Abstract
The similarities and differences between immersed tunnels and Submerged Floating Tunnels (SFT), also known as Archimedes Bridge, are explored. It follows the development of SFT through ITA Working Group 11 “Immersed and Floating Tunnels” that has resulted in proposed designs for tunnels in Europe and where SFT might be used world-wide.

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1. Introduction

There are many similarities between immersed and floating tunnels, but before these are examined, it will help to define what these two concepts are. Both immersed tunnels and submerged floating tunnels (SFT) are methods for crossing water beneath its surface, and both consist of one or more prefabricated hollow tunnel elements (sections) constructed in the dry at a location which is not their final location. The ends of each element are closed with bulkheads to keep out the water. The fabrication facility is then flooded or the elements are launched, possibly incrementally. Almost all elements are designed to be able to just float at this stage, or can do so with a little buoyancy assistance. After floating to their final destination, the two concepts differ.

In their final condition, permanent ballast is added to immersed tunnels, if needed, to ensure that they cannot float. They are lowered into a pre-dredged trench and covered up, usually with a protection layer about 2 m thick on top. Immersed tunnels are therefore located at shallow depth beneath bed level. Some 200 immersed tunnels have been built since the first sewer immersed tunnel was completed in 1893. This year, it is exactly 100 years since the first immersed railway tunnel was completed, but it was another 18 years before the first road tunnel was completed.

In contrast, the Qiandao Lake prototype will be the first SFT to be constructed. For an SFT, no trench is required and they are not covered up; their final location is somewhere between the surface and bed level, surrounded by water. Two support concepts have been considered for SFT despite their “floating” name, either buoyant tunnels held down by tethers or heavier-than-water tunnels on supports like a bridge; the supports could be piers founded at...
bed level, hangers from pontoons or arching between the tunnel ends. More information on these concepts is given in the ITA Working Group 11 State-of-the-Art Reports of 1993 [1] and 1997 [2].

2. History of SFT

The first underwater tunnel was built over four thousand years ago, but immersed and floating tunnels are much more recent. Certainly an engineer and builder of railways, S. Préault, proposed but did not build an SFT across the Bosphorus in 1860, an elegant underwater tunnel viaduct with spans of about 150 m founded on piers, located some 20 m below the surface. Per Hall proposed a deeper SFT for the Bosphorus in 1976, but by 1977 his proposal had become a buried immersed tunnel for environmental reasons (fish habitat). An immersed tunnel is now in place beneath the Bosphorus awaiting the last of the TBM’s to reach it. Going back now to 1882, Edward Reed proposed a submerged railway tunnel across the English Channel supported on caissons, but Parliament in England rejected it for fear of invasion. It was patented and since then, many other patents have been taken out for SFT, including some in the UK, USA, Norway, Sweden and Italy. Once the first immersed tunnel had been successfully built in 1893, the way was open also for constructing SFT – initially at least those that would be pier supported.

Since 1923 [3], the potential of an SFT has been recognized in Norway as a way to create a practical coastal highway across fjords that would otherwise be too deep even for bored tunnels to make sense; some of the existing bored tunnel connections even with 10% grades are very, very long. This need for shorter shallower tunnels for a number of fjord crossings has led to detailed investigations and field tests that still continue today. The most well known crossing evaluated in some detail in Norway is for Hogsfjord, but the SFT was abandoned for local political reasons. Private investors have examined a number of other locations. Another serious contender is the Sula-Hareld crossing. The first of a series of Strait Crossing Symposia in Norway began in 1986 (the fifth was in 2009) in which SFT have played an increasing greater part.

Meanwhile in 1969, Alan Grant made a prize-winning proposal for a 5.3km SFT between Calabria and Sicily across the 350m deep Messina Strait in Italy, which was patented in 1984 under the name Archimedes Bridge. A number of detailed studies followed until finally the SFT was abandoned only a few years ago in favor of a bridge, reportedly due to sinking ship issues. This project led in 2001 to a Sino-Italian joint venture that researched a 3.3 km SFT in Jintang Strait and then in 2004 to SIJLAB that proposed the Qiandao Lake SFT prototype [4] that is awaiting construction go-ahead.

