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Compared cost evaluation among traditional versus innovative strait crossing solutions

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Abstract

Among the traditional solutions in use to cross waterways Cable Supported Bridges (CSB), such as suspension and cable stayed ones, nowadays represent one of the most widely realized. However this structural typology feature several problems, in particular when large spans have to be surpassed. Submerged Floating Tunnel (SFT) is instead an innovative technical solution in the field of waterway crossings, particularly suitable and advantageous in case of long waterway crossings. As a matter of fact, thanks to its modularity, the SFT structural performance is not greatly affected by the crossing length; also, its cost varies linearly with its length, differently from Cable Supported Bridges.

At the stage of selection of the structural solutions to be adopted a decisive role is played by economic aspects. In particular, the building cost of each available solution has to be assessed in order to come to the final choice. Therefore simple procedures for the evaluation of the realization cost of the crossing solutions are needed; such a kind of procedures, considering only the costs related to quantity of steel, are already available for traditional Cable Supported Bridges. The scope of the present study is to provide a similar procedure for Submerged Floating Tunnels, thus allowing for quickly comparing the cost-effectiveness of the latter solutions with the one of traditional CSB solutions. Some crossing examples are also provided, highlighting the conditions where the SFT innovative solution proves to be more economically competitive than traditional ones (CSB).

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Keywords: submerged floating tunnel; cable supportde bridge; cost assessment

1. Introduction

Waterway crossings represent one of the most important issues of the modern civil engineering, as new and longer crossings are demanded in several places all over the world. Cable Supported Bridges, such as suspension and cable stayed ones, nowadays are the most suitable solution to cross large distances. However, in case of waterway crossings the presence of water can represent a circumstance to take advantage of, instead of considering it just as an obstacle to get over; this is the main idea which led to a new concept of cable supported bridge: the Submerged Floating Tunnel (SFT).

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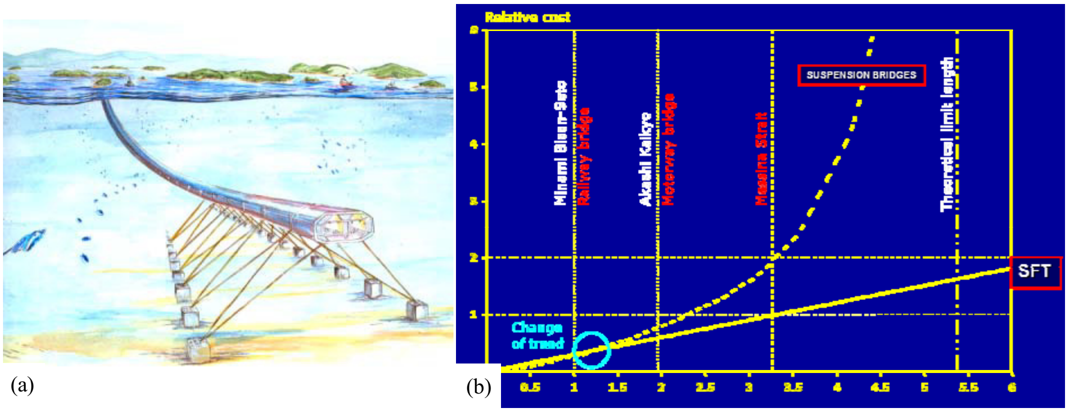
SFT fundamentally consists in a tubular structure floating at an immersion depth, fixed in position through anchorage systems made up of groups of cables or tethers connected to the seabed (Fig. 1(a)). The tunnel is made up of prefabricated modules assembled in situ; each module is provided with at least one anchoring group. The SFT is permanently subjected to a positive upward residual buoyancy, providing the necessary pre-tensioning to the anchorage system [1, 2].



(a) (b)

Fig. 1. (a) Longitudinal views of the Jintang Strait (China) SFT crossing [1]; (b) Qualitative cost trend curves for SFTs and SBs

The SFT solution presents several advantages with respect to traditional Cable Supported Bridges (CSB), the most important being the reduced environmental impact, both from the visual and air pollution points of view, perfect suitability for very large crossings and constant cost per unit length due to its modularity [2]. In particular, the latter aspects are particularly interesting when comparing the effectiveness of this innovative structural typology with classical solutions such as Suspension Bridges (SB). In fact, whereas the cost of a SFT increases linearly, the cost of a SB rises up way more rapidly as the crossing length increases, tending to become infinite as the main span length tends to a limit value for which the suspension cable system is not even able to carry its own weight. Fig. 1(b) illustrates qualitatively the trends of cost previously described.

