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Cable Supported Immersed Inversed Bridge: A challenging proposal

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Abstract

Cable Supported Bridge (CSB), such as suspension and cable stayed ones, are widely used for waterway crossings and the only bridge typology able to surpass long spans. However, the effectiveness of their cable system greatly reduces and its cost enormously rises as the crossing length increases. Submerged Floating Tunnels (SFT) represent an innovative technical solution in the field of waterway crossings, being tubular structures, submerged in the water at a fixed depth, kept in position through anchorage groups made up of cables or tethers linked to the seabed. The anchorage system of SFTs features several striking advantages as it is stable and, above all, provides a supporting condition to the tunnel which is unnoticeably affected by the crossing length but it can be less effective and more costly when large water depths are encountered.

Even though Cable Supported Bridges and Submerged Floating Tunnels appear to be well distinct structural solutions, several similarities can be noticed between the two: the bridge deck/tunnel is supported through vertical or sloped cables, the load conditions are analogous, the gravity loads on the cable supported bridges being replaced by the upward residual buoyancy in the SFTs and the role of wind being played by currents and waves actions; the tunnel structure can be realized with a multi cell cross-section having a fluid-dynamic shape, as most of the modern cable supported bridges feature. Therefore some of the knowledge and ideas developed in the cable supported bridges field can be conveniently transferred to the SFTs one.

As a matter of fact, the cable system configurations in use for cable supported bridges can be combined with the concept of a tunnel floating underwater, giving rise to a new typology of submerged floating tunnel, the Cable Supported Immersed Inversed Bridge (CSIB). This solution seems to be convenient in intermediate to deep waters, featuring several advantages with respect to traditional Cable Supported Bridges under both the economic and the environmental impact points of view. In case of deep waters and crossing length belonging to the range of feasibility of CSBs, this new solution features some important advantages also with respect to the "classic" SFT. The aims of this paper are to give a description of the differences and points in common existing between conventional Cable Supported Bridges and SFTs and to illustrate the main features and the potential applications of this alternative submerged floating tunnel solution.

Keywords: Submerged Floating Tunnel; Cable Supported Immersed Inversed Bridge; cable system

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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. Among the traditional bridge systems the cable supported bridges, such as suspension bridges and cable stayed bridges, constitute the most suitable solution in those cases where large distances have to be covered. 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), which is a tubular structure floating at an immersion depth fixed in position through anchorage systems made up of cables connected to the seabed. The tunnel is permanently subjected to its own weight and to the buoyancy assured by the presence of the water; the tunnel cross-section is designed so that the buoyancy overcomes the structural weight and the tunnel is then subjected to a volume force directed upward. The cable system plays also the role of constraining the tunnel, minimizing displacements and stresses induced by the environmental loadings, such as the seismic and hydrodynamic actions [1] that can be particularly severe in case of sea strait crossings. Some SFT proposals developed in the past are shown in Fig. 1.

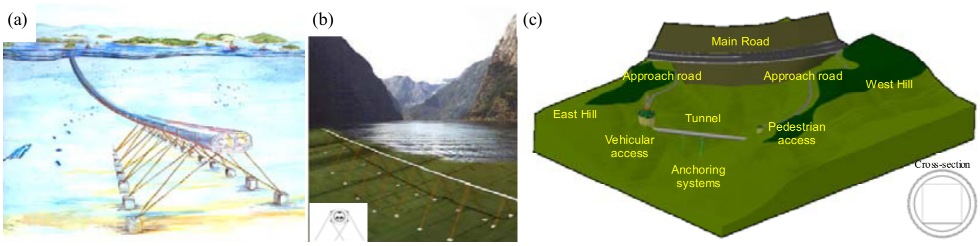

Fig. 1. Views of some proposed SFT: (a) The Jintang Strait (China) crossing by the Ponte di Archimede S.p.A (2001); (b) The Stordfjorden (Norway) crossing by the NSFT Company (2009); (c) The Qiandao Lake (China) by the Sino-Italian cooperation project SIJLAB (2007, [2])

The main purpose of this work is to give a description of the differences and points in common existing between conventional Cable Supported Bridges and Submerged Floating Tunnels and to investigate the possibility of transferring the knowledge and technologies already developed for the former ones to the field of the latter ones. In particular, the attention is focused on design and constructional aspects but also on the opportunity of developing new proposals of floating tunnels involving cable system arrangements analogous to those commonly used in suspension and cable-stayed bridges. The Cable Supported Immersed Inversed Bridge is presented.

