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Design aspects of the AB prototype in the Qiandao Lake

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Abstract

Submerged Floating Tunnel, also known as Archimedes Bridge, appears to be a very suitable technical solution for waterway crossings. In spite of it, no SFT has been constructed yet in the world, probably due to the total lack of experimental data on the actual behaviour of SFTs under both traffic and environmental actions, such as currents, waves and earthquakes. The scope to fill the gap between theory and reality can be pursued only by the construction of a full-scale prototype of SFT. At this aim, the SIJLAB (Sino-Italian Joint Laboratory of Archimedes Bridge), a joint venture involving Italian and Chinese institutions, has carried out the design of the first SFT (Archimedes Bridge) prototype in the World, to be fabricated and erected in the Qiandao Lake (People's Republic of China).

This paper deals with the description of the various aspects faced in the design of the Archimedes Bridge prototype. The features of the selected location and the structural scheme, together with all the design requirements and design phases and outputs, are illustrated. The structural analyses aimed at investigating the prototype behaviour under the environmental loads and selecting the most suitable cable system configuration are described and the obtained results are discussed. The conception and the design of the constructional details, such as the anchoring connections, the internal and end joints, the windows are presented. The technical solution for the foundation of the anchoring system is illustrated. Finally, the fabrication and erection procedures are briefly described, they representing an important aspect of the design of such a revolutionary technological system.

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Keywords: Submerged Floating Tunnel; Archimedes Bridge; prototype; structural analyses; design; fabrication; erection

1. Introduction

The crossing of waterways still represents one of the most challenging and complex issues in Civil Engineering. Even though traditional structural solutions, such as cable-supported bridges, immersed and underground tunnels, have been successfully built all over the world, they probably reached their maximum level of development, thus requiring new and more advanced technologies to be conceived and developed in order to fulfill the need for more demanding crossings. As a matter of fact, the afore mentioned traditional structures feature many problems and disadvantages, which become more important as the distance to be covered grows up, so that the crossing of long span waterways can be, in many cases, very difficult and sometimes impossible.

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A revolutionary technical solution, perfectly suitable for the realization of very long waterway crossings, is already available: the Submerged Floating Tunnel (SFT), which is based on the idea of exploiting the load carrying capacity of water, due to the Archimedes buoyancy. In fact, SFT is conceived as a tubular structure to be placed at a pre-fixed depth in the water, so that the dead and live gravitational loads are counterbalanced by the Archimedes buoyancy. The vertical and horizontal stability of SFT is guaranteed by the presence of adequate anchoring systems, conveniently placed along the longitudinal layout of the tunnel itself.

The environmental impact of SFTs is extremely slight, since they are submerged in the water, therefore invisible. Moreover, they are stable during all the phases of construction, they being conceived as modular structures, their cost is approximately proportional to their total length and, at least from a theoretical point of view, the total length could be unlimited. Finally, since it deals with structures placed at a pre-fixed depth in the water, the slopes necessary to reach the tunnel are smaller than those required for immersed tunnels, thus also reducing the air pollution produced

The main structural aspects characterizing the Submerged Floating Tunnel solution are related to the selection of the materials, the definition of loads, the characterization of both type and configuration of the anchoring system, the conception of the shore connections, the analysis of service conditions, the evaluation of the dynamic behaviour under live and environmental load, the fatigue effects, the structural safety issues in case of extreme events (both environmental, like earthquakes, abnormal waves or currents, and accidental, like fires, internal or external explosions, deliberate attacks), the identification of adequate monitoring and maintenance operations, the definition of the construction and installation methodologies [1, 2].

The construction of a SFT, characterized by the above mentioned advantages and critical design aspects, appears nowadays as a real challenge, since it deals with a completely innovative structural solution. A probably natural wariness is due to the fact that no SFT has been erected up to today. Consequently, no experimental data on its actual behaviour are available, which could fill the gap between the theoretical studies on SFT and its construction.

Based on the above considerations, it is apparent that the first necessary step for the actual development of Submerged Floating Tunnels as a widespread technical solution for waterway crossings is represented by the design and construction of a full-scale SFT prototype, useful for collecting the necessary experimental data. This important initial step is going to be undertaken in the near future, since a Sino-Italian joint venture (SIJLAB – Sino-Italian Joint Laboratory of Archimedes Bridge) has carried out the executive design of the first SFT prototype in the World, to be fabricated and erected in the Qiandao Lake (PR of China) [3, 4]. This paper deals with the description of all the peculiar aspects of the SFT prototype design, explaining in detail the technical solutions adopted and describing the construction and installation procedures, with particular reference to the activity of the University of Naples “Federico II” team, led by Federico M. Mazzolani. A more detailed presentation is given in [3].