Economic aspects represent an issue of exceptional importance when the final structural solution to be realized in a waterway crossing has to be selected. Therefore it is fundamental to properly estimate the building cost of each available solution. Thus simple procedures for the assessment of the cost of the crossing systems, such as he ones already developed by Gimsing [3] for Cable Supported Bridges, have to be provided. In this paper a similar procedure for Submerged Floating Tunnels is presented, which thus allows for quickly evaluate the cost of such an innovative crossing solution and for comparing its cost-effectiveness with the one of other traditional solutions, such as CSBs.

In this context, some applications are also provided, highlighting the conditions where the Submerged Floating Tunnel proves to be more economically competitive than traditional Cable Supported Bridges.

Nomenclature

α	lateral slope of cables of W-shaped anchorage groups of a SFT
γ_{cb}	cable steel specific weight
C_{sb}	total cost of the cable system and pylons of a suspension bridge
C_{SFT}	total cost of the cable system of a SFT
f_{cbd}	cable steel design strength

g	uniform permanent load of a suspension bridge
h_{pl}	pylon height
h_i	height of the i^{th} cable group of a SFT
k_m	suspension cable sag in the main span
k_a	suspension cable sag in the side spans
ℓ_m	main span length
ℓ_a	side spans length
p	uniform live load of a suspension bridge
Q_{cm}	steel quantity of the suspension cables in the main span of a suspension bridge
Q_{ca}	steel quantity of the suspension cables in the side spans of a suspension bridge
Q_{hm}	steel quantity of the hangers in the main span of a suspension bridge
Q_{ha}	steel quantity of the hangers in the side spans of a suspension bridge
rb	residual buoyancy of a SFT
u_{cb}	unitary average cost of cable steel
u_{pl}	unitary average cost of pylon steel

2. Simple procedures for the assessment of crossing solution structural cost

2.1. Cost evaluation procedure

In order to determine the optimal configuration of a cable supported bridge it is mainly necessary to estimate, beside of the structural performance, the structural cost, this being mainly due to the cost of the supporting system C_s and of the deck/tunnel C_d, as shown in Eq. (1):

$$C_{TOT} = C_{ss} + C_d \tag{1}$$

A procedure to assess the cost of the supporting system of Suspension and Cable-stayed Bridges has already been developed by Gimsing [3]. The costs relative to foundations, shore connections and anchor blocks are not considered in this simplified procedure.

In this paper, due to the lack of space, attention is focused on Submerged Floating Tunnels and on Suspension Bridges (SBs), this being the bridge typology holding the record of the longest span in the world.

2.2. Suspension bridges(SB) cost evaluation procedure

A symmetrical three-span suspension bridge, subjected to uniform dead load (g) and live load (p), is considered. The cost of the supporting system, made up of the cable system and pylons, can be evaluated through the procedure conceived by Gimsing [3]. The overall cable steel quantity is due to the quantities related to the main cable and the hangers in both the central and side spans. Reference is made to the geometric quantities illustrated in Fig. 2. The minimum cable steel quantity, needed to carry the assumed dead and live loads, for the main cable and the hangers in the central span (Q_{cm} and Q_{hm}, respectively) and in the side spans (Q_{ca} and Q_{ha}, respectively) are given by:

