internal explosion or external vessel impact. Once the local buoyancy was negated, the tethers would become slack, allowing the water to pond and further increase the downward loading. This unstable divergent condition would quickly cause the entire structure to collapse.

2. Construction of “Tether Towers”

The following discussion is intended to present what the writer feels are potentially doable design and construction methods for helping to overcome the problems touched on above. The discussion will follow the logical construction sequence that might be used to build a long SFT in deep water.

2.1. Preparing the bottom of the waterway to receive the tether anchors

Of course, prior to the design of the Project it will be necessary to carry out a detailed program of geotechnical investigation and testing to determine the characteristics of the bottom profile. A very hard or a very soft bottom could present special, but not insurmountable, problems. For the purposes of this hypothetical study we will assume a typical layered bottom of silts and sands.

The bottom would first be excavated down to well-consolidated ground using airlifts or clamshell dredge(s). Then a long segmented or telescopic pipe would deliver crushed stone or large gravel in a grid pattern to form a stable layer. This layer would be smoothed to a relatively flat level surface using a remotely controlled grading device similar to the one used for the foundation for the Bosporus Rail Tunnel (see Fig.1). This unit would be lowered to the bottom and would smooth the gravel to a desired plane and elevation. CCTV would document the result of the treatment, and sonic location and elevation transmitters would record exact vertical and horizontal position of the grading blade continuously in real time [2].
2.2. Casting of concrete anchor block and assembly of tether towers

The actual load carrying tethers would be large steel pipe -- say 1 to 2m diameter -- with a heavy wall thickness adequate for the loading, long-term corrosion, safety factors, etc. It is thought that instead of using individual free tethers, there might be significant advantages in combining groups of four hollow steel pipe tethers into rigid braced welded towers. These “Tether Towers” would be assembled in a specially constructed barge that would first be used to cast a large concrete anchor block. This casting would imbed the legs of first module of the tower. Removable pad eyes used to lower the anchor with the tether tower would be provided at each of anchor block’s four corners. Once the huge anchor block was cast with the first section of tether tower, the casting platform would open and permit the block to be lowered into the water to a point where a new prefabricated steel tether tower module could be hoisted into position and welded to the previous module. This sequence would be repeated until the tower reached the calculated height needed for the anchor and tower. This height must provide for suitable interface space for the connection with the SFT. The tether tower assembly barge, as envisioned, would be equipped with two assembly wells so that two towers could be assembled at the exact spacing of half the length of an element. In this study the elements are assumed to be 150m long so the towers are spaced 75m apart.

Once the tower and anchor block assembly was in final position a special survey tower would be installed on the top of each tether tower extending above the water surface to allow a check of the towers’ exact as-built elevation and alignment. If acceptable, then stone backfill would be placed to cover and lock the anchor in place. Depending on the measurements of the in-place towers elevations, the connection “feet” attached under the SFT element would be pre-set to proper extension in the dry dock so that when the tunnel element is installed onto the Tether Tower and
the legs bolted to the connection, the tunnel will be at exact grade prior to de-ballasting the element and thereby applying tension to the tower.

3. Tunnel construction

3.1. General considerations

The feasibility of this proposed hypothetical SFT scheme is very dependent on the on-site field conditions. It should be quite feasible in marine conditions where water currents are rather mild as in protected fjords and where weather windows are long enough where wave action is not too severe during placing of elements. The design basis of this hypothetical tunnel is that it will be arched and anchored to shore abutments and held in position vertically by the tether towers acting in tension. The arched shape will provide horizontal support for either upstream or downstream currents. The inherent flexibility of the arch will allow expansion and contraction in the tunnel without the need for special joints. As the length, and thereby slenderness ratio of the crossing, reaches some point it may be that some lateral anchorages are required.

Since the premise of this proposed scheme is that it is adaptable to a deep water crossing, the use of anchors would not be feasible for holding the tether barge, dredge, element placing barge, and any other equipment that might be used that would require accurate station-keeping. Instead, all such equipment would have to use heavy duty thrusters for holding position and alignment using GPS and gyro alignment for reference.

Prior to connection to the tunnel tube, the tether towers become very tall in deep water and while they are very stiff, the currents near the surface might tend to cause them to overturn at the anchor block. A method to add stability would be to make them positively buoyant until they are connected to the tunnel. A buoyancy tank could also be added to the uppermost tether tower module to further enhance this stability with a large vertical positive buoyancy force. Remotely operated valves could later allow the tower legs (tethers) and tank to fill with water after being connected to the tunnel and tensioned. When flooded, the buoyancy of the tower would be lost and the dead weight would add to the downward force holding the tunnel. In addition, the anchor blocks would be covered with backfill after their installation to increase their holding power and stability.