Nomenclature

ρ_w	density of the water
D	diameter of the tunnel or of the cables
C_D	Drag coefficient
C_I	Inertia coefficient
$u(t)$	water-structure relative velocity
$a(t)$	water-structure relative acceleration
G	sum of the structural and non structural weights of the tunnel
B	tunnel buoyancy
RB	residual buoyancy
C	dense crowd live load
d	tunnel displacement at the mid-span section

M	tunnel bending moment
N	cable axial force

2. Features of the selected location

The first SFT prototype in the World is planned to be built in Qiandao Lake, which is an artificial lake located in Chun'an County (Zhejiang Province, PR of China), whose name can be translated into “Lake of thousand islands”, since there are 1078 large islands in the lake with a few thousands smaller ones (Fig. 1(a)). It covers an area of 573 km² and it has a capacity of 17.8 km³. The lake is an important tourist area of the Zhejiang Province. This is the reason why it has been selected as the prototype location, as the prototype itself will represent a tourist attraction.

The exact location of the SFT prototype has been identified after a careful inspection in Qiandao Lake by a joint Sino-Italian committee (Fig. 1(b)). This area has some advantages for the prototype installation: it is near to a main road, which can be conveniently used for reaching the site, also by heavy trucks; moreover, there is the possibility of creating a construction yard, with none or reduced need for excavations, close to both the main road and the bay, so that the launching operations can be easily carried out.

The location of the two accesses to the prototype has been selected in order to achieve a tunnel total length equal to 100 m. The ad-hoc access structures are two “tube in tube” reinforced concrete towers completed by roofs whose structural features are inspired to the Chinese traditional architecture. They are linked to the existing main road through two approach roads, planned to be for both pedestrian and vehicular uses, respectively. A view of the Archimedes Bridge prototype, in absence of water, is depicted in Fig. 1(c).

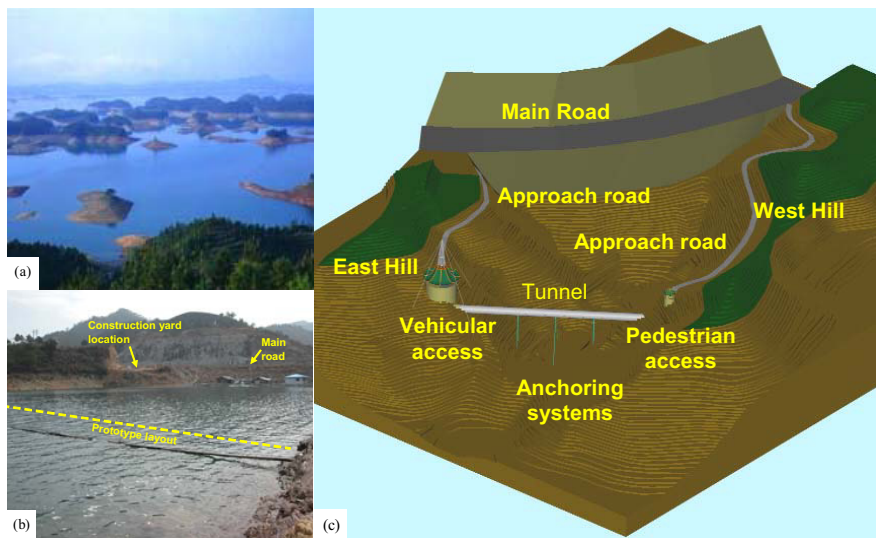


Fig. 1. (a) A view of Qiandao Lake (Zhejiang Province, PR of China); (b) Location of the SFT prototype at Qiandao Lake; (c) View of the SFT

3. The conceptual design of the Archimedes Bridge Prototype

3.1. Design pre-requisites and main features

The design of the SFT prototype in Qiandao Lake is based on some pre-requisites, summarized hereafter:

- The size of the prototype should be large enough to represent a full-scale specimen, but at the same time not too large, for allowing its suitable excitation and stress state measurement during the experimental simulations of its dynamic behaviour; moreover, the prototype dimensions have to be compatible with its final destination of use, i.e. a pedestrian tourist crossing.
- The ratio between the height of the cross-section and the whole length of the tunnel is small enough, so that experimental results can have a general validity and can be extrapolated to actual SFT structural cases.
- The buoyancy ratio, i.e. the ratio between the buoyancy and the permanent weights acting on the tunnel, has to be larger than a lower limit, set equal to 1.20, in order to ensure an adequate level of pre-tensioning to the anchoring system and larger than an upper limit, set equal to 1.30, in order to conveniently limit the permanent stress regime of the tunnel and of the anchoring system.
- The materials are selected in order to work together in a composite action so to exploit and optimize their behavioural advantages, at the same time neutralizing their defects; as a result, the cross-section is conceived to satisfy all the strength, stiffness, ductility, durability and waterproof requisites.

