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The conceptual design of a roadway SFT in Baja California, Mexico

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Abstract

The Submerged Floating Tunnel (SFT) is an innovative water crossing solution under development. It is considered convenient against conventional structures for wide and deep water crossings. SFT is environmentally friendly, as it is submerged, and cheap over long distances thanks to modularity. No SFT has been constructed yet, however many feasibility studies have been proposed worldwide. The improvement of offshore and tunnel engineering provides important tools for making SFT a reality in a near future.
This paper describes the conceptual design of a SFT for crossing the Gulf of California linking the mainland of the northwest of Mexico to the Baja California peninsula. This represents a great challenge due to the severe environmental and territorial conditions, with distance longer than 100km and sea depth up to 3km. Together with structural and environmental design issues, leading to the selection of the location of the SFT, the cross section types, the anchorage and foundation systems, the access structures are defined also through a focus on the specific structural safety measures and safety equipment required for the tunnel service.

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Keywords: Water crossing of the Gulf of California; Submerged Floating Tunnel; Environmental design features, SFT design and safety issues .

1. Introduction

The motivation for building a Submerged Floating Tunnel in the Gulf of Baja California comes from the geographical configuration of Mexico. In the northwest of the country, the long Peninsula of Baja California has rather difficult connections to the mainland. The most used transport systems to link the peninsula to the mainland are planes and ferries, as travel by roads is really too long. In addition, the plane and ferry routes are limited to some airports and harbors only. As a consequence, the Baja California Peninsula is isolated in a great part of the territory,

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despite the fact that some of the virgin regions could be advantageously exploited for developing tourism, agriculture, aquaculture, mining and other profitable activities. The future exploitation of these opportunities strictly depends on the realization of a water crossing fix connection. In this perspective, after analyzing traditional solutions like subsea tunnels, the Submerged Floating Tunnel was selected as realistic and suitable choice [1,2] for crossing the Gulf of California and finally link the peninsula to the Mexico mainland. The paper presents in a first part the comprehensive environmental characterization of the site for the selection of the location and the subsequent definition of environmental loads, in a second part the main design issues of the tunnel, leading to the conception of a possible configuration [3].

2. Environmental conditions

2.1. General features of the gulf of California

The Gulf of California is an extension of the Pacific Ocean located between the Peninsula of Baja California and the northwestern Mexico (Fig. 1a). The Peninsula is more than 1500km long with widths varying from 92 to 222km. The sea surface of the Gulf covers approximately 247000 km^2, with depths exceeding 3km. At the south it is opened to the Pacific Ocean, which largely determines the climate and oceanographic features. The geomorphologic environment of the sea area is a complex structure characterized by submarine basins produced by a series of tectonic faults [4] (Fig. 1 b, c), which were caused by the separation of the Baja California Peninsula from the mainland, with average speeds of 4-6cm/year. It is estimated that the formation began about 4 to 5 million years [5]. Furthermore, tides in the gulf are very peculiar and are among the largest in the world. The fluctuations are measured up to 9m at the north. The sea of the Gulf has a huge concentration of microscopic organisms and extraordinary biological diversity due to abundant sunlight and nutrient-rich waters. These factors, as well as the crystal clear waters, inspired the name of "the world's aquarium."

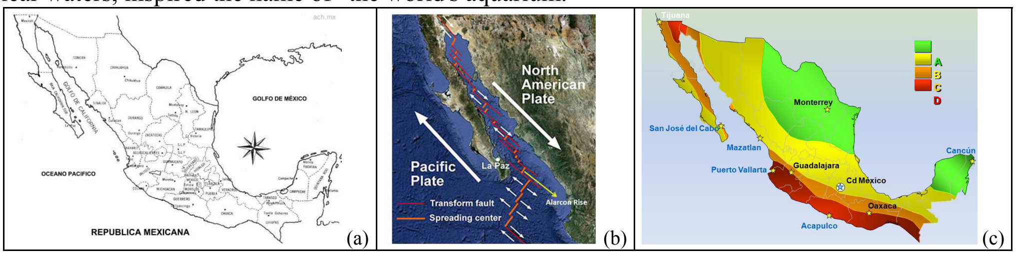


Fig. 1: (a) Map of Mexico (ArchMX), (b) Regional tectonic map [4], (c) Seismic zone map of Mexico [6].