2. Submerged floating tunnels and cable supported bridges: Similarities and differences

2.1. Load conditions

The load conditions affecting Cable Supported Bridges and Submerged Floating Tunnels are quite similar. In fact in the CSBs the structural and non structural weight constitute a uniformly distributed downward vertical load to which the live load due to vehicular traffic is added. In SFTs the overall permanent weights and the traffic loads are counteracted by the Archimedes buoyancy leading to a residual buoyancy, which constitutes a uniformly distributed upward vertical load. In the SFT case the intensity of the residual buoyancy can be conveniently determined by the designer, considering that a large value of the net buoyancy implies larger cables forces and a more expensive structure but an excessively low value would lead to an unsatisfactory response of the cable system to environmental actions. A suggested design criterion [2] is to provide a buoyancy enclosed between an upper bound equal to 130% of the permanent weight and a lower bound equal to 120% of the sum of permanent weights and traffic loads. However this criterion could lead to excessively large residual buoyancy in those cases where large internal dimensions are needed, so that lower bound values could be considered. Moreover, it could be useful to concentrate the net buoyancy in the tunnel zones near the cable anchorage points, providing a larger ballast amount in the central zone between two adjacent cable supporting points, thus reducing the local bending stress permanently induced in the tunnel.

The wind load represents the most onerous loading condition for cable supported bridges over-coming long distances; as a matter of fact in the last years the research activity in this field is mainly devoted to the development of advanced structural solutions featuring the required aerodynamic stability, which means that the wind design velocity, reaching values up to 70 m/s, has to be safely lower than the limit velocity leading to the flutter phenomenon. SFTs in a similar way are subjected to water wave and current loading. The water density is noticeably larger than the air one, this being unfavourable as the pressure field is directly proportional to the fluid density and the flutter velocity decreases with increasing fluid density [3]. However, the water velocities that can occur at the depths of interest for SFTs applications are largely lower than wind velocities, so that the hydrodynamic load condition should be less onerous than wind loading for cable supported bridges.

2.2. Cable systems

The most natural classification of cable supported bridges is based upon the arrangement of their cable system, which can be of the suspension system or cable stayed type (Fig. 2, [4])

Fig. 2. (a) Golden Gate suspension Bridge (San Francisco, USA, 1937); (b) Tatara fan cable-stayed Bridge (Japan; 1999); (c) Øresund harp cable-stayed Bridge (Denmark, 2000)

Another distinctive feature of the cable supported bridges is the way the cable system is anchored at its ends. The cable systems can be therefore classified as earth anchored, if both vertical and horizontal components of the cable force are absorbed by the anchor block, or as self anchored, if only the vertical component is transferred to the anchor pier, while the horizontal one is taken by the stiffening girder. The earth anchored system, mainly used in suspension bridges, requires massive anchor blocks to withstand the large horizontal cable force, whereas self anchored systems, mainly used in cable-stayed bridges, induce a compressive force in the girder.

In cable supported bridges designed to carry vehicular traffic the cable system is usually composed of vertical cable planes so that it is mainly able to transfer vertical loading. Generally two or more vertical cable planes are provided, thus assuring also torsional support to the stiffening girder. Clearly, with vertical cable planes the resultant of the cable forces is included in the vertical plane, providing no support against lateral loads, such as the wind ones, to the girder, if second order effects are not taken into account. Considering the second order effects, a restoring force due to out-of-plane displacements arises in earth anchored systems, often referred as the pendulum effect, which is linearly proportional to the lateral displacement of the system (Fig. 3).

The pendulum effect gives rise to a significant reduction of bending moments induced in the girder, especially as the bridge main span increases but, to be effective, it requires pylons having considerable lateral stiffness and long side spans, the latter condition being unfavourable for the efficiency of the cable systems. Moreover, in the case of self anchored system no lateral support to the stiffening girder is provided, which therefore has to carry the whole wind load. The problems induced by lateral wind loads in bridges featuring long spans and slender girders can be solved by using inclined cable systems. However, these solutions have been adopted only for some pipeline bridges.