The total length of the SFT prototype is equal to 100 m. It is obtained by assembling five 20 m long modules, which are pre-fabricated in the yard and then assembled together in situ. The tubular structure has a multi-layer cross-section (Fig. 2(a)), composed by three different materials, thus achieving a “sandwich” configuration of the cross-section: an internal layer made of steel, an intermediate layer made of concrete and an external layer made of aluminium. Therefore a synergetic cooperation among used materials is attained. Steel is characterized by low weight, due to the small size of the structural elements, high mechanical performance and resistance to fatigue but it is vulnerable to corrosion. Consequently, it is placed in the internal part of the structure, so to exploit its high mechanical performances (tensile strength, resistance to fatigue and against impacts, large ductility) and, at the same time, to be protected from the contact with water, for corrosion prevention. Concrete is characterized by low cost, stabilizing weight against buoyancy, good response to the water environment and good mechanical behaviour in compression, but a very poor behaviour in tension. As a consequence, it is used for the intermediate layer of the cross-section, holding different tasks, such as: protecting steel from corrosion, assuring the ballast weight and cooperating with the steel pipe for the axial, bending and shear resistance of the tunnel, the steel and concrete pipes being conceived as a composite structure. Finally, the aluminium exhibits high resistance to corrosion, good mechanical resistance and workability but also poor fire resistance and low stiffness. According to this, an alveolate aluminium extrusion is used as external tube of the sandwich structure, creating a corrosion resistant layer. Furthermore, the aluminium alveolate shape works as an energy absorber in case of external impact. Moreover, the relative position of the metal layers at the internal and external sides of the cross-section proves to be advantageous also from the constructional point of view, they serving as a formwork for the concrete casting.

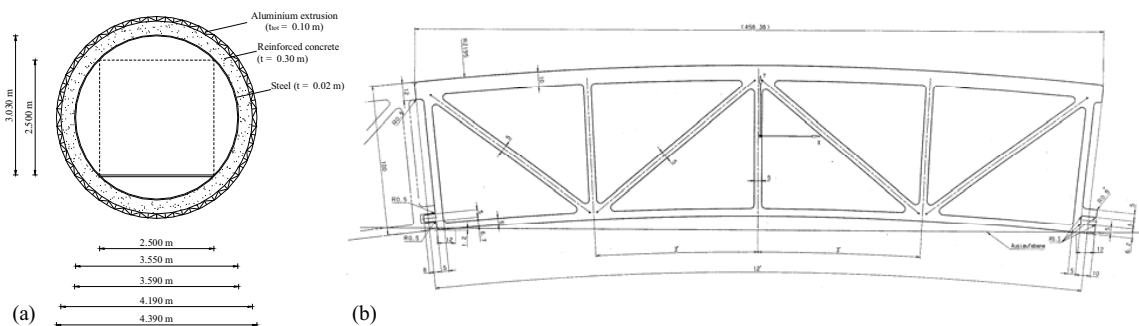


Fig. 2. (a) Tunnel multi-layered cross-section lay-out; (b) ALCAN preliminary design for the extruded aluminium elements

The materials used for the prototype are S235 steel grade, C20/25 concrete and 6061-T6 aluminium alloy.

The size of the SFT prototype cross section has been fixed in order to assure the possibility of introducing an automotive for carrying inside and install all the necessary experimental apparatus, also allowing for testing the prototype under traffic dynamic loading. The motor-way being 2.50 m in net width (Fig. 2(a)), the internal diameter

is set equal to 3.55 m. The thicknesses of the steel and concrete pipes have been assigned in order that the related self-weight of the tunnel could balance the Archimedes buoyancy, for the optimization of the residual buoyancy, which is the resultant between the tunnel self weight and Archimedes buoyancy. Based on the previous consideration, the steel pipe is 20 mm thick, whereas the concrete pipe is 300 mm thick. For what concerns the alveolate aluminium layer, whose external surface is continuous, it is obtained through assembling 30 extruded elements, 450 mm width each, which is the largest size for a 20 m long extruded element, as long as the prototype module. A preliminary design, by ALCAN, for such extruded elements is shown in Fig. 2(b). This solution is based on a classical groove-and-tongue mutual constraint on the internal side (i.e. at the concrete interface) and a continuous friction stir welding [3] on the external side (in contact with the water).

The steel and concrete tubes are designed in order to work together as a composite steel-concrete section. At this aim, 24 steel shear connectors per cross-section, 0.40 m spaced along the longitudinal axis of the tunnel, are provided. Connectors are designed as ductile devices, according to Eurocode 4 [6]. They have a 360 MPa strength, a 18 mm diameter and a 120 mm height.

The cables have a diameter equal to 60 mm and a nominal strength of 3140 kN.

3.2. The structural scheme

The SFT prototype is a straight tubular structure located at a water depth corresponding to a net water clearance ranging from 2.0 m to 10.0 m, due to the variation of the water surface level through the seasons. The tunnel axis is horizontal. It is located at 90.8 m above the sea level.

Two different restraint conditions are considered for the two ends of the tunnel, which allow the free elongation of the structure, due to thermal variations or seismic actions: at one end a fixed hinge, in which all the translational degrees of freedom are restrained; at the opposite end, only the translational degrees of freedom transversal to the tunnel axis are restrained, whereas the longitudinal displacements and the rotations are allowed.