As a result of the interest in SFT and to give more worldwide attention to both immersed tunnels and SFT, the International Tunnelling Association (ITA) established a Working Group on Immersed and Floating Tunnels in 1989 to present the state of the art. Specialists from around the world in these fields make up the Working Group and they publish extensively. Meetings are held each year at the ITA annual congress when a number of technical papers are also presented and published. Besides the two stand-alone State-of-the-Art Reports and a guide for owners [5], the Working Group is compiling a searchable database with public access; it contains information about immersed tunnels and is now to be extended to SFT. Initially, the information is aimed at removing the mystique and explaining the methodology and terminology. A number of other specialized working groups have also been set up in other countries, including Norway, The Netherlands, Italy, China, Japan and the European Union.

Interest grew worldwide in the years following 1989. In Japan, a conceptual investigation into a 34km crossing of Funka Bay on Hokkaido began in 1990 and a crossing to Honshu was also studied. A proposal for an immersed tunnel–SFT combination across the Gibraltar Strait was rejected by the Spanish Morocco Authorities in 1995. A joint Norwegian-Danish-Italian group under the aegis of the European Union published the FEHRL Report on SFT in 1996 [6]. The author proposed road and rail SFT across Lake Washington near Seattle in 1999, but the replacement for the existing floating bridge will again be a floating bridge. In 2003, a crossing of Lake Zurich by SFT was proposed [7] as part of a ring road study. Indonesia briefly considered a 25km underwater link between Java and Sumatra across the Sunda Strait, but decreasing traffic volume no longer justifies a fixed link.
3. Design issues

While immersed tunnels and SFT may be very similar in the way that they are constructed and installed, there are many additional aspects to consider in the design of an SFT. It is quite probable that SFT elements will be prefabricated in a dry fabrication facility just like immersed tunnel elements; with the ends sealed, they will similarly be outfitted and towed to their final destination before being immersed. It is not impossible that an SFT could be incrementally launched like some bridges with segments match cast at a shoreline facility and then pushed out, perhaps eliminating most immersion joints. Recent requirements in Europe and in USA for separate egress corridors (escape tunnels) are changing concepts for the interiors of single-tube tunnels, but escape into a parallel traffic tube can avoid this requirement; egress corridors are still used when space is available.

3.1. Seismic loads

The dominating loads on an immersed tunnel are usually hydrostatic pressure and extreme loads such as seismic and sunken ship. An SFT also experiences the hydrostatic pressure and the extreme loads, but not necessarily in the same way. An SFT supported from bed level on columns would suffer the seismic loads much like a bridge, but supported in any other way could be almost independent of seismic loads; this leads to the conclusion that an SFT is the only form of tunnel that can safely cross an active moving fault. That does not mean that seismic events can be ignored, and it may be quite a challenge to make the transition from an SFT to fixed terminal structures. Preliminary designs of suitable seismic joints for the Messina Strait SFT were developed to handle a 7.5 Richter event, but such
joints can be complex. This ability to cross moving faults is certainly a unique and valuable feature. Some readjustment of tethers to bed level, if used, might be required after fault movements. Ideally, tether adjustment should be possible from inside the tunnel, but this could be difficult to achieve.

Immersed tunnels are not immune to the need for seismic joints; changes in soils (soil to rock, for example) or changes in mass at terminal joints can result in differential behavior during a seismic event necessitating seismic joints. The BART immersed tunnel in San Francisco has seismic joints capable of absorbing vertical, lateral and axial seismic deformations; the joint (Fig. 1) functioned perfectly during the last major earthquake. The Bosphorus tunnel needed only axial seismic joints at the transitions between immersed and bored tunnels. Most immersed tunnels in seismic regions that have flexible joints are equipped with short finger-tight prestressing bars across these joints; these bars essentially need act only when joints try to open up due to a seismic event and thus ensure that the amount that the joint can widen is limited to an acceptable amount. Seismic joint design can vary considerably.