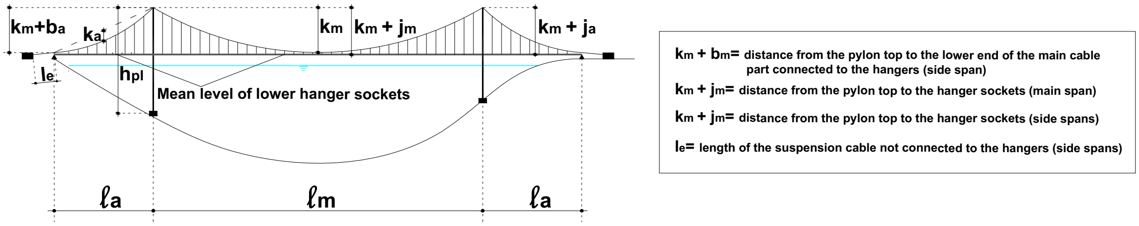


Fig. 2. Geometrical configuration of a symmetrical three-span suspension bridge

$$Q_{cm} = \frac{\gamma_{cb}}{f_{cbd}} \cdot (\mathrm{g}+\mathrm{p}) \cdot l_m^{\;2} \cdot \frac{\sqrt{1+16\cdot\left(\frac{k_m}{l_m}\right)^2}}{8\cdot\frac{k_m}{l_m} - \frac{\gamma_{cb}}{f_{cbd}}\cdot l_m \cdot \sqrt{1+16\cdot\left(\frac{k_m}{l_m}\right)^2}} \cdot \left[1+\frac{8}{3}\cdot\left(\frac{k_m}{l_m}\right)^2\right] \tag{2}$$

$$Q_{hm} = \frac{\gamma_{cb}}{f_{cbd}} \cdot (\mathrm{g}+\mathrm{p}) \cdot \left(j_m + \frac{k_m}{3}\right) \cdot l_m \tag{3}$$

$$Q_{ca} = 2\cdot\frac{\gamma_{cb}}{f_{cbd}} \cdot \frac{(g+p)\cdot l_m^{\;2} + Q_{cm}}{8\cdot k_m} \cdot l_a \cdot \sqrt{1+\left(\frac{k_m}{l_m}+4\cdot\frac{k_a}{l_a}+\frac{b_a}{l_a}\right)^2} \cdot \left[1+\frac{8}{3}\cdot\left(\frac{k_a}{l_a}\right)^2+\frac{1}{2}\cdot\left(\frac{k_m+b_a}{l_a}\right)+\frac{l_e}{l_a}\right] \tag{4}$$

$$Q_{ha} = \frac{\gamma_{cb}}{f_{cbd}} \cdot (\mathrm{g}+\mathrm{p}) \cdot \left(k_m - \frac{4}{3}\cdot k_a + 2\cdot j_a - b_a\right) \cdot l_a \tag{5}$$

Assuming a constant stress equal to the design strength f_{pld} throughout the pylon, Eq. (6) for the necessary amount of steel for each pylon Q_{pl} can be derived [3]:

$$Q_{pl} = \frac{(\mathrm{g}+\mathrm{p})\cdot l_m + Q_{cm}}{8} \cdot \left(\frac{k_m+4\cdot k_a+b_a}{k_m}\cdot\frac{l_m}{l_a}+4\right) \cdot \left[e^{\frac{\gamma_{pl}}{f_{pld}}\cdot h_{pl}} - 1\right] \tag{6}$$

Therefore the total cost C_s of the supporting system of a symmetrical three span suspension bridge is given by:

$$C_{ss} = \left(Q_{cm}+Q_{ca}+Q_{hm}+Q_{ha}\right)\cdot u_{cb} + 2\cdot Q_{pl}\cdot u_{pl} \tag{7}$$

where u_{cb} and u_{pl} are the unitary average prices for erected and protected suspension cable steel and pylon steel.

It is worth noticing that the maximum length of a suspension bridge, previously mentioned in section 1, can be calculated as the root of the denominator of Eq. (2). This theoretical limit length gives rise to the vertical asymptote depicted in Fig. 1(b).

Assuming that the material quantity per unit length g related to the stiffening girder is constant, the cost of the deck C_d is equal to (u_d is the unitary average prices for erected girder steel):

$$C_d = \mathrm{g}\cdot \mathrm{L}\cdot u_d \tag{8}$$

2.3. Submerged Floating Tunnel (SFT) cost evaluation procedure

The cable system of a Submerged Floating Tunnel is made up of single groups of cables, generally lying in the plane of the tunnel cross-section, located along the tunnel axis with a fixed inter-axis. Therefore the total cost of the cable system $C_{cb,sft}$ is simply given by the sum of the costs of each cable group $C_{cg,i}$. The SFT is considered to be subjected only to the permanent residual buoyancy rb, as the live loads reduce the cable tension forces. The geometrical configuration of the cable system is depicted in Fig. 3: the geometrical arrangement of the cable groups is the W-shaped one, it being the most effective one [4].