The tunnel stability is assured by an adequate anchoring system, made of steel cables fixed at the lakebed and connected to the tunnel by means of spherical hinges. During a preliminary design of the prototype, five different cable configurations, have been analyzed and their behaviour under both vertical and horizontal loads has been evaluated by means of an equivalent static analysis and then compared [3, 9]. On the basis of the attained results, the three cable configurations shown in Fig. 3 have been selected. The analysis results have confirmed the physical predictions, showing that: vertical cables are very effective in presence of vertical actions only, whereas their restraint effect in the horizontal direction is negligible; inclined cables are very effective, both in vertical and horizontal direction, only if they are four cables in a W-shaped configuration, whereas two inclined cables only provide a not very effective restraint condition in both the vertical and horizontal direction and they give rise to a relevant torsional stress in the tunnel, when subjected to horizontal actions.

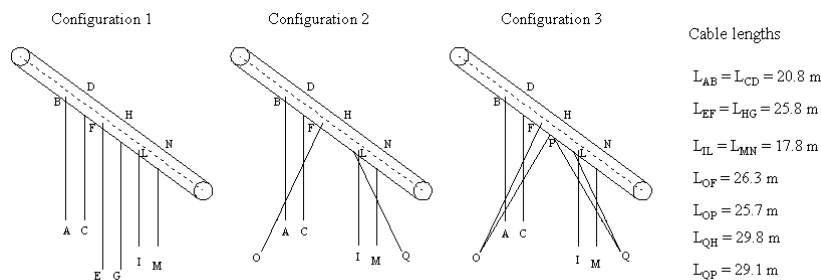


Fig. 3. The cable configurations considered for the SFT prototype

Each tunnel module should be anchored to the lakebed by means of a group of cables. However, based on the actual lakebed geometry, which is characterized by gradual depth increment from the shore to the centre of the inlet, two groups of cables have been eliminated, due to their short length (Fig. 4(a)). As a consequence, the prototype structural schemes are endowed with three groups of cables only.

The first and second ones are considered only for the sake of comparison, the most effective configuration for the prototype being evidently the third one. In any case, numerical analyses have been carried out considering all the cable configurations. In addition, the prototype is arranged to set up all the cables systems for testing.

The joints between adjacent modules of the tunnel are fully restrained, so that no relative displacement or rotation is allowed between them, and they are also designed as full strength connections.

4. Structural analyses

4.1. Structural model

The behaviour of the SFT prototype under the environmental actions has been analyzed by means of both static and dynamic analyses. The software ABAQUS [7] has been used, which allows to examine the hydrodynamic behaviour of structures immersed in a fluid by means of a specific analysis routine, namely the ABAQUS/Aqua package. The static analyses are obviously affected by some approximations, they serving as a first rough evaluation of the order of magnitude of displacements and internal forces rising in the tunnel due to the hydrodynamic loads.

The tunnel is modeled through twenty tri-dimensional quadratic beam elements. The steel-concrete-aluminium composite cross-section is modeled by an equivalent concrete section, with a total area equal to 5.1 m^2 and a moment of inertia equal to 12.33 m^4 . The cross section area is calculated through an equivalence in terms of weight, considering all the permanent loads acting in the tunnel, i.e. the weight of structural and non structural elements. The moment of inertia of the tunnel, for the sake of simplicity, is calculated considering the steel and concrete tubes only, they acting as a composite structure, through an equivalence in terms of stiffness.

Also the cables are modeled through beam elements, with a circular cross-section (nominal diameter equal to 60 mm) characterized by an area equal to 0.00249 m^2 and a moment of inertia equal to $6 \times 10^{-7} \text{ m}^4$.

Internal rigid constraints are imposed between the end nodes of the cables and the centre of mass of the tunnel cross-section, where the anchoring system is located (Fig. 4(b)). According to the assumed structural scheme, one end of the tunnel is pinned and the other one is free to have axial displacements. Geometric non-linearity is considered in the model, in order to adequately reproduce the cables non-linear behaviour and the effects of large displacements.

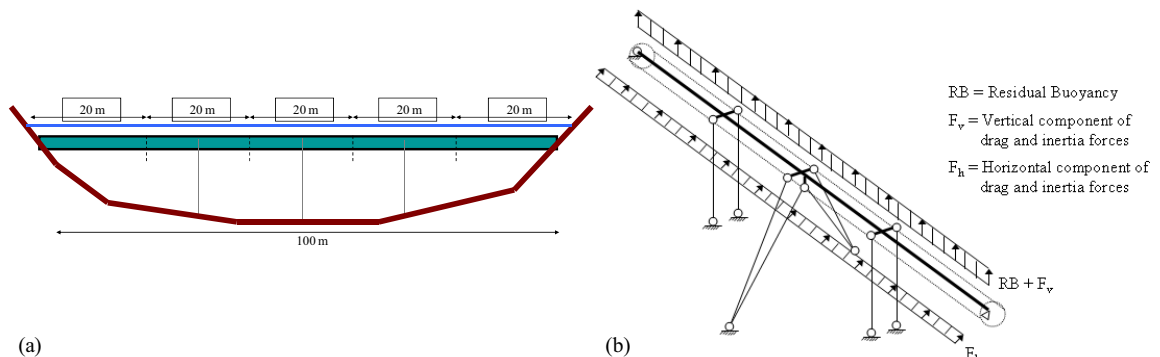


Fig. 4. (a) Longitudinal view of the prototype; (b) Structural model for the simplified static analyses (third cable configuration)

4.2. Loading conditions

In the simplified structural model for static analyses (Fig. 4(b)) both the vertical loads, corresponding to the residual buoyancy as the resultant of the self-weight and the Archimedes buoyancy, and the horizontal loads, due to waves and currents, are modelled as static distributed loads acting on the tunnel only and they are calculated a priori, therefore neglecting the effect of their direct application on the cables. The characteristic value of the self weight

(G_k), the Archimedes buoyancy (B_k) and the residual buoyancy (RB_k), together with the characteristic load corresponding to dense crowd (C_k) are indicated in Table 1.