As there are two major operations that must be done in serial order: first preparing the tether towers and then lowering and connecting the elements, there could be some considerable schedule advantage for building the SFT from both ends and meeting near the middle of the crossing rather than from one end to the other. Equipment usage would also be more efficient. A special closure joint would, however, be required. Either method will have the problem of lack of the arching action that ultimately provides the lateral stability to the tunnel. Some large capacity, deep anchors may be necessary as shown in Fig. 3.

![Fig. 3. Plan of SFT being constructed from both abutments](image-url)
The actual construction of the tunnel beyond the preparatory works for the anchors and tethers as described above would proceed much in the same manner as for building an immersed tunnel.

3.2. Shoreline work

The shoreline structures must be considered as **abutments** designed to take the compressive or tensile thrust caused by the water currents acting on the arched tunnel. If the shoreline is rock this should be a relatively simple straightforward structural design. If, on the other hand, the shoreline (one or both) is deep marine sediments for example, then a somewhat more complex piled structure would be needed. In either case the two abutment structures would probably be constructed in the dry in cofferdams. A special bulkhead and immersion joint collar would likely be incorporated to permit the first tunnel element to be connected as a typical tunnel placing operation.

3.3. Element design and fabrication

The 150m long tunnel elements could be constructed in existing dry docks or slipways or a purpose-built large graving dock much as immersed tunnel elements are constructed. Since these SFT elements are designed to be very light – capable of floating even with the track or vehicle ducts flooded – the draft requirements will be much less than for a regular immersed tunnel. On the other hand, a certain amount of ballast may be need for stability during float-out. Also, in this assumed design, two large pits will be needed in the bottom of the dry dock to accommodate the framed tether connections that would be later bolted to the tops of the tether towers. When the element is floated out of the dry dock, these extensions must rise out of the pits and have safe clearance over the dry dock sill. Each tunnel element will have larger outside dimensions at each end to provide room for the immersion joints that will extend beyond of the structural shells of the SFT.

For these light elements a large portion of the typical cross section must be structurally braced waterproof steel shells designed to take full water pressure outside (and inside for the flooded condition). The structure would resemble steel-concrete-steel “sandwich” construction except that only a portion of the cross section would be filled with self-compacting concrete. The rest of the section would be filled with syntactic foam for buoyancy and to prevent it from gradually filling with water from seepages. Syntactic foam is structural foam made lightweight and water resistant by a high concentration of glass micro-spheres. Such foam will not deform or loose buoyancy under high water pressure. The overall tunnel element must be designed to resist the longitudinal bending moments caused by the buoyancy forces acting over the 75m spans between tether towers.

The selection of the element length is a compromise of a series of factors. For immersed tunnels it is driven by the economies of reducing the number of immersion joints balanced against immersion barge size and machinery capacities. Areas of significant currents may limit the element length due the difficulty in holding and lowering the
element broadside to the water flow. In this case of the SFT, the bending forces resulting from buoyancy are a much larger factor than the bending forces of a ballasted immersed element. During placing the latter typically only weigh 4% of their displacement.

3.4. Placing equipment

The Placing Barge or “Lay Barge” is likely to be very similar to catamaran placing equipment used in immersed tunnel construction. Since the SFT elements must be ballasted to a negative buoyancy of 2-4% for stability during lowering, clearance under the straddling carrying beams should not be a problem, however much of the ballasting operation must be done before the element can enter the catamaran to reduce the very large freeboard of the inherently light element. Normally such ballasting is done with the element hung in the placing barge and the ballast controls in the control cab.

Fig. 5. Typical placing barge (This one was used to place 30,000 tonne elements.)

Since the element will be lowered onto the eight pipe tethers prior to bolting them, it will be essential that the vertical sinking speed at contact is low to prevent damage. This should not be a problem where calm conditions exist at the surface. Where significant swells or wave action are anticipated however, measures may have to be taken to stabilize the Placing Barge. One idea would be the use of a double hull semi-submersible barge whereby large, heavy weights could be lowered to the bottom allowing the SS barge to float on a lower hull held underwater. In between the lower hull and the upper hull there would be a cross-braced supporting structure essentially transparent to changes in water elevation due to waves or swells. The element would be supported from the upper barge held in the air by the submerged barge and would see virtually no motion. When the operation is completed with the anchor blocks raised, the double barges would provide the flotation needed during the SS barge’s tow back to the yard.