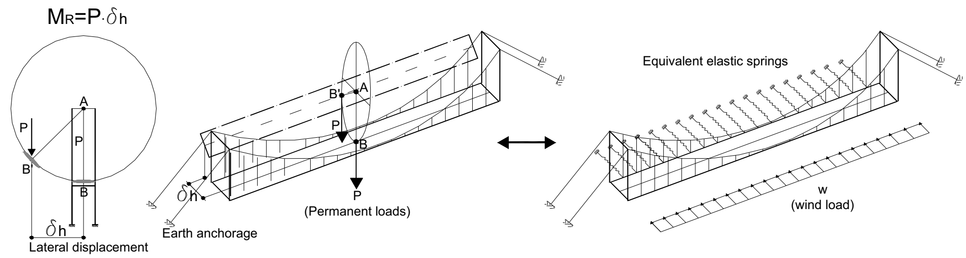

Fig. 3. The pendulum effect for cable supported bridges: the lateral displacements of the cable system give rise to a restoring couple equal to $P \cdot \delta_h$; the cable system lateral support can be thought as a bed of elastic springs [4]

Furthermore, the cable system of a cable supported bridge can offer different levels of stiffness, depending on its configuration. In fact, a cable system, here meaning the ensemble of cables and parts of the girder and the pylons necessary to transfer the axial forces induced by the cables forces, can be classified as [4]: (a) stable of the 1° order, if the system is able to achieve equilibrium and no node displacements occur; (b) stable of the 2° order, if equilibrium can be attained only through displacements of the nodes of the system; (c) unstable, if the cable system is unable to achieve equilibrium. The fan type cable-stayed system featuring an anchor cable and self anchoring is stable of the first order (Fig. 4(a)), the suspension system is clearly stable of the 2° order (Fig. 4(b)), whereas the harp type and the fan type without the anchor cable are usually unstable (Fig. 4(c)). The level of stability of the cable system is very important for the rigidity offered by the cable systems under asymmetrical loading [4].

The cable system up to now conceived for SFTs do not belong to any of the typologies used for traditional cable supported bridges, as it is composed of groups of cables, placed with a certain inter-axis along the tunnel length, connecting the tunnel directly to the seabed. Each cable of the system is subjected to the tension force due to residual buoyancy and traffic loads and to its own weight, lightened by the buoyancy, and it is anchored to the earth through the foundation block of its cable group.

The previous considerations lead to point out that the cable system of an SFT is stable of the first order (Fig. 4d). In fact each cable group is able to transfer any load variation to the ground independently from the other cable groups, without requiring any displacement of the system nodes. Obviously, the live load intensity has to be conveniently lower than the residual buoyancy, in order to avoid the loosening of the cables.

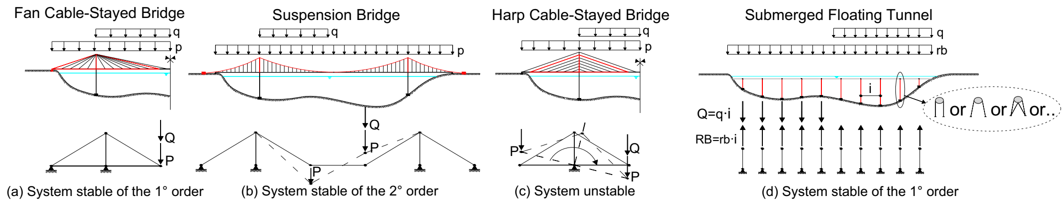

Fig. 4. Stability of the cable systems for cable supported bridges (a), (b), (c) and for SFTs (d)

In most of the proposed SFT solutions each cable group is made up of vertical or inclined cables in a number ranging from two to four (Fig. 5(a)) and it is placed in a plane transversal to the tunnel axis. Such a kind of cable system would not induce any axial force in the tunnel, differently from a cable-stayed system. Since reasonable inter-axis (λ) between the foundation blocks can be in the range of 50-100 m, a significant local bending of the tunnel can occur due to permanent loads (i.e. the residual buoyancy). A way to reduce the bending stresses induced in the tunnel by the residual buoyancy (RB) without increasing the number of foundation blocks could be the use of cables inclined also in the longitudinal direction, such as the example solutions illustrated in Fig. 5(b). The V solution involves four cables group and, since all the cables lie in a plane orthogonal to the tunnel axis, no axial force stresses the tunnel. L1 solution doubles the tunnel supporting points but induces a compressive force in the tunnel parts enclosed between the inclined cables; however, the compression force favours the water tightening of the tunnel inter-modular joints if they are located in the compressed zones. L2 solution allows to reduce the cables diameter and to connect the crossing cables each other, thus reducing their sag variations under increasing loads, but the detailing of the cables connections would be more complicated. It is worth underlining that the maximum axial force induced in the tunnel by the above described solutions would be considerably lower than the one produced in the stiffening girder by a cable-stayed system carrying a vertical force per cable of the same intensity.