Table 1. Characteristic values of prototype dead and live loads

G_k [kN/m]	B_k [kN/m]	RB_k [kN/m]	C_k [kN/m]
125.0	160.0	35.0	10.0

The hydrodynamic action F due to waves and currents is modelled through the Morison equation (1):

$$F(t) = F_D(t) + F_I(t) = 0.5\rho_w C_D D |u(t)| u(t) + \frac{\pi}{4} \rho_w C_I D^2 a(t) \quad (1)$$

The inertia coefficient C_I is assumed equal to 2.0 and the drag coefficient C_D is assumed equal to 1.0, these values being commonly adopted in offshore engineering practice for circular structural elements.

As far as the dynamic analyses are concerned, the special purpose ABAQUS/Aqua package allows to automatically calculate, in each instant of time, the buoyancy, the drag and the inertia loads. The drag and inertia forces are calculated by means of the Morison equation, in which, differently from the “static” case, the $u(t)$ and $a(t)$ vectors are the water-structure relative velocity and acceleration vectors, respectively.

The water velocity vector is due to the steady current and to the waves, whereas the water acceleration vector is due to the waves only. The steady current is modelled by a velocity vector parallel to the still water surface, linearly decreasing with the depth, becoming zero at the lakebed. The wave action is evaluated by the Airy wave theory, which allows to determine both the horizontal and vertical components of the velocity and acceleration at each point of the water and at each instant of time.

The field data necessary to evaluate the hydrodynamic actions were given by the Chinese team:

- wave height (H) equal to 1.0 m;
- wave length (λ) equal to 8.25 m;
- surface current velocity equal to 0.1 m/s.

with the assumption that the lakebed profile is at a constant depth equal to 30.0 m.

The consequent “static” values of the drag and inertia horizontal (F_h) and vertical (F_v) components, due to both current and waves, are, respectively, 4.875 kN/m and 4.860 kN/m.

Five load combinations are defined, according to the Eurocode 0 provisions [6]. Combinations 1, 2 and 3 are relative to service conditions under: vertical dead loads only, vertical dead loads and hydrodynamic action, vertical dead and live loads, together with hydrodynamic action, respectively. Combinations 4 and 5 are relative to ultimate conditions under: vertical dead loads and hydrodynamic action, vertical dead and live loads, together with hydrodynamic action, respectively. It is worth noticing that combinations 2 and 4 are the worst ones for the behaviour of the tunnel and the cables in tension, whereas combinations 3 and 5 are considered because they could lead to the loosening of the cables.

4.3. Analysis of results

The results of both the static and dynamic analyses are summarized in Tables 2 to 4, where the maximum displacements and internal forces are indicated for all the study cases. With regard to the tunnel behaviour, it can be noticed that generally the static analyses underestimate both the internal forces and displacements, as it was expected.

Therefore, the effect of the cable configurations on the structural behaviour is evaluated on the basis of the dynamic analyses results. It is evident that the cable configuration 3 assures the best structural performance, leading to the smallest stress and displacements demands, whereas the configuration 1 is the worst performing. In fact, as respect to the configuration 1, configurations 2 and 3 have a 48% and 64% reduction of displacements, respectively and 62% and 80% reduction of bending moments. With reference to the cable behaviour, the worst condition is related to the configuration 2, in fact the axial forces in configurations 1 and 3 have a 26% and 36% reduction as

respect to configuration 2, respectively.

The limit value for the tunnel displacements in service conditions (d_{lim}) is assumed to be equal to 0.20 m, corresponding to 1/500 of the whole length (L) of the tunnel; the design value of the ultimate bending moment of the tunnel (M_{Rd}) is equal to 70000 kNm and the design axial force strength for the cables (N_{Rd}) is equal to 1045 kN.

Table 2. Maximum displacements in the tunnel, based on the static and hydrodynamic analyses (d_h : horizontal displacement, d_v : vertical displacement; d : resultant displacement)

Cable configuration	Type of analysis	Displacements [m]			
		d_h	d_v	d	d/L
1	Static	0.018	0.027	0.033	1/3030
	Dynamic	0.092	0.019	0.094	1/1064
2	Static	0.012	0.030	0.032	1/3125
	Dynamic	0.040	0.029	0.049	1/2040
3	Static	0.008	0.025	0.026	1/3846
	Dynamic	0.025	0.022	0.034	1/2940

Table 3. Maximum bending moments in the tunnel, based on the static and hydrodynamic analyses ($M_{sd,h}$: horizontal bending moment demand; $M_{sd,v}$: vertical bending moment demand; M_{sd} : resultant bending moment demand; M_{rd} : bending moment strength of the SFT)