3.5. Placing and connecting an SFT element to the tunnel

The final equipping of each element with ballast tanks, pumps, control systems, attitude indicators, CCTV, etc. Could be carried out in the fabrication dry dock or after float-out if schedule so dictates. After float-out from the dry dock or graving basin the new element would be towed to a position alongside the placing barge where the ballast electrical power and control system could be connected and allow the element to be ballasted to the correct freeboard to enter the placing barge and get connected to the lowering falls. The proper mating of the tether towers will be assured by the prior match-drilling of the two uppermost prefabricated tether tower module flanges with the flanges on the eight framed leg assembly that will protrude from the bottom of the element. The actual vertical location of the four flanges as referenced from the horizontal axis of the SFT element will be very carefully set based the surveyed top of each tether towers. Any slight gaps that the
divers should find between the flanges would be filled with shims or simply bolted tight. While it may be expected that the taller tether towers may drift in horizontal coordinates prior to placing, large centering pins (see Fig. 6) aided by thruster control on the towers should permit capturing the towers and aligning the bolt holes so that divers should have little trouble with the bolted connections.

Given suitable forecasted weather conditions, the placing barge would be towed to the site for the operation of lowering the element and attaching it to the tunnel in-place and the two completed tether towers. The placing barge would then stabilize itself in position and orientation using thrusters with GPS and gyrocompass references. Since the tether towers will be somewhat flexible at large depths, their exact position may vary somewhat from theoretical. It may be necessary to have simple detachable unidirectional electrically driven thrusters attached to push the towers in the horizontal directions as the tether connections under the element approach them. These could be controlled by divers and/or CCTV.

As the element is lowered it must be held off the tunnel in-place somewhat to clear the tunnel face and Gina Gasket. The tether extensions under the element being placed will be provided with tapered noses to engage centering holes in the legs of the tether towers. Once all the legs were properly captured and the element could be lowered to final grade, it would be moved onto the bearing surface of the tunnel-in-place. Guide beams and centering guides would perfectly align the two mating faces (see Fig. 9.). After diver inspection the crew of workers inside the tunnel would extend a hydraulic jack and capture the free element. Then the jack would retract and compress the soft nose of a Gina gasket.

This done, the inside crew would pump out the joint space between the bulkheads while watching a pressure gage. When pumping is stopped and the pressure does not rise again, the initial seal is thereby confirmed, and pressure can be further lowered to atmospheric. As this done an unbalanced force of several thousand tonnes will completely compress the Gina gasket. This provides a perfect seal that will permit pumping the joint space dry and allow survey personnel to check vertical and horizontal alignment in the newly placed tunnel section.

In the United States a few recent immersed tunnels have used adjustable wedges for horizontal alignment control. Such a system might be ideal for an SFT, especially a long, deep one such as this example. The wedges are preset based on validation survey data measured on the bearing faces, however at joint depressurization if the outboard horizontal position of the element deviates from tolerance, this wedge system allows quick, easy adjustment to alignment. To do this, the joint space must be repressurized, the wedges moved a calculated distance, and the joint again depressurized. Properly carried out, the realignment hits its target alignment within a few millimetres. In this case where the SFT will be curved, the theoretical curvature is built-into the fabricated joints. Small errors at the
faces that cause unacceptable errors at the outboard end of the element being placed however can be corrected using
the wedge system.

With the element supported on the tether columns the small amount of longitudinal motion caused by the gasket
compression should be allowed by the mobility at the top of the tether towers. The mating flanges on the eight
tethers can then be bolted by divers. The feasibility of these underwater bolted connections was proven to the writer
in witnessing the very large bolted connection used on the Bosporus Project (See Fig.7). While this SFT is designed
not to sink when in service, in order to connect it to its tethers, it must be ballasted to sink into position. The amount
of water ballast needed to do this should provide each SFT element with a negative buoyancy of 3-4%. To do this
water ballast tanks must provided in the traffic duct plus the lower flotation compartments (normally empty).
External ballast will not be required.

Once the tethers are completely bolted and verified ready to take the forces of flotation, then all the water may be
pumped out. Strain gages attached to the legs may be used to verify the load distribution to assure acceptable
conditions. If necessary, positive buoyancy could be applied by de-ballasting the last few elements in gradual stages
to avoid building up large unequal forces in the tether towers.

![Fig. 7. Example of a complex match-drilled underwater bolted flange connection: Bosporus Rail Tunnel Access Shaft connection at -23m](image)

### 3.6. Construction stages

During the construction of an immersed tunnel there is a safety rule that should never be broken. This rule should
also be applied to the SFT that is constructed progressively as discussed in this paper. The rule is that there should
always be three watertight bulkheads protecting the tunnel from flooding. The water tightness must include any
piping or electrical services passing through the bulkheads. Marine hatch doors may provide access from one

![Fig. 8. Showing stages of construction and bulkhead removal](image)
element to the other but these must be kept closed when no work is going on. Fig. 8 illustrates how this rule is implemented showing the elements in three different phases of construction. From left to right, a) The latest element is ballasted and is being lowered into place, connected to the tethers and joined to the tunnel b) The previous element is now completely floating, all the ballast tanks have been removed, and the inboard bulkhead has been removed to permit the completion of the structural welding to form a full-strength welded connection between it and c.) the element on the right where final internal work can proceed including casting concrete and foam in-fill to complete the joints and installing the electrical/mechanical equipment (usually following on much later).