Generally the solutions proposed for SFT cable systems involve cables inclined transversally with respect to the tunnel axis, thus realizing a spatial cable system. However only solutions including four cables per group (see type B, C and D in Fig. 5(a)) provide both torsional and lateral support to the tunnel. This feature guarantees a better behaviour of the structural system with respect to lateral loading of long span tunnel, improving also the response to current/wave excited oscillations. Some other proposals feature only vertical cables, so that the cable system would be noticeably less effective in the lateral direction, providing lateral restoring forces only due to second order effects, i.e. the previously described pendulum effect.

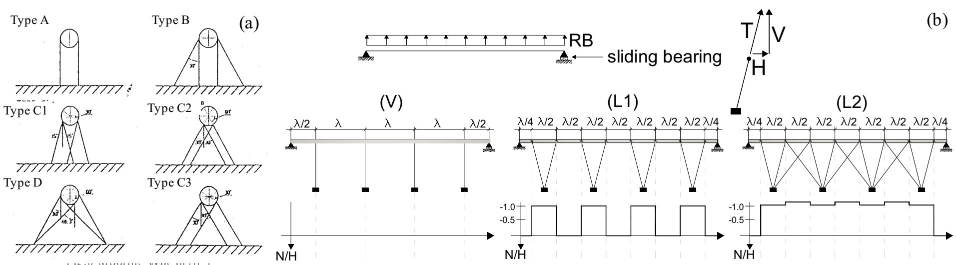

Fig. 5. Possible SFT cable system arrangements: (a) Cable groups tested by Maeda et al. [5]; (b) Examples of SFT cable system with longitudinally inclined cables and related tunnel a-dimensional axial force (N) diagram

2.3. Tunnel cross-section

In modern cable supported bridges the principle of streamlining the cross-section in order to consistently reduce the drag coefficient and the tendency to develop wind-excited oscillations is largely used. This design philosophy was first applied in the 1960s in the Severn Bridge, featuring a hexagonal shaped steel box cross-section with side sharp edges having the task to divide the air flow (Fig. 6(a)). Several other bridges featuring streamlined girder have been realized subsequently and this trend reached its maximum point with the girder cross-section proposed, after numerous wind tunnel tests, for the Messina Strait Bridge (Fig. 6(b)): the girder is composed of three longitudinal steel box girders, with smoothly curved bottom plates connected to each other through cross box girders having an inter-axis of 30 m; between the cross and the longitudinal girders open grids are located, so that the no disturbance of the air flow occurs. The girder cross-section has a depth of only 2.50 m, thus giving the extreme value of 1/1320 of the depth to span (3300 m) ratio.

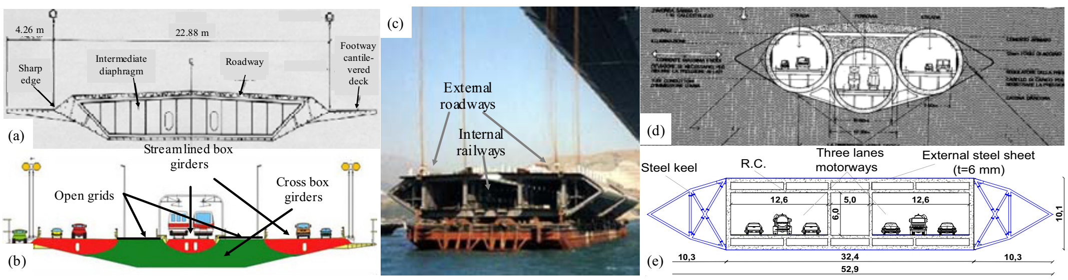

Fig. 6. Fluid-dynamic girder cross-sections. CSB: (a) Second Severn Bridge (UK, 1966); (b) The Messina Strait Bridge proposal (Italy, 1992); (c) Tsing Ma Bridge (Hong Kong, 1997); SFT: (d) The Messina Strait Tunnel proposed by Grant (Italy, 1969); (e) Proposal for the Akashi Strait (Japan, [6])