2.2. The selection of the SFT location

The main selection criteria for the location of the SFT are related on one side to the limitation of the depth, in order that the anchorages could be feasible and guarantee the opportune lateral stiffness for the SFT structure, on the other side to the preservation of the natural protected areas (Fig. 2).

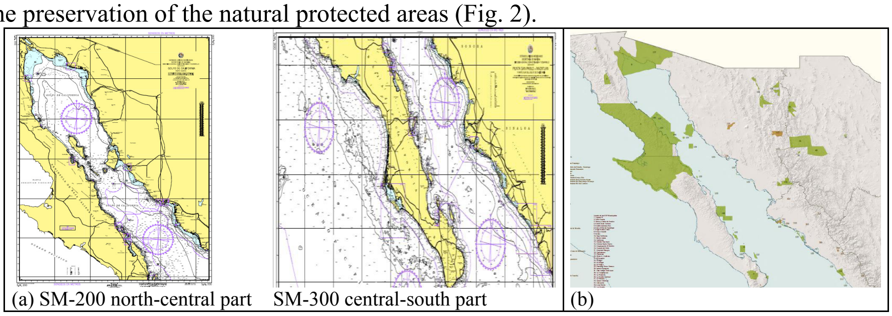


Fig. 2: a) Nautical charts of the Gulf of California published by the Army of Mexico [7], b) Natural Protected Areas of the Gulf of California [8].

The seabed profiles are obtained from the bathymetry of the Gulf (Fig. 2a, b), which has been elaborated through the software AutoCAD 2011, called CivilCad2011, for obtaining a bathymetry grid, as the base for drawing the sections in any part of the Gulf, giving the length and the depth at any point (Fig. 3).

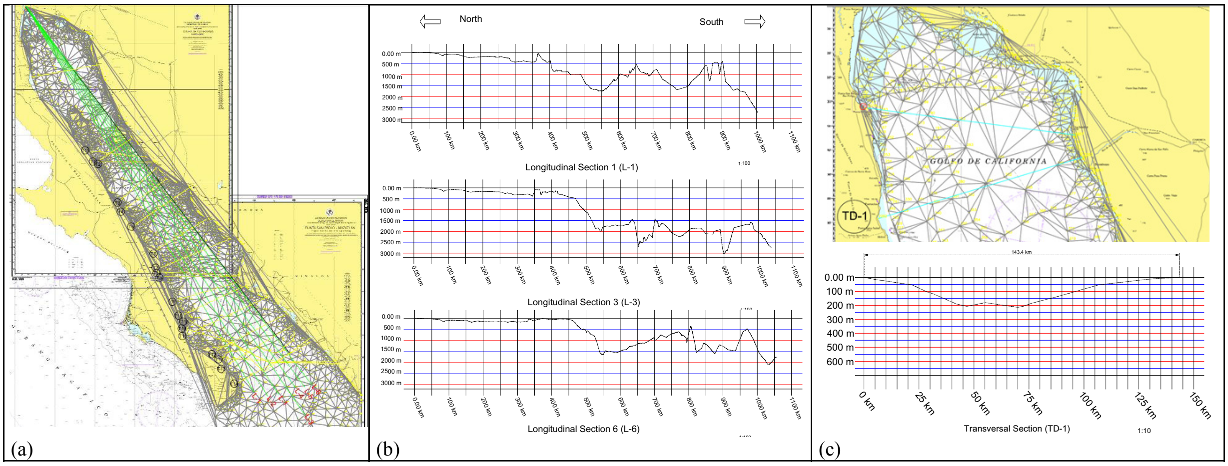


Fig. 3: (a) Plan view of the longitudinal and transversal sections in the Gulf of California; (b) typical longitudinal sections; (c) selected SFT location.

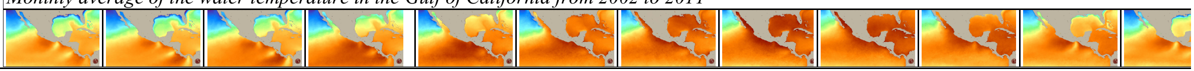
Along the longitudinal sections from the north to the south, the Gulf of California can be subdivided in four main areas [9]: the North area with a maximum depth of about 200m; the Northern Middle area with a maximum depth of roughly 400m; the Southern Middle area with depths up to 1000m; the South area with depths up to 3000m.