3.2. Sinking ships and ships’ anchors

There is this ship that travels around the world and sinks onto every immersed tunnel, or at least it seems like that; small craft have sunk onto immersed tunnels, but the author knows of no case where a large vessel has. There are several issues here: Firstly there is the protective cover over the immersed tunnel that helps to distribute the load; secondly the ship will also rest on adjacent ground and thirdly if the ship is resting on the tunnel like a hard spot, the ship would buckle to even out the load. This is explained with pictures in the State-of-the-Art Reports. However, with an SFT, there are other issues. If the tunnel is too shallow, it could be rammed by a passing ship, but even if it were deeper, a serious hazard would still be the unlikely event of being hit by a submarine; it is essential that the SFT be essentially unsinkable; this is addressed later. How deep should the tunnel be to avoid surface shipping? If crossing a lake, a few meters could be sufficient (sail and pleasure boats), but elsewhere it depends upon the draught of the ships. Currently, few if any vessels have a draught exceeding 25m, so that a minimum depth of say 30 m should be safe. It is most unlikely that a whale would affect a tunnel, but presumably a tether might be affected, however unlikely that might seem; until such an event is recorded, it would probably be safe to ignore it.

If a ship were to sink onto an SFT, it would be unlikely to come to rest balanced on top. If the water is deep enough, the ship could slide off as long as the SFT does not sink downwards with the ship. If the water is not deep enough, the ship could come to rest supported at one end on the bed, but with the ship still resting on the tunnel. In each of these cases, the ship load would cause large bending and shear forces between the support locations as well as local stresses. In each case, substantial vertical and horizontal loads would occur that could lead to displacement and potential leakage at flexible joints. Clearly, the size of ship and probability of occurrence must be properly defined and an acceptable level of risk evaluated to ensure user confidence. Solving the ship issues is definitely one of the greatest design challenges.

Ships anchors come in all different shapes and sizes, up to a weight of about 18 tonne. The largest anchor chains have a breaking load of some 800 tonne. The State-of-the-Art Reports provide guidance on how to handle design issues arising from an anchor dropping onto immersed tunnel protection. To avoid an anchor snagging the side of an immersed tunnel, it is becoming usual to provide “anchor release bands” clear of the immersed tunnel to each side. These consist of a band of large-sized rock that in theory chokes the gape of an anchor and tends to bring the anchor up to the bed surface where it will drag across the top of the tunnel before reengaging. Supposing the anchor did lock onto the tunnel, the passive pressure available each side of the tunnel would prevent the tunnel moving. The anchor chain might well break before the vessel could be brought to a sudden halt, but some local surface damage to the surface of a concrete wall could occur. The tunnel walls are unlikely to break.

Anchors are a hazard to an SFT. It is not unusual for a ship to travel with an anchor hanging in the water, presumably an oversight. There would be a real risk of a direct hit on the tunnel roof or sides, and anchors could snag tension anchors. Calculations will need to show that the tunnel would survive direct impact of a large anchor. The effects of a tension anchor cables being caught by an anchor would need to be investigated. It could result in lateral displacement of the SFT and this in turn might open up joints. It could also cause a tension anchor to break, but that in itself should not be a critical issue, because the tunnel will need to survive the loss of a tension anchor.
3.3. Differential settlements

One of the greatest benefits of an immersed tunnel is that the tunnel weighs less than the material excavated. Consequently, differential settlements are not usually a serious design issue. Prudent selection of flexible joint locations can overcome differential settlements arising from varying underlying soil stiffness. Screeded foundations can be placed with great accuracy, and sand flow is also very reliable. Nevertheless, it may be desirable for settlements to be strictly limited, in which case soil improvement or pile support may be required.