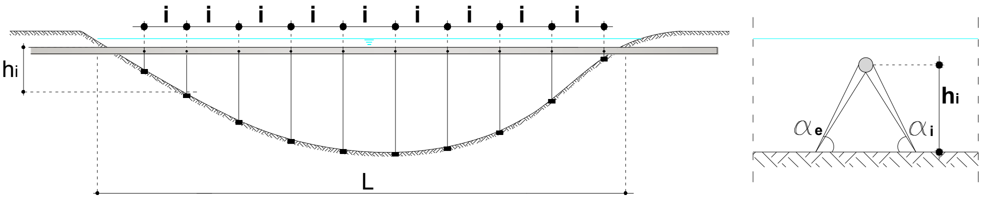


Fig. 3. Geometrical configuration of a Submerged Floating Tunnel

The cost of the SFT cable system can be thus assessed through the simple following equation:

$$C_{sft} = \sum_{i=1}^{n}\left[\frac{\gamma_{cb}}{f_{cbd}}\cdot\frac{rb\cdot i}{2}\cdot\left(\frac{h_i}{(\sin\alpha_e)^2}+\frac{h_i}{(\sin\alpha_i)^2}\right)\cdot u_{cb}\right] \tag{9}$$

The tunnel cost C_d can be evaluated analogously to (8), as the tunnel cost per unit length is constant.

3. Cost comparison between Suspension Bridges and SFT

3.1. The case studies of the Messina Strait and Akashi Strait

The Akashi Strait, crossed by the suspension bridge featuring the largest main span in the world (1991 m), and the Strait of Messina, where a suspension bridge having a main span of 3300 m is planned to be built, are selected as case studies, in order to perform a cost comparison between the most advanced Suspension Bridge (SB) designs up to now and SFT preliminary proposals, assumed to be built in the same locations.

The SFT proposed for the Strait of Messina crossing features a steel shell-concrete circular cross-section whereas the one considered for the Akashi Strait have a steel-concrete rectangular cross-section, with lateral steel keels having a hydrodynamic shape (Fig. 4). The cable system is made up of W-shaped cable groups in both cases.

The proposed SFT solutions were designed considering the stresses induced by the residual buoyancy and the hydrodynamic actions due to extreme wave and currents foreseen in the considered location and assuming a flat seabed profile, having a depth equal to the average one (200 m for the Strait of Messina, 80 m for the Akashi Strait). The quantity of materials involved in the construction of the SBs in the Strait of Messina and Akashi Strait can be found in literature [5]. It is thus possible to estimate the total cost of the considered SFTs and suspension bridges, once the cost per m^3 of each material is defined, according to the indications given in [3]. The assumed unitary costs, being dimensionless as they are divided by the unitary cost of steel S460, are given in Table 1.

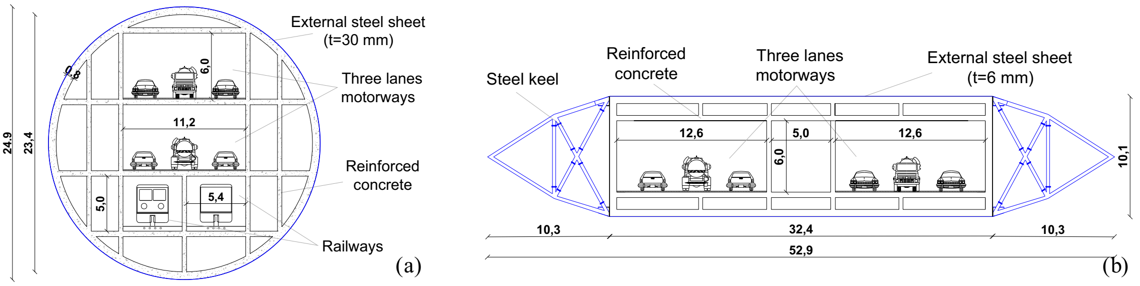


Fig. 4. SFT cross-section proposals: (a) Strait of Messina; (b) Akashi Strait

Table 1. Dimensionless cost/m^3 of constructional materials used for SBs and SFTs in the Messina and Akashi Strait

	Concrete C25/30	Steel S355	Steel S420	Steel S460	Steel S690	Cables steel (SB)	Cables steel (SFT)	Ballast
Cost/m3 [-]	0.022	0.945	0.985	1.000	1.125	1.000	2.000	0.009

Fig. 5 shows the comparison of the total cost of the SB and SFT solutions for both case studies, also highlighting the different contributions in terms of structural elements (cable system, pylons and deck/tunnel) and materials involved (r.c., different grades of steel, steel for cables, ballast).