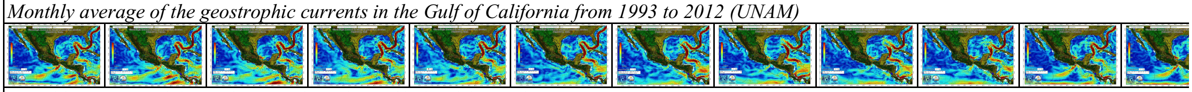
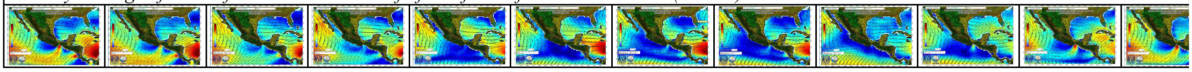
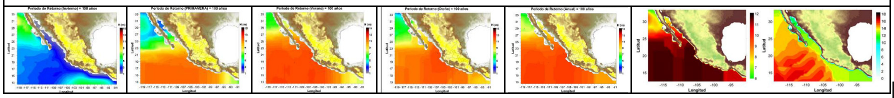
For the SFT location, according to the depth criteria, assuming as limit the reference depth of 400m, the North and the Northern Middle areas of the Gulf have been examined. In addition as the Northern Middle area was limited by several Natural Reserved zones, definitely, the suitable crossing location was found, as shown in Figure 3c.

2.3. The required environmental data

As the SFT waterway crossing is offshore located, the environmental information required for the design of offshore structures would be the guide for collecting data about the natural state of the Gulf of California related to the feasibility of a SFT. They are listed in Table 1, where the source institutions are also identified.

Table 1. Summary of the collected environmental data at the Gulf of California

Environmental data	Source institution
The seabed depths	Department of Oceanography and Climatology of the Navy of Mexico
Soil type	Mexican petroleum company [10]
Geological Faults	National Autonomous University of Mexico (UNAM)
Seismicity for ground acceleration	National Commission of Electricity from Mexico (CFE)
Water temperature	National commission for the knowledge and the biodiversity use (CONABIO)
Monthly average of the water temperature in the Gulf of California from 2002 to 2011	
	
Currents Winds velocity	Atmospheric Centre of Science of the National, Autonomous University of Mexico

Monthly average of the geostrophic currents in the Gulf of California from 1993 to 2012 (UNAM)	
	
Monthly average of the surface winds in the Gulf of California from 1999 to 2006 (UNAM)	
	
Tides	Center for Scientific Research and Higher Education of Ensenada [11] and National Oceanographic Service of the Geophysics Institute from UNAM
Maximum wave height and wave period, Storm conditions	National Autonomous University of Mexico (UNAM)
Wave height maps in a return period of 100 years (Rivillas, 2008)	
	[12]
Vessel traffic	Secretariat of Communications and Transportation from Mexico [13] and Port Authority of Baja California Sur [14]
	
Protected Natural Areas	National Commission of Natural Protected Areas [8]

For the selected location, both the normal (NC) and the extreme (EC) environmental conditions in the Gulf are considered. Furthermore, the maximum historical values for some of the more relevant features of the sea state have been found. The environmental data in the selected SFT location are summarized in Table 2. Considering the length of about 150km, data are given every 25km. The design of the structure is governed by the most severe values.

2.4. Comparison among extreme conditions of the main SFT study sites

The environmental conditions of the main sites where feasibility studies have been proposed are compared in Table 3 with reference to the most severe events, in terms of wave and current. The sites are the Qiandao Lake (China), the Jintang Strait (China) and the Messina Strait (Italy), which represent mild, intermediate and severe conditions respectively [15-18]. Seabed depths and water clearances are also given. From Table 3 it can be observed that the environmental conditions of the Gulf of California are among the intermediate (Jintang Strait) and the most severe conditions (Messina Strait) in terms of wave features, besides, the current velocity is lower. Hence, being the environmental conditions at the selected location in the Gulf of California comparable with the ones of the existing case studies, the results of the hydrodynamic study carried out by Martire et al. [19,20], evaluating the behavior of different SFT types, have been used as a base for the design choices in the California Gulf. In particular the anchorage configuration in Figure 4, showing the best behavior against hydrodynamic actions, has inspired the SFT in the Gulf of California [21]; as the same with regards to the structural performance against seism [17-20].