The idea of conveniently shaping the girder cross-section can be applied also to SFTs, as currents and waves could induce the same problems related to wind in cable supported bridges. In SFTs the vehicular traffic will take place internally, therefore the cross-sections depth have to be larger than the one of the streamlined girders of cable supported bridges. In this aspect a similarity can be found with cable supported bridges featuring stiffening trusses, generally preferred for bridges carrying both railways and roadways, the former ones being located on the lower deck. As a particular example, the Tsing Ma Bridge (Hong Kong, 1997, Fig. 6(c)) has the peculiarity of being equipped with two side triangular brackets, accommodating the hanger cables anchoring and covered by stainless steel shells; in this way the aerodynamic properties of the girder are improved. The solution of a tunnel cross-section with a hydrodynamic external shape is adopted already in the first SFT proposal developed by Alan Grant (Messina Strait, Italy, 1969): in this case the SFT cross-section is composed of three steel-concrete composite tubes connected together by a steel frame substructure and enclosed into a steel careening featuring a hydrodynamic shape. Alternatively a rectangular steel-concrete multi cellular cross-section, similar to the one used for Immersed Tunnels and easily realizable, integrated with lateral steel keels providing the desired hydrodynamic shape to the structure (Fig. 6(e)), can be considered. The main difference with the CSBs is related to the need of external walls having enough strength to resist the hydrostatic pressure and of supplementary internal cells constituting a further barrier preventing flooding in the traffic cells and, if needed, assuring additional ballast by filling. Also a SFT solution similar to the Messina Strait Suspension Bridge could be envisaged, considering three separated tunnels with a hydrodynamic shape, connected through cross box girders located at a fixed distance along the tunnel axis.

3. A new challenge: Cable Supported Immersed Inversed Bridges

3.1. Cable Supported Immersed Inversed Bridge solutions

The cable systems usually adopted for cable supported bridges can be combined with the floating tunnel concept obtaining structural solutions which could be competitive with traditional cable supported bridges and, in some cases, also with the Submerged Floating Tunnels solutions up to now proposed.

As depicted in Fig. 7(a), the idea of exploiting the bearing capacity of the water can be used to realize a suspension bridge featuring cable system having the usual configuration but being mirrored with respect to the water surface; this structural solution can be described as an "immersed inversed suspension bridge". Similarly, structural solutions analogous to fan type and harp type cable stayed bridges can be envisaged, thus giving rise to the "Immersed Inversed Fan Cable Stayed Bridge" (Fig. 7(b)) and the "Immersed Inversed Harp Cable Stayed Bridge" (Fig. 7(c)). In Harp Cable-Stayed bridges it is usual to stabilize the cable system providing intermediate supports in the side span, so that the stiffness of the system is considerably increased; in their immersed versions a similar solution could easily be adopted by means of vertical cable groups or piers connecting the tunnel to the seabed in the stays anchoring points of the side span. Finally, the combination of the suspension system and the fan cable-stayed system can be considered too (Fig. 7(d)), this being a competitive solution in the long span range.

Clearly the idea of a Cable Supported Immersed Inversed Bridge (CSIB) makes sense only if the water depths are large enough to allow for the realization of cable systems economically competitive. In fact, given a certain span length and a uniform load to be carried, the necessary cable steel quantity significantly reduces as the cable system height increases in the lower height range [4]. As a matter of fact suspension bridges usually feature h/ℓ ratio (h= height of the cable system; ℓ = span length) equal to about 1/10, due to the limitations imposed by the stiffness requirements, whereas larger values are considered for cable-stayed bridge. It is also worth noticing that, slightly larger values of this ratio can be considered for immersed suspension bridges, as the deformability issues related to the presence of live loads is less relevant, due to the higher value of the permanent loads (i.e. the residual buoyancy).

Pylons of cable supported bridges accomplish the double task of supporting the cable system and the stiffening girder, in particular in the lateral plane. In long span bridges the use of spatial cable systems could provide a significant improvement of the structure lateral and aerodynamic stability. Pylons having a "Y-shape" are needed when cables are disposed in laterally inclined cables (Fig. 8(a)). However, this is not the optimal structural solution for the lateral stability of the pylons themselves and would complicate the erection procedures.