The presented costs are divided by the total cost of the SB solution, in both case studies, thus being dimensionless. It can be immediately noted that the SFTs total cost is largely lower, it being 25.6% (Messina) and 36.3% (Akashi) of the cost of the relative SB, basically due to the huge reduction of the cost of the supporting system. In fact SFT cable system cost is the 2.7% (Akashi) and 8.6% (Messina) of the cost of the SB supporting system (cable plus pylons). Furthermore, the cost of the tunnel structure is pretty much the same one of the SB deck for the Strait of Messina crossing, whereas it is the 62.9% of the cost of the SB deck for the Akashi Strait case.

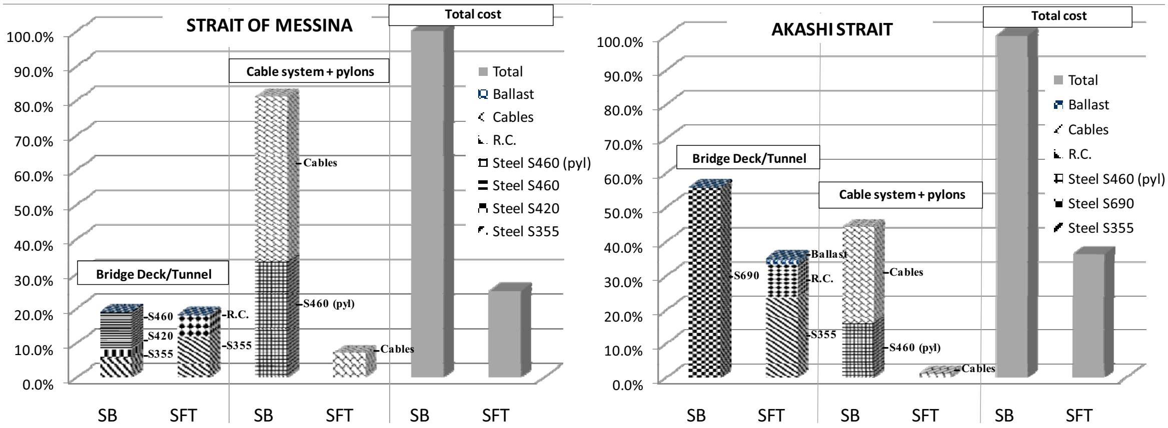


Fig. 5. Comparison of the cost of SFT and SB solutions

Finally, it is worth underlining that the previous cost comparison is made between completely designed SBs and preliminary designs of SFTs. Therefore the proposed results may slightly differ from actual and definitive ones; however, due to the large scatter between the cost of SFTs and SBs, SFT would still prove to be largely cheaper.

3.2. Application of the cost evaluation procedure for suspension bridges and submerged floating tunnels

A numerical application of the relationships previously introduced is carried out, with the purpose of providing useful abaci for the selection of the most efficient structural solutions for strait crossings, given the crossing length and water depth

In particular, a comparison between the structural costs of a SFT and a Suspension Bridge (SB) crossing waterways, with variable lengths L and a flat seabed profile, is considered. The SB is assumed to have a main span length l_m equal to the waterway length L, similarly to the configuration of the Strait of Messina Bridge (Fig. 6). Two set of geometric and mechanical data of the SB are considered, namely C1 and C2, the first one leading to the highest structural cost whereas the second one leads to the lowest one (Table 2).