Table 2. Summary of the environmental conditions at the selected location, at different depths

Environmental conditions	0-25		25-50		50-75		75-100		100-125		125-143.4	
	NC	EC	NC	EC	NC	EC	NC	EC	NC	EC	NC	EC
Type of ground under seabed												
at 0-100m	Clays, Siltstones		Sandstones		Sandstones		Sandstones, Clays, Siltstones		Sandstones, Clays		Sandstones, Clays	
at 100-200m	Siltstones, Sandstones						Sandstones		Clays, Siltontes		Clays, Siltstones	
Peak Ground Acceleration [cm/s²]	*0.86*											
Temperature [°C]												
at surface	16-32											

at 150m depth	-		5 - 16						-		-	
Winds [m/s]	*7*	*30.8*	*6.5*	*33.6*	*4.5*	*36.4*	*4*	*36.4*	*4*	*39.2*	*5*	*42*
Currents [m/s]												
at surface	0.32	1.4	0.28	1.4	0.28	2.2	0.26	2.3	0.30	2.9	0.30	2.5
at 25m depth	0.21	0.9	0.25	1.23	0.25	1.9	0.22	2	0.21	2	0.0001	0.0001
Tides [m]												
Mean Higher High Water	*2.10*	*3.83*	*2.10*	*3.83*	*2.10*	*3.83*	*2.15*	*3.14*	*2.15*	*3.14*	*2.15*	*3.14*
Mean Lower Low Water	*-2.02*	*-3.12*	*-2.02*	*-3.12*	*-2.02*	*-3.12*	*-2.14*	*-3.15*	*-2.14*	*-3.15*	*-2.14*	*-3.15*
Maximum amplitude	*4.12*	*6.95*	*4.12*	*6.95*	*4.12*	*6.95*	*4.29*	*6.29*	*4.29*	*6.29*	*4.29*	*6.29*
Wave												
height (Hw) [m]	6	8	6.5	8.5	6.5	8.5	6.5	9	7	9	8	9.5
period (Tw) [s]	3	8	3	12	4	12	4.5	12	5	10	5	8
length (λw) [m]	14	99.8	14	224.6	25	224.6	31.6	224.6	39	156	39	99.8
Minimum clearance above the SFT [m]	*25 m*											
NC: Normal Condition; EC: Extreme Condition												

Table 3. Comparison between locations for SFT proposals

Site	Condition	Depth [m]	Clearance [m]	Wave			Current
				Height [m]	Length [m]	Period [s]	Velocity [m/s]
Qiandao Lake	Mild	30	2	1,0	8,25	2,3	0,1
Jintang Strait	Intermediate	100	25	5,8	76,5	7,0	4,1
Messina Strait	Severe	200	30	13,5	200	11,5	3,45
Gulf of California	Intermediate-severe	213	25	9,5	99,8	8,0	2,9

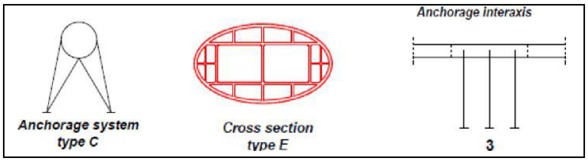


Fig. 4. The assumed anchorage configuration type for the SFT [21].

3. Structural Issues

3.1. Cross Section Geometry

The maximum length of the past proposals is about 4km, while the SFT length in the selected location of the California Gulf have a much larger length of about 150km, which is another degree of magnitude. Therefore much severe safety requirements should be accomplished, they being related to either structural, or functional, services, psychological, emergency issues. With these regards tunnel design codes from America, Europe, Asia and Mexico have been examined [3], together with the main innovative features of the longest and most modern railways and roadway tunnels in the World. In Table 4 the 5 longest tunnels, one per country, are listed. Considering the acquired information, the design of the cross section for the Baja California SFT is based on the requirements given hereafter.