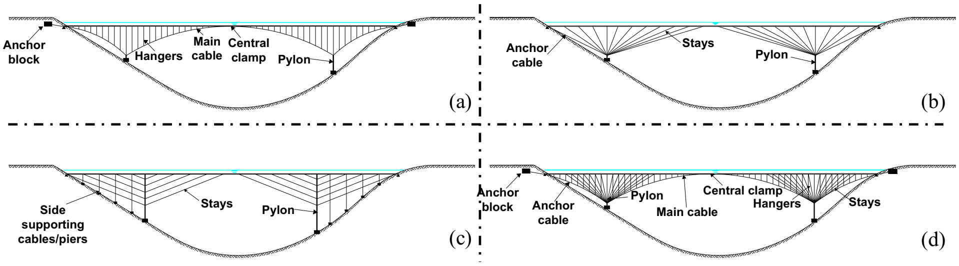

Fig. 7. Longitudinal views of (a) Immersed Inversed Suspension Bridge; (b) Immersed Inversed Harp Cable-Stayed Bridge; (c) Immersed Inversed Fan Cable-Stayed Bridge; (d) Immersed Inversed Combined Suspension Cable-Stayed Bridge

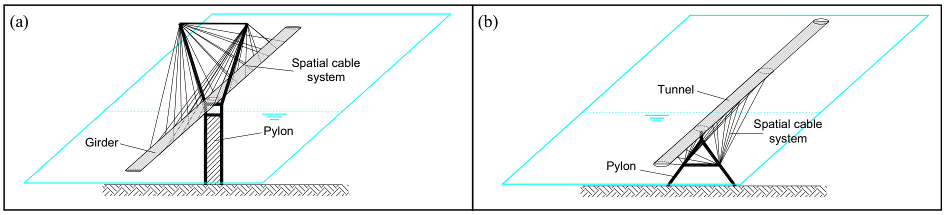

Fig. 8. Sketch of possible pylon configuration for spatial cable system in (a) CSB and (b) CSIB

In CSBs, when the seabed depth at the pylons location is such that the main cables of the suspension system or the cable stays of the fan type system can be anchored directly to the seabed, the pylons would only serve as intermediate support for the tunnel. Therefore it would be convenient to substitute the pylon with one or more cable groups of the types described in Fig. 5(a). More generally, for suspension systems and fan cable-stayed system, the pylon can be interrupted at the height where the cables are anchored, providing additional vertical cables connecting the top of the pylon with the tunnel and inclined earth anchored cables restraining laterally the tunnel (Fig. 9). This would imply a higher tension force to be carried by the pylon foundations, as the benefic effect of the pylon weight would be lost or reduced, but the cost savings would still be convenient.

Concerning the CSIB featuring a spatial cable system, the pylon could be realized with an inverse Y or V shape (Fig. 8(b)), which are more rational structural schemes. Moreover, as the vehicular traffic takes place inside the tunnel there would be no clearance requirement conditioning the cable transversal inclination, as it occur in case of a spatial Cable Supported Bridges.

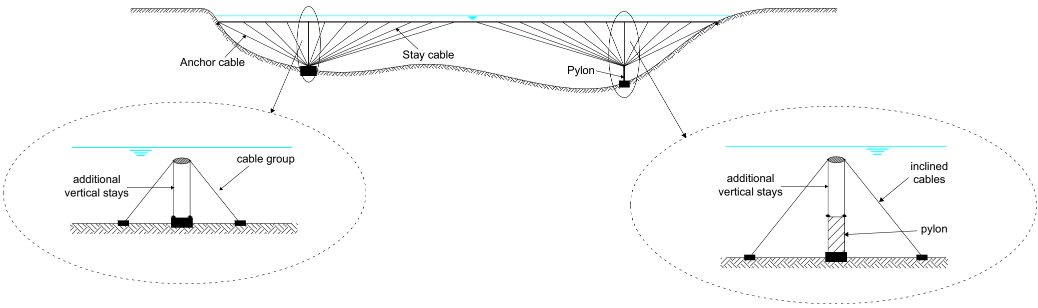

Fig. 9. Possible variations of the configuration at the pylon location

3.2. Main advantages of CSIB

The CSIB solutions present several advantages if compared