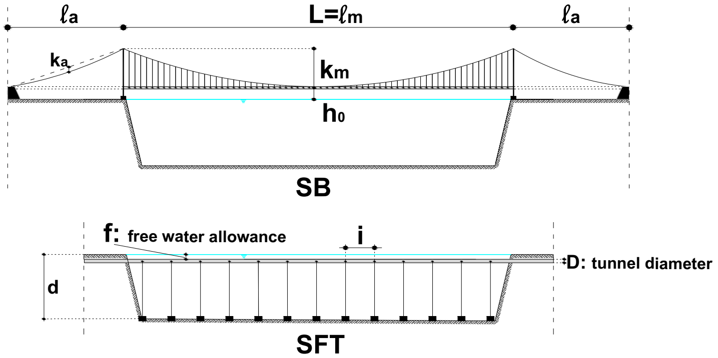


Fig. 6. Geometrical configuration of the considered suspension bridge and submerged floating tunnel

Table 2. Geometrical and mechanical data

	D [m]	f [m]	h_0 [m]	ℓ_m	ℓ_a	k_m	γ_{cb} [MN/m^3]	γ_{pl} [MN/m^3]	$f_{cb,d}$ [MN/m^2]	$f_{pl,d}$ [MN/m^2]
C1	25	25	70	L	$0.5 \cdot l_m$	$0.08 \cdot l_m$	0.10	0.0785	1000	320
C2	25	25	30	L	$0.25 \cdot l_m$	$0.12 \cdot l_m$	0.08	0.0785	1860	320

The design strength of the pylon steel f_{pld} is reduced to 60-80% of the material strength to take into account the stress induced in the pylons by the out of plane wind actions.

The SB permanent loads g are assumed to be equal to 0.24 MN/m, which is a common value for a SB featuring a slender aerodynamic deck. For the live loads p, a value of 0.16 MN/m, corresponding to a motorway plus railway crossing, is considered. The cost of the tunnel structure for SFTs is set equal to the cost of the SB deck, as it was found previously for the Messina Strait case study. The crossing length L, the seabed depth d and the residual buoyancy rb acting permanently on the SFT are considered as variables, in order to assess their influence and importance on the cost of the three crossing typologies considered.

The unitary cost u_{pl} of the steel used for the pylons is set equal to 1 and all the other unitary costs are defined proportionally to it. Table 3 illustrates the assumed values for the unitary costs.

Figs. 7 and 8 show the comparison of the cost trend curves of SFTs and SBs as the crossing length and the seabed depth vary. The curves are dimensionless, as the actual costs are divided by a reference cost, assumed equal to the one of the Messina Strait suspension bridge. In particular, the curves in Fig. 7(a) are referred to a variable crossing length, assuming d=200 m and rb_k=0.7 MN/m, while curves in Fig. 7(b) consider a variable seabed depth and a fixed length L equal to 3000 m; clearly SFTs feature a lower limit for the seabed depth $(d_{min,SFT})$ allowing for their realization, it corresponding to the condition where the SFT cables would feature a null length. It can be noticed that the SFT solution is noticeably cheaper than the SB one, particularly for large values of the crossing length; as a matter of fact, Suspension Bridges are economically competitive with SFTs only for crossing lengths being lower than 500 m. Furthermore, also for very large values of the seabed depth the SFT is largely less expensive than suspension bridges. It is worth noticing that the cost of SBs does not increase as the seabed depth increases, the pylon height not being influenced by it for the assumed geometrical configuration (Fig. 6).

The comparison between SFTs and SBs cost curves becomes less heavy for the SBs if larger values of rb_k and d, and lower values of L, are considered, as shown in Fig. 8(a) (rb_k=1.5 MN/m, d=800 m) and Fig. 8(b) (rb_k=1.5 MN/m, L=500 m). As a matter of fact, the SB solution turns out to be economically competitive with the SFT one even for larger crossing lengths, up to 2000 m and for shorter crossings (L=500 m) a minimum seabed depth approximately equal to 300 m is sufficient to let the SB be cheaper than the SFT.