Cable configuration	Type of analysis	Bending Moments [kNm]			
		$M_{sd,h}$	$M_{sd,v}$	M_{sd}	M_{sd}/M_{rd}
1	Static	12408	8701	15155	0.216
	Dynamic	86270	7235	86573	1.237
2	Static	13943	5857	15123	0.216
	Dynamic	30242	12117	32580	0.465
3	Static	11817	3394	12295	0.176
	Dynamic	13650	10127	16996	0.243

Table 4. Maximum axial forces in the cables, based on the static and hydrodynamic analyses

Cable configuration	Type of analysis	Axial forces [kN]	
		N_{sd}	N_{sd}/N_{rd}
1	Static	618	0.591
	Dynamic	761	0.728
2	Static	677	0.648
	Dynamic	1030	0.986
3	Static	574	0.549
	Dynamic	663	0.634

Based on the dynamic analyses results, the following considerations can be made:

- In service conditions, the displacement limit value is not achieved in the tunnel for any cable configuration;
- In ultimate conditions, for the tunnel the safety checks in terms of bending moment are not satisfied in configuration 1; whereas the shear force checks are always satisfied;
- In ultimate conditions, the axial force in the cables is approximately equal to the design one (1045 kN) for configuration 2, whereas it is smaller for configurations 1 and 3.

Concerning the cables behaviour under the hydrodynamic actions, it must be noticed that they could undergo get loose, without any negative consequences on the tunnel behaviour.

The methodology for the seismic analysis of SFTs, developed in general and applied to the case study of the Messina Strait Crossing [10] by the team of Prof. Federico Perotti at the Technical University of Milan [9], has been

used for the analysis of the seismic behaviour of the prototype. The obtained results show that the assumed design configuration of the prototype is able to safely withstand the worst conditions expected in the area.

5. Constructional details

5.1. Anchoring connections

The anchoring system is made of three series of steel cables, which link the tunnel to the foundation. The end connections of the cables are conceived and modelled as spherical hinges. They are essentially based on a “hook” concept. Each tunnel module is equipped with three anchoring connection devices at its mid length section (Fig. 5(a)), in order to allow to set up all the cables configurations. The detail of the anchoring connection is shown in Fig. 5(b). The conception derives from the necessity of satisfying both the strength and waterproof requirements and, at the same time, of allowing an easy installation procedure, compatible with the fabrication of the whole SFT module. It is a stainless steel hook connected to the internal steel tunnel tube through a bolted system contained inside a “pyramidal” steel box, filled of cement mortar, which is placed between the steel and aluminium layers, within the concrete cast, and welded to the steel tube. This system assures the appropriate strength and stiffness of the system connection and facilitates its installation. The anchoring connections to the foundations also use hook elements, which are integrated into the cast of the foundation.

With regards to the cable ends, two different special devices are used, in order to link the cables to the tunnel and to the foundations hooks. In particular, the device at the tunnel side guarantees a pin joint behaviour, it allows an easy substitution of the cable and it gives the possibility of stretching the cable after its positioning, if necessary, whereas the device at the foundation side has a fixed length and therefore it does not allow the stretching of the cable. The “stretching” device is located at the tunnel side since it is easier to reach from the water surface.

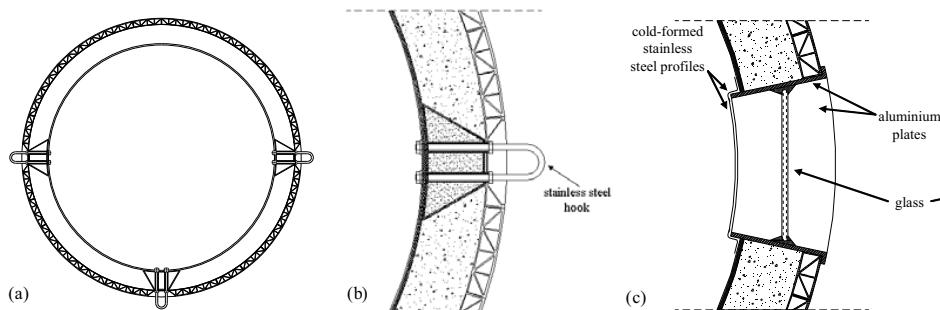


Fig. 5. (a) Cross-section where the anchoring connection devices are located; (b) Anchoring connection detail; (c) Windows detail

5.2. Windows

Two couples of windows per module are provided, in view of the tourist attraction destination of the tunnel. The design of the window detail is based on the necessity of passing from the internal steel layer to the external aluminium layer, allowing the concrete casting and guaranteeing the waterproof behaviour. The window glass is located inside a pre-assembled box made of four aluminium plates, which is inserted in the SFT module before the concrete casting is made. The assembling of the window device is completed by four cold-formed stainless steel elements on the edges of the system at the internal side (Fig. 5(c)).

5.3. Inter-modular joints

The joints between adjacent modules are designed as full strength connections, i.e. to be able of transmitting the ultimate forces and moments of the current section of the tunnel, according to the Eurocode 3 provisions [11].