Reasonable ground conditions, as long as the differential movements can be tolerated, allow segmental immersed tunnel elements to be used, reducing cracking issues and longitudinal moments; the segments are temporarily stressed together into an element until the immersion joint is completed. Although the prestressing together of segments has usually been cut after installation, there can be benefits to retaining the prestress.

For a cable-supported SFT, adjustments in the supporting cable lengths are needed during installation and can doubtless be repeated if needed after differential settlement if indeed it occurs. Interestingly enough, for tension anchors, settlement could even be upwards, depending upon how the anchors are held at bed level. A pier-supported SFT can deal with differential settlements much like a bridge structure, although it is likely that little later adjustment would be possible.

3.4. Traffic loads

An immersed tunnel is a structure held laterally by fill material that over time will exert at-rest pressures on the tunnel. Traffic loads, both lateral and vertical, are usually negligible as far as the primary structure is concerned. Whereas an immersed tunnel is continuously supported long its length, an SFT has discrete supports like a bridge. Like a bridge, a column supported SFT will need to transmit all traffic and accident loads to the supports.

A cable-supported SFT must have sufficient reserve buoyancy to be always able to carry the maximum weight of traffic, including any leakage and fouling on the exterior. Besides this basic fact, all traffic – cars or trains – will cause dynamic effects due to moving vertical loads, acceleration, braking and traveling around curves.

3.5. Other Loads due to water

In some locations, icebergs or even pack ice might need to be taken into account for any type of tunnel, since these can also gouge the seabed and while afloat can exert considerable forces due to wind effects and water movements. Nevertheless, once buried, an immersed tunnel is largely independent of what happens in the water column, while an SFT is directly exposed to what happens. The locking fill around an immersed tunnel effectively fixes it so that immersion joints and segment joints do not carry dynamic loads other than seismic. The water surrounding an SFT, on the other hand, will move due to the effects of waves, currents, tides, ocean swells, storm surges and tsunamis; the water does not provide any fixity and little damping. Many of these effects decrease as the SFT is placed deeper beneath the surface. Landslides or rock slides can cause an effect similar to a tsunami. This has been a serious consideration in locating potential SFT sites in Norway, most aptly demonstrated by a scale model in Trondheim of a fjord where part of a mountainside falls into the fjord and the resulting wave inundates two villages with a high tsunami-like wave with devastating effects. Wave loading causes a rolling motion with horizontal and vertical forces, whereas most of the other fluid loads are primarily horizontal. However, only larger waves or waves with longer periods are likely to have any appreciable effect unless close to the natural frequency of the system.

The magnitude of these loads depends upon the shape of the SFT and tethers, and the drag factors that result. Durability of the tethers must be ensured. These factors will not be improved with marine growth on the exterior, including barnacles as well as seaweed. It may be necessary to have regular exterior maintenance to remove marine growth – a challenging task that will doubtless have to be automated. Unlike an immersed tunnel, the water on the exterior of an SFT is continually being refreshed. This will increase the risk of any corrosion that in turn can cause a change in surface roughness. Although the mass of the tunnel is large, oscillations could also arise due to vortex shedding, especially if small rotations due to displacement can cause the vortex shedding to switch to the other side. The tethers themselves are subject to dynamic excitation.
If the SFT is suspended from floating pontoons, the effects of a water level change at the landfalls could be significant. Water level changes can occur due to air pressure, wind, tides and tsunami. In the hydraulic model made to determine currents suitable for immersion of the Bosphorus immersed tunnel, air pressure and wind played a dominant role.