Table 4. Selection of the 5 longest tunnels, one for every country [Wikipedia / List of long tunnels by type]

Name	Location	Length in km (mi)	Year Completed	Line

Railway tunnels				
Gotthard Base Tunnel	Switzerland (Alps)	57.1 (35.5)	2016	Gotthardbahn
Seikan Tunnel	Japan (Tsugaru Strait)	53.9 (33.5)	1988	Kaikyo Line (Hokkaidō Shinkansen)
Channel Tunnel	France/UK (English Channel)	50.5 (31.3)	1994	Channel Tunnel
New Guanjiao Tunnel	China (Qinghai)	32.645 (20.3)	2014	Qinghai–Tibet Railway
Guadarrama Tunnel	Spain (Sierra de Guadarrama)	28.4 (17.6)	2007	LAV Madrid - Valladolid
Roadway tunnels				
Lærdal	Norway (Lærdal - Aurland)	24.51 (15.2)	2000	E16
Yamate Tunnel	Japan (Tokyo)	18.20 (11.3)	2007-10-15	C2, Shuto Expressway
Zhongnanshan Tunnel	China (Shaanxi)	18.04 (11.2)	2007	G65, Xi'an-Zhashui Expressway
St. Gotthard	Switzerland (Uri - Ticino)	16.918 (10.5)	1980	A2/E35
Arlberg	Austria (Vorarlberg - Tyrol)	13.972 (8.7)	1978	S16/E60

According to the module production used in the immersed tunnels technology, a rectangular shape of the standard cross-section can be assumed, 32m wide and 12m high, the module being 200m long (Fig. 5a). For improving the hydrodynamic behavior of the cross-section under extreme environment condition, “ad hoc” triangular shaped lateral steel wings are added. Emergency lines along the tunnel are the minimum requirements for tunnel safety in the European Union [22]. Double wall sections on the perimeter can protect the transport lines in case of out or inside collisions, identifying a cellular barrier, whose cells can be filled with ballast in order to regulate the buoyancy ratio.

A special cross-section, the module being 100m long, should be located every 6km, in order to discontinue the monotony of the journey (Fig. 5b). The special module is larger than the standard one, it being 61.75m wide, accommodating either parking areas, or services stations, equipped with first aid facilities and toilets, or technical rooms for the tunnel operating system, like electrical and mechanical plants. Not least a pedestrian area is added, according to the Mexican code for the parking areas design [13]. A total of four first aid spaces are placed along the special cross-section, two in each directions. A transition module, 40m long, should connect the special to the standard module.

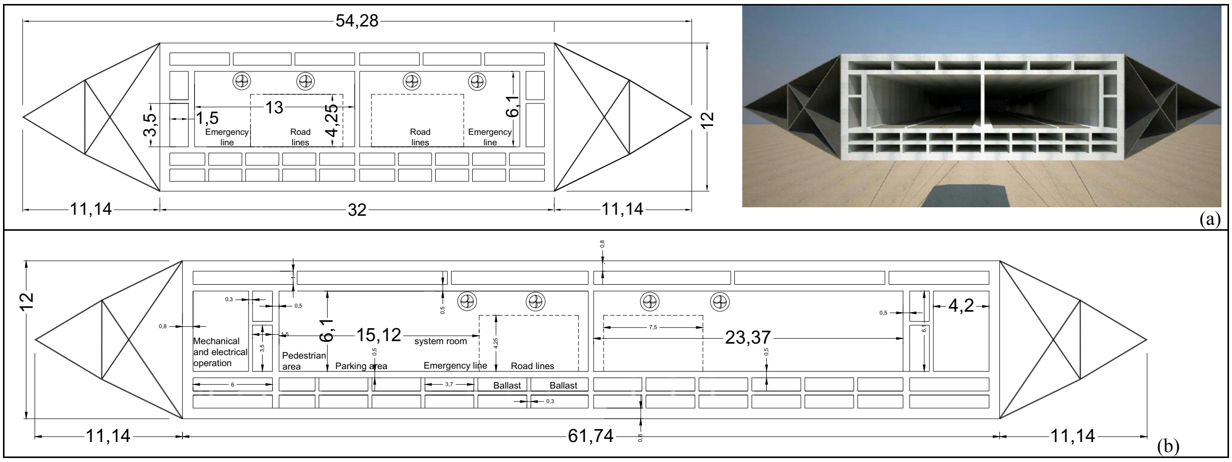


Fig. 5. (a) Standard; (b) special cross section [m].