The inter-modular joints for the SFT prototype are essentially bolted connections, designed for being set up and assembled when the modules are already submerged. The joint consists in two steel ring end plates, each one belonging to one of the adjacent modules. Flanges are mutually connected by means of high strength steel bolts. The bolted flanges are placed at the internal concrete and steel layers. At the external aluminium layer, a rubber ring crushed between the modules guarantees the water tightening of the connection. A sliding rubber ring is placed between steel and aluminium elements, in order to allow relative displacements due to thermal variations. The tensile forces are transmitted by the bolts in tension, whereas the compressive forces are transmitted by the contact between the adjacent steel end plates, being 40 mm thick. The design shear forces are transmitted by friction, whereas the ultimate shear force is assumed to be transmitted by shear in the bolts. 144 bolts, having a diameter of 30 mm and belonging to the strength class 10.9, are used in each joint. Details of the joint are shown in Fig. 6.

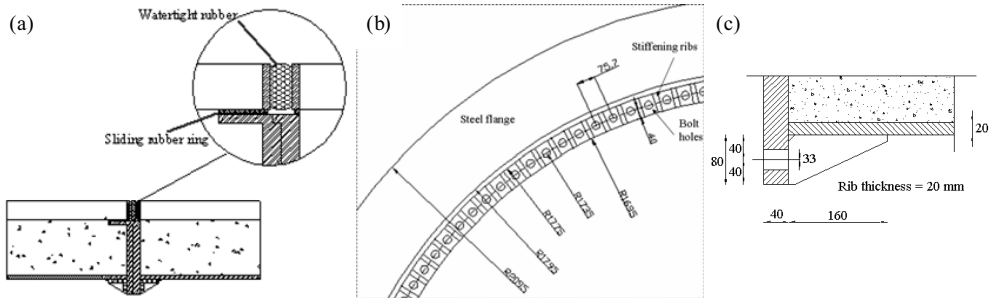


Fig. 6. Detail of the inter-modular joints: (a) rubber gaskets; (b) Bolt holes; (c) Stiffening ribs

5.4. Shore connections

The connections of the SFT prototype to the shores are made by means of special end joints, which are connected to the modules of the prototype at the extremities. One of the two end joints must behave like a spherical hinge. With regard to the displacements, the tunnel is axially linked to the shore by means of a mechanical device behaving in elastic range (with high stiffness) in service condition, but it can undergo large plastic deformations when axial forces, during a seismic event, exceed a given limit value, giving rise to hysteretic dissipation of energy. The other end joint must allow both free rotations and axial displacements, in order to give the structure the possibility of free expansion in presence of thermal variations. Furthermore, both end joints must assure the water tightening. The design of the end connections fulfils all the mentioned requirements. It is based on the concept of separating the waterproof and mechanical functions of the device (Fig. 7(a)). The constructional solution of this system has been developed in cooperation with ALGA, leading to the output shown in Fig. 7(b).

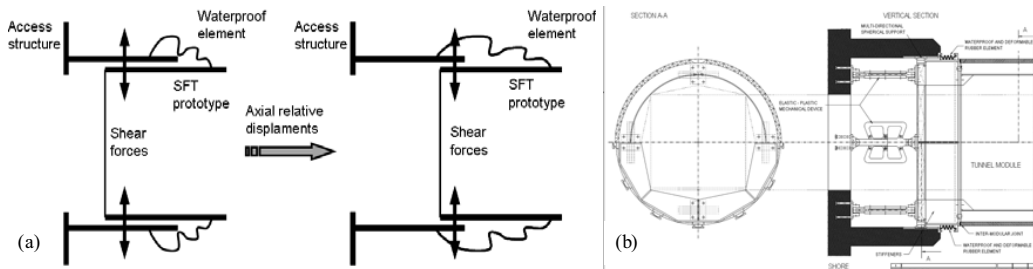


Fig. 7. (a) Conceptual design of the tunnel end joints; (b) ALGA design solution for the end connections of the SFT prototype

6. Foundations

The anchoring system is fixed to gravity foundations at the lakebed, which are designed to withstand the upward forces transferred by the anchoring cables by means of their self-weight, taking account of the buoyancy. A single foundation block is designed per couple of cables, namely “coupled block”, whereas separate foundation blocks are used for the inclined cables, namely “single block”.

The gravity foundation typology has the advantage that the blocks can be partially pre-fabricated in the construction yard in the initial configuration, which should guarantee the necessary buoyancy to be towed on site by a towboat. The technical solution consists of foundation blocks composed of a pre-cast and a in-situ cast part. The pre-cast part of the foundation is essentially an empty open box made of reinforced concrete walls. Once towed to its final destination, it is then filled with concrete, in order to get increasingly heavier up to reach the lakebed and then achieve the design weight for foundation stability. The pre-cast structure is endowed with stiffening reinforced concrete ribs. At the intersections between perpendicular ribs, a special reinforcement is located, for anchoring the cable connection device to the concrete block.