3.6. Other SFT design issues

The position of an SFT needs to be maintained by its supporting system, be it supporting columns, tethers or some day in the future by thrusters. None of this is new technology. If thrusters are not to be used to hold position horizontally – and it is desirable not to need them – then tether arrangements must do so. Element joints must be capable of absorbing movements that do occur. Thrusters, were they ever to be used in the future, would need to have backups, presumably mounted in pairs; one pair would be needed horizontally to control lateral position and one pair vertically on each edge to control vertical position and rotation.

Should a leak occur, water runs to the low point and may accumulate there. For an immersed tunnel, low point sumps are invariably beneath the waterway. For an SFT, such extra weight could cause an SFT to sink. There could therefore be considerable advantage to locating low points outside the SFT and even arching the SFT upwards within the waterway making no place for water to accumulate within the SFT.

Taking dynamic loads into account, both individually and combined, their effects must differ from the system resonant frequency or else oscillations could build up. Dynamic behavior of the whole system must be considered. Besides the obvious wave loads, dynamic loads can also be caused by passing ships and their wakes, any of the extreme impulse loads such as earthquake, ship impact and rockfalls, instability such as angles of loll or tethers going slack, galloping motion and underwater explosions.

One essential requirement is that motions not be so large that they are obvious visually (snaking effects), and motions must be gentle enough so that the tunnel does not feel unstable. These requirements may be challenging to meet in some locations. The more flexible joints that there are, the more difficult it may be to limit motions. Restraints will be required across all joints to keep the joints sealed and dry.

3.7. Unsinkable tunnels

It is essential that SFT be unsinkable. It may not always be possible to locate the low points beyond the SFT as suggested above. In case of ship collision, one or two compartments could be holed and flood. In either of these cases, the amount of water accumulating must not be more than can be held up by the remaining buoyancy. One method considered is to have a double skin, as do many ships. The space within the outer skin can be divided into compartments. Another option is to fill buoyancy spaces with lightweight foam, for example, so that these spaces physically cannot fill. Static stability in the flooded condition needs to be confirmed. Traffic in each direction should run in separate tubes, isolated by hatches capable of carrying the flooded water pressure, as should service tunnels and escape corridors.

3.8. Very long tunnels

Since SFT are being considered for long crossings, albeit conceptually, ventilation becomes an issue with dissipation of heat being a normal operating criterion. Immersed tunnels are currently also being designed for long crossings, 5km for the Hong Kong-Zhuhai-Macao bridge-tunnel and 18 km for the Femern Belt tunnel between Denmark and Germany. Heat is generated principally by engines (propulsion systems), air conditioning and braking. Future high speed transit systems may also need to consider rolling drag and air friction [8]. Since this heat has nowhere to go, it must be ventilated away once traffic numbers increase.
Ventilation under fire conditions is usually a governing condition nowadays for immersed tunnels since the pollutants from vehicle exhausts are being reduced. Features incorporated in some designs include smoke exhaust ducts. The use of deluge systems which are becoming more frequently specified affects the behavior of air flow and must be taken into account.

As the length of a tunnel increases, it may be necessary to consider multiple fabrication facilities in order to complete the project in a reasonable time. Weather windows suitable for the installation stage may decrease as the distance from shore increases because conditions may become too rough for towing and other operations. Atlantic Ocean tows for the Ted Williams Tunnel were considered, for which a survival wave of 7 m, used for ship design, would have had to be taken into account [9]. The immersion rig or lay barge can be made less sensitive to waves by making it semi-submersible with only a small water-plane area (Fig. 2). However, as length increases, so does total cost, and this may be a limiting factor for long crossings.

As with other long tunnels, trans-alpine for example, long tunnels will require locations at regular intervals at which equipment can be housed, such as transformers, sump pumps and other mechanical and electrical equipment. There is no real reason why elements at such locations need be identical in size and layout to other elements. It may even be possible to provide emergency parking shoulders or vehicle turn-arounds, for example with a gap in a central wall. Such special elements can vary both in width and depth (but for immersed tunnels most likely with roof levels in common with adjacent elements).