Due to the considerable length of the tunnel, two points for evacuation are a necessary safety requirement. They can be realized through two towers groups (Fig. 6), with helidecks on the top, 4 towers - 2 helidecks for each group. They are located at two special modules and in addition to the evacuation function, they contain further rest areas, with restaurants, shops and belvederes for breaking the monotony of the long driving along the tunnel.

From the structural point of view, the SFT design materials can be C20/25 reinforced concrete for the rectangular cross-section and S235 steel for the triangular shaped lateral parts. In Table 5 design loads and residual buoyancy values are given in both standard, special and transition section cases, both as distributed and total loads.

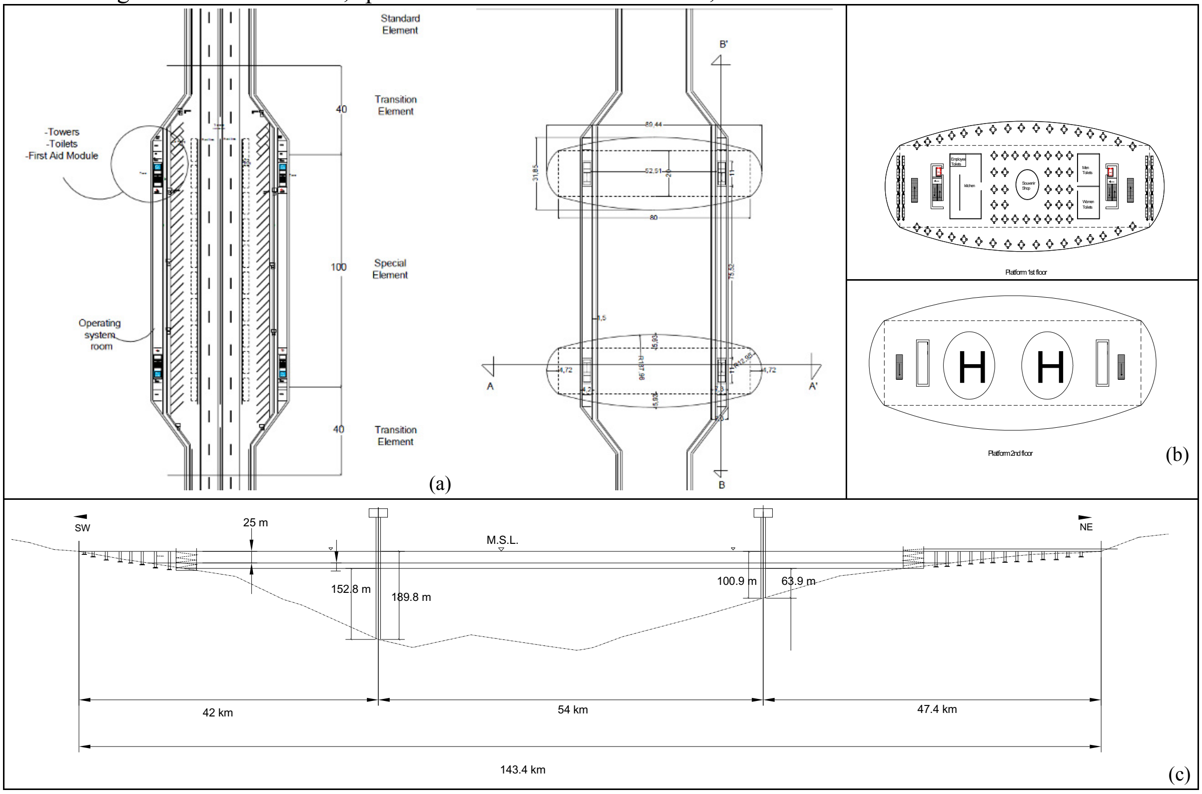


Fig. 6. (a) Longitudinal distribution of the SFT at the towers location; (b) Tower platform services; (c) Schematic longitudinal view of the SFT.

Table 5. Design loads and Buoyancy values

Element		Weight			Live Load	Buoyancy	Residual Buoyancy RB		Buoyancy Ratio BR	
		Concrete	Steel	Facilities		Archimedes	RBmin	RBmax	BRmin	BRmax
Standard	[kN/m]	3041	408	51	720	5329	1109	1829	1.26	1.52
	[kN]	608220	81640	10140	144000	1065804	221804	365804	1.26	1.52
Special	[kN/m]	5603	408	100	1000	8956	1844	2844	1.26	1.47
	[kN]	560307	40820	10000	100000	895551	184423	284423	1.26	1.47
Transition*	[kN]	163323	16328	2028	28800	273911	63431	92231	1.30	1.51

*not available per unit length

3.2. Anchorage system and foundation

The SFT of the Gulf of California can be anchored by steel cables to gravity foundations made of concrete boxes laying on the seabed (Fig. 7). This configuration is considered the easiest and fastest construction process [21].