Table 3. Dimensionless values assumed for the materials unitary costs

	u_{pl} [-]	$u_{cb,SB}$ [-]	$u_{cb,SFT}$ [-]	u_d [-]
C1	1.0	1.25	2.5	1.0
C2	1.0	2.0	4.0	1.0

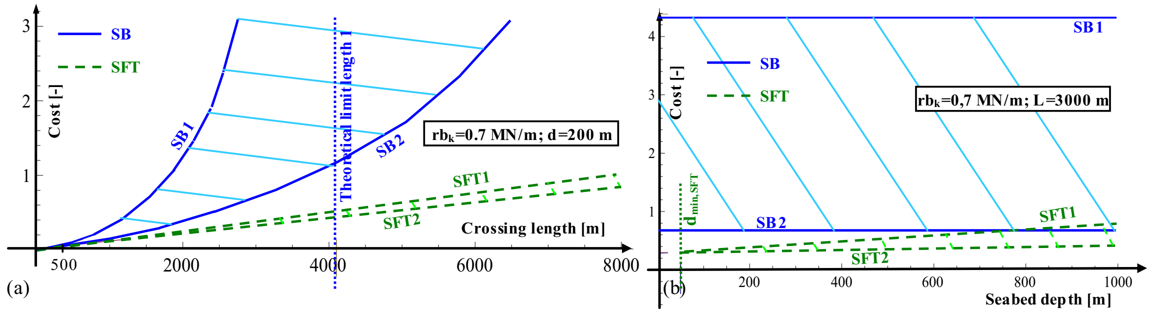


Fig. 7. SFT and SB cost curves as a function of the: (a) Crossing length (rb_k=0,7 MN/m; d= 200 m); (b) Seabed depth (rb_k=0,7 MN/m; L= 3000 m)

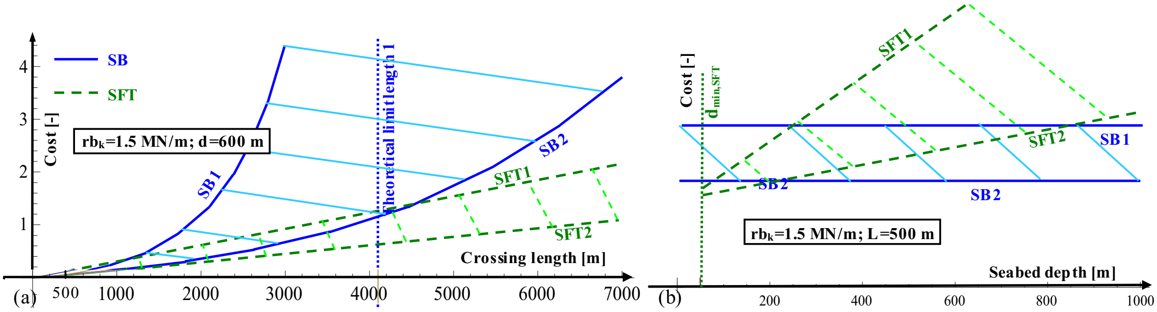


Fig. 8. SFT and SB cost curves as a function of the: (a) Crossing length (rb_k=1,5 MN/m; d= 800 m); (b) Seabed depth (rb_k=1,5 MN/m; L= 500 m)

4. Conclusive remarks

The simplified procedure presented in this paper, for the assessment of the structural cost of a Cable Supported Bridge, similar to the one proposed by Gimsing [3] but here including the innovative typology of Submerged Floating Tunnels, allows to quickly compare the overall cost of the superstructure, therefore constituting an important tool to help making decisions during the early stage of a waterway crossing planning.

The cost assessment procedure developed is applied and a comparison between the cost trend curves relative to

SFTs and SBs is made, considering different values of the geometrical and mechanical parameters governing the problem. The obtained curves confirm that the SFT solution is largely cheaper than traditional SB one, particularly when large distances have to be surpassed. The seabed depth and the residual buoyancy acting on the SFT are the other parameters that mainly influence the cost comparison between these structural typologies: in fact, as the value of these parameters increases, SBs become more economically competitive with SFTs. However, the SFT solution still proves to be considerably more economically effective than the classic SB one.

Two noticeable case studies are considered to compare the cost of potential SFT solutions and of actual SB designs: the Messina and Akashi Straits. The obtained results show that in both cases the proposed SFT solutions are considerably less expensive than the corresponding suspension bridges, as the SFTs cost approximately 1/4 (Messina Strait) and 1/3 (Akashi Strait) of the SBs. In particular, it is the enormous difference in the supporting system cost that gives rise to such a large scatter between the SFT and SB overall costs.

These remarks, together with the other advantages assured by SFTs [2], confirm that such a revolutionary crossing solution will represent the future in the field of waterway crossings.

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