4. Repair of breached tunnel

A great deal of the cost of this hypothetical project lies in the requirement that this SFT not collapse in the case of a breach in the hull. Even so, the tunnel would quickly fill with water, perhaps cause loss of life, and would damage electrical and mechanical systems such as lighting and fans. The structure would not collapse entirely but a certain portion might be badly damaged. There would not be much point in this extra cost unless repairs could be made.

Obviously damage could range widely depending on the cause:

Small punctures could be sealed from the outside of the SFT structure by welding a plate over the opening, pumping the water out of the tunnel, and repairing the interior structure. An explosion tearing a wall out of the tunnel might require removing a length of the tunnel. This can be done by using a barge mounted diamond rope saw device to cut vertically through the tube structure at undamaged locations and lifting the damaged section free. Once unbolted from the tethers, the damaged section might even float. A new section would then be fabricated with clearance at each end to permit it being slipped in between the square cut ends of the tunnel. Specially built collars equipped with concrete grout bags attached to the sides and bottom of the SFT would receive the new section. After the new piece was adjusted into position an upper half collar would be bolted in place at both cuts and the grout bags inflated to restore the water tightness of the tunnel. The whole tunnel can then be pumped dry so that the new structural connections can be made from the inside [3, 4]. The bolted connections to the tether tower would have to be matched from the wrecked portion or by some survey means. A tether tower might be damaged and also require repair. A worst case would be damage from a sinking vessel where several elements and tether towers might be deformed or destroyed. In such case, a major restoration project could be required lasting many months.

The main point is that repairs would be possible in many situations, unlike the situation where the entire tunnel would collapse.

Fig. 9. Inboard end of typical immersed tunnel element showing the centering guide beams, and shear beam that align the register of the opposing faces in a joint. The rectangular hole in the shear beam is for the hydraulic jack used to pull the elements together at the joint to establish initial seal.
5. Conclusions

The reader should have no illusions. What is described in this paper is a very expensive tunnel, much more costly that what is currently being proposed for SFTs in a number of countries. It is made so costly because of greatly increasing its cross section and also thereby, the tethers and anchor size, in order for the tunnel to stay floating stably in the event of a disastrous breach in its hull.

The writer asks himself for the reason–despite the urgent need in Norway and other countries for water crossings where the SFT concept is the only feasible means–why no SFT has so far been built. There is an inherent fear in visualizing a tunnel crossing suspended in the open water column. One thing is to bury a tube underground, as is the case for immersed tunnels, but it is the mental image of having it hanging exposed that may discourage drivers and potential owners alike. In the case of owners–especially investor–in a toll crossing for example, their biggest concern may be the chance of losing everything in seconds after an explosion in the tunnel. The writer believes that if a design is proposed to them that would assure them of only localized repairable structural damage, even if the up-front capital cost is high, the owners would seem more prone to proceed with such a project. Chances are that insurance costs would be much lower, especially considering the long-term life-cycle operating costs of such a facility.

The original ideas outlined here may be useful whether the SFT is “unsinkable” or not. It is hoped that they might be. The handling, attaching, and adjusting of individual loose tethers seems to have been treated very lightly over the years and that has always bothered the writer. The tether tower scheme proposed here permits rather precise survey control and installation without less likely need for readjustment. The combination of vertical tethers and an arched tunnel seems a way to get away from the problems that may be inherent in the use of inclined tethers. Perhaps the tether towers will be less likely to have vortex problems because of turbulent flow. The use of very conventional immersed tunnel techniques with elements of similar length seems to the writer the proper way to approach a long SFT crossing, at least to start with, certainly. The use of thrusters appears to be common in the offshore oil industry, however the writer has had only limited experience with their use.

There are of course, a lot of aspects that require rigorous mathematical analysis such as hydrodynamics of the tether towers and the tunnel itself. Structural analysis and optimization would follow. Also, the actual field conditions both physical and environmental, will greatly influence the design and construction aspects of such a tunnel. Environmental impacts such as the blockage caused by the tethers could be a serious concern and this paper makes no effort to optimize these. As stated at the beginning, the main intent is to throw some ideas on the “table” for what they might be worth. What the writer has tried to do however is to think through the design and construction process step-by-step using his best judgement and construction experience to help engineers in the field arrive at an SFT that would be stable and safe and that owner might be willing to invest in.

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