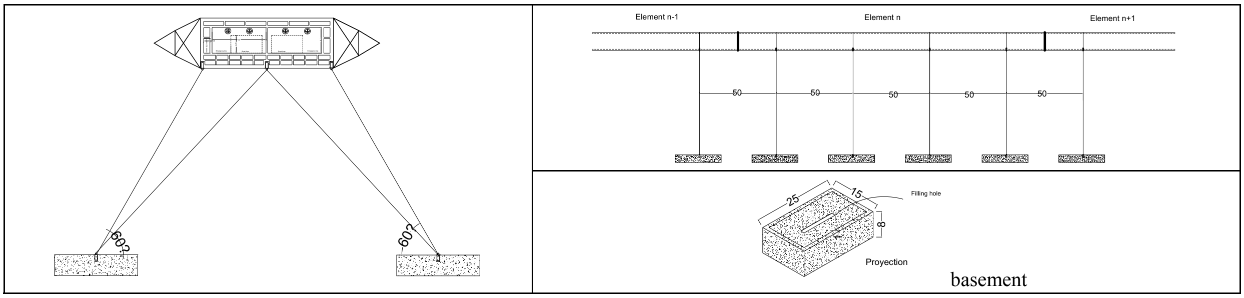


Fig. 7. Anchorage configuration [m]

A total of four anchorage systems are provided along the longitudinal axis per each standard module with constant spans of 50m in-between; while, the special module is supported by 3 anchorage systems in order to have roughly the same span between systems. The transition module is supported just by one anchorage system.

Two basement blocks should be necessary per each cable system. The buoyant concrete boxes, with standardized dimension of 15m x 25m x 8m, can be precast in site and then transported on water to the final position, where they are filled with ballast concrete for sinking them to the seabed. The cable system must be able to resist the tensile axial force generated by the residual buoyancy of the SFT. Thereby, the foundations as well as the cable must be designed for the maximum residual buoyancy, in absence of live load. The forces taken into account for the design of the anchorage system corresponding to the maximum buoyancy are given in Table 5. The real weight of the basement block is bigger than the maximum residual buoyancy, with a safety factor is 1.5.

As a preliminary design, the commercial cables with 180mm diameter and ultimate load of 31,000kN have been selected, by assuming a safety factor of 1.3. In addition the group of cables is designed to resist the buoyancy acting either if one cable fails or if it is temporary removed in case of maintenance.

3.3. Access Structure

The SFT of the Gulf of California may be placed 25 meters under the mean sea level in order to allow the shipping traffic in the area. The type of the access structure has been decided after analyzing different solutions and comparing their feasibility. A cylindrical structure containing a helicoidally shaped ramp has been proposed (Fig. 8). It allows connecting the land roadway to the SFT level, which is located at a depth of about 25m below the sea surface. The connection between the land roadway and the access ramp can be realized through a viaduct (Fig. 6). This solution abruptly reduce the cost as respect to the case of a transition underground tunnel, moreover it allows reducing the SFT net length from 143.4 to 112 km.

The geometry of the ramp that contains two road lines has been designed according to the Mexican codes [13].

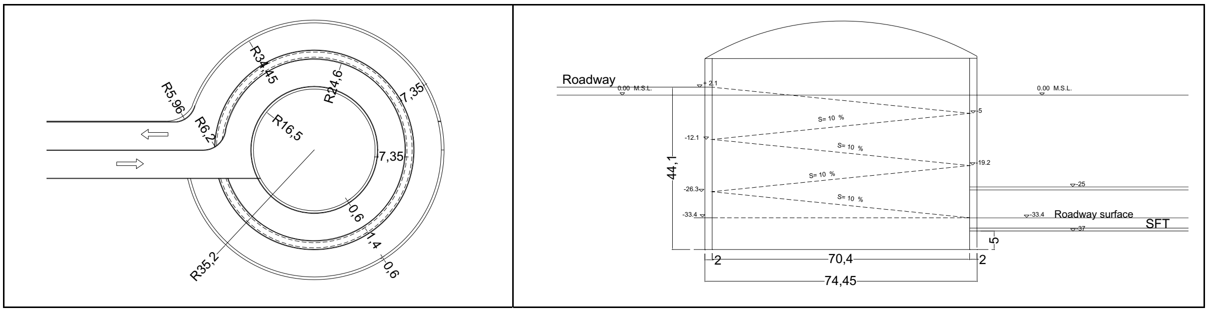


Fig. 8. Geometrical design of the access structure [m].