7. Fabrication and erection

All the construction phases, from the fabrication of the modules to the installation in the Lake, have been studied in detail and fitting practical solutions have been developed, as briefly described hereafter.

The 100 m long tunnel is made of five 20 m long pre-fabricated modules, which are built in the construction yard. The construction of each module is carried out according to the following steps:

- (1) The internal steel tube is obtained by using five 4 m long tubular sub-elements. Each of these sub-elements is obtained starting from steel sheets (20 mm thick) whose extreme edges are butt-welded after bending (Fig. 8(a)). After the set up of the sub-elements, they are mutually welded in the transversal direction (Fig. 8(b)). Steel shear connectors are then welded to the external surface of the steel tube.
- (2) Once the steel tube is ready, a steel closure plate is welded at its base, then it is put in vertical. The aluminium layer, composed of 30 extruded elements, is placed around the steel tube, so creating a couple of vertical concentric cylinders (Fig. 8(c)). The aluminium elements are adequately coated on the internal side, in order to avoid any danger of electro-corrosion due to the contact with the concrete.
- (3) The steel and aluminium cylinders are used as a formwork for the concrete casting. After this operation, a steel plate, prepared for setting up the inter-modular joint, is located on the top. The complete module is put in horizontal and then it can be launched.

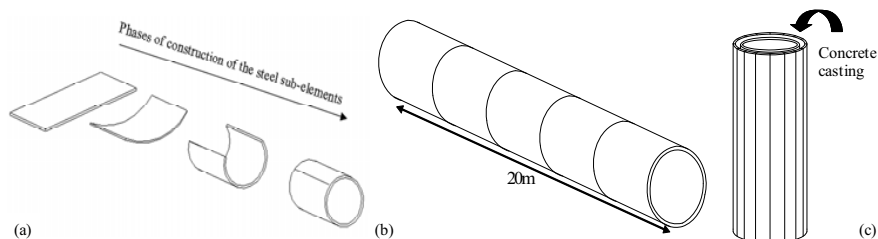


Fig. 8. Fabrication of SFT modules: (a) Steel tube sub-element; (b) Complete steel tube; (c) Concrete casting

The erection procedure for the SFT prototype is carried out according to the following steps:

- (1) Set up of the construction yard.
- (2) Construction of the vehicular and pedestrian approach roads.
- (3) Set up of bulkheads made of steel piling in the areas where the access structures are erected, in order to allow the construction in dry conditions. Subsequent water suction from these areas through pumps. Contemporary construction in the yard of cable block foundations.
- (4) Construction of the reinforced concrete access structures in the suctioned area.
- (5) Transportation and positioning of the foundation blocks. Contemporary construction of the prototype modules.

- (6) Set-up of the special end joints at the access structures.
- (7) Launching of the SFT prototype modules and connection between them.
- (8) Set up of the anchoring system.

As already pointed out, although the target configuration is the one with two couples of vertical cables and a W-shaped cables system (cable configuration 3), also the other two cable configurations will be sequentially set up, in order to compare their behavioural differences.

8. Conclusive remarks

This report presents main aspects of the design of the Submerged Floating Tunnel prototype (also called Archimedes Bridge prototype) to be erected in Qiandao Lake (Zhejiang Province, PR of China). The design has been carried out within a cooperation between Italian and Chinese institutions, in the frame of the Sino-Italian Joint Laboratory of Archimedes Bridge (SIJLAB), whose main partners are the “Ponte di Archimede International” Company, the University of Naples “Federico II”, the Technical University of Milan and the Chinese Academy of Sciences – Institute of Mechanics. The realization of the prototype represents an important step in the development of the SFT technology. In fact, despite the evident advantages of such an innovative solution for waterway crossings, no Submerged Floating Tunnels have been built in the World yet, mainly due to the absence of experimental data, which are fundamental for removing the natural psychological scepticism.

The cross-section of the tunnel is of a sandwich type, made of steel, concrete and aluminium layers. This choice allows the exploitation of the advantageous properties of different constructional materials by neutralizing, at the same time, their negative peculiarities. The geometry of the prototype has a straight layout and it is stabilized by an adequate anchoring system, made of steel cables, located at three different sections of the tunnel. Three cable configurations are selected for testing and their behavioural characteristics will be compared. The behaviour of the SFT prototype in presence of the hydrodynamic actions has been predicted by means of both simplified and refined hydrodynamic analyses. These numerical results will be checked by the in-situ dynamical structural identification.

The constructional details are carefully conceived and their basic principles, together with their main peculiarities, are shown. In particular, the attention is focused on the connections between the tunnel and the anchoring cables, on the inter-modular joints, on the special dissipative joints between the tunnel and the shores and on the window details. The conception of the fabrication and erection procedures is studied and described in detail, starting from the construction of the tunnel modules up to the complete installation in the Qiandao Lake. A system of partially pre-cast reinforced concrete foundations has been also designed, conceiving its installation procedure.

In conclusion, the set up of the first SFT prototype in the World can undoubtedly be considered a revolutionary event, which links the past, characterized by the “theoretical” studies / designs of SFTs, to the near future, where the use of this technology for waterway crossings will become a challenging reality.

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