4. SFT terminal joints

The transition from an SFT with its dynamic motions to a fixed land tunnel must be achieved without perception to a user, as with other SFT joints. In effect, the joint is similar to a seismic joint except that a transition tunnel will be needed, capable of bridging the relative motion. It may also be desirable to provide some axial damping to the SFT to provide the axial restraint that is perhaps not provided by the SFT support system or tethers. For the Messina Strait SFT, hydro-pneumatic axial damping [10] was to have been provided at one joint at the transition element, as well as a seismic joint (Fig. 3) similar in principle to that of BART (Fig. 1). Since there is an active fault beneath the proposed tunnel location, there would have been permanent axial length changes to be absorbed.
Benefits of Immersed Tunnels and SFT

Immersed tunnels and SFT cross waterways beneath the surface and therefore do not spoil scenery. Both types of tunnel can or could be directly connected to land tunnels at each side of a crossing and consequently provide an invisible crossing. The land tunnels could be cut-and-cover, mined or bored tunnels. A good example of this is the Bosphorus immersed tunnel that avoids excessive rock excavation for a land-side transition structure by connections underwater to bored tunnels constructed later. The “hidden tunnel” aspect may be an important feature in areas where tourism and the surface environment are important.

In most cases, as soils get weaker and as ship clearances get higher and wider, the cost of a tunnel such as these becomes more competitive than that of a bridge, especially if the tunnel can be kept shallow. Where the crossing is of a deep waterway, an SFT may be possible at a shallower depth than an immersed tunnel. Keeping the tunnel as shallow as possible may keep gradients shallow and crossings shorter; these factors lead to a reduction in fuel consumption, less pollution and lower maintenance costs.

Only one immersed tunnel has been removed to the knowledge of the author. The removal of immersed tunnels and SFT is probably simpler than for most other types of structure. The process essentially need only reverse the method of installation. Because they are structures capable of floating, they can be disconnected, sectioned and towed elsewhere, most likely for destruction.

5. The future of SFT

So why has an SFT not been built yet? There may be reluctance to being the pioneer who builds the first one, in case something unexpected goes wrong. It may just be that the concept is not sufficiently known that the possibility exists. Even though the concepts of floating bridges and tethered oil production platforms have been accepted by the general public, the concept of doing the same thing but for an underwater tunnel has not – yet. The perception of future tunnel users must be that an SFT is a safe and reasonable way of crossing water before they venture to use an SFT. How this is achieved is also a major challenge.

References

[1] Tunnelling and Underground Space Technology 1993; 8(2): 119 - 285. (Available on line at ITA Website)
[2] Tunnelling and Underground Space Technology 1997; 12(2):83 - 354. (Available on line at ITA Website)
[3] Tveit P. Submerged floating tunnels for Norwegian Fjords. Strait Crossings 2009; 515-520.
[4] Fiorentino A et al. The Archimede’s Bridge Prototype in Qiandao Lake (PR of China) Design Report. SIJLAB 2008.
[5] Immersed Tunnels – a Better Way to Cross Waterways. Tribune – special edition, May 1999. (Available on line at ITA Website)
[6] Analysis of the Submerged Floating Tunnel Concept. Forum of Euroean national Highway Research Laboratories (FEHRL). TRL 1996.
[7] Ingerslev LCF. Immersed and floating tunnels across Lake Zürich. AITES-ITA 2004 World Tunnel Congress, May 2004.
[8] Collins AK et al. GDP-23 TransAtlantic Submerged Floating Tunnel. University of Southampton School of Engineering Sciences, 2009
[9] Hakkaart CJA. Transport of tunnel elements from Baltimore to Boston, over the Atlantic Ocean. Tunnelling and Underground Space Technology 1996; 11(4): 479-483.
[10] Gursoy A. Seismic joints and transition tunnels for the Messina Straits fixed-link crossing. North American Tunneling ’96. Balkema.