3.4. Towers and service platform

Nowadays the safety requirement is a key issue to take in account in tunnel design since the beginning of the design process, whatever the tunnel typology is, such as subsea, immersed or a land tunnel. As a general principle, a tunnel must be safer than open roadways, particularly in case of long dimensions.

The case of Submerged Floating Tunnels is a special example, with the extra concern that the structure is surrounded by water, which could produces further psychological reactions in the users.

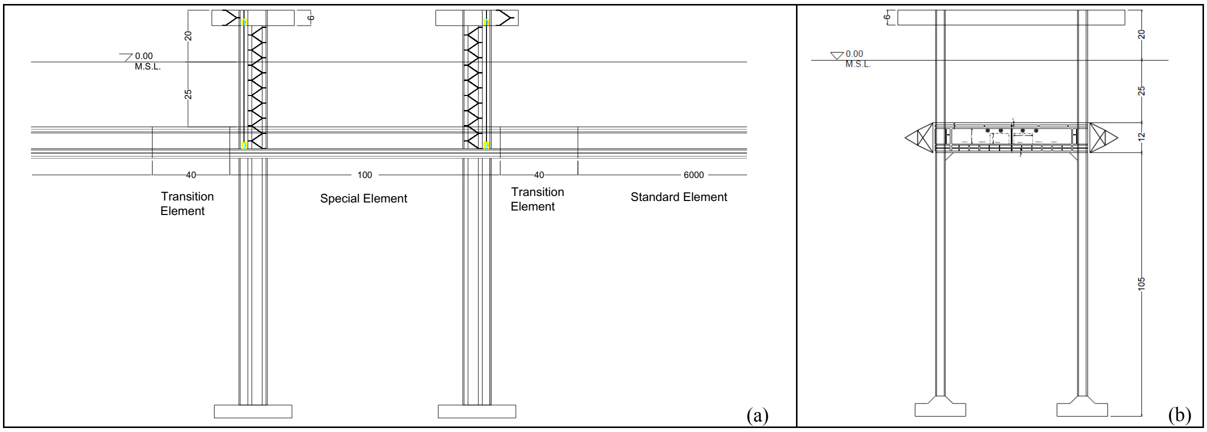


Fig. 9. Configuration of the towers in the special element: (a) longitudinal; (b) transversal view.

In the specific case of the California Gulf SFT, the length of 112km is about twice the one of the longest tunnel in the world, the St Gotthard tunnel in Switzerland, 57km long, even though it is just for railway use, and four times longer than the longest road tunnel, the Laerdal Tunnel in Norway, 24.5 km long.

The evacuation during the emergency is one of the main safety requirements. In the examined case, it has been solved by locating the two towers groups at a strategic distance, which almost symmetrically divide the total length of SFT (§3.1). From the structural point of view, these structures could provide horizontal and vertical stiffness to the SFT. The configuration and location of the evacuation towers assumed are shown in the Figure 6 and Figure 9.

4. Conclusive remarks

The SFT seems to be suitable for realizing a fix connection of the peninsula of Baja California to the Mexican mainland. The paper presents the synthesis of the feasibility study carried out, which derives from a close examination of all the aspects related to the realization of a long tunnel floating and submerged, from the safety, to the psychological reaction, from the structural to the functional design points, the type of surface navigation, the environmental conditions, by also taking advantages of the similarities with consolidated structural types like underground or immersed tunnels and offshore structures. Once again SFT proves to be a high potential structural solutions for water crossings. A definitive study should deepen all the structural and functional aspects, the cost (including the realization), the social, economic and financial impacts on the region. Of course the construction of a prototype could definitely fix any uncertainties, affirming the significant value of the innovative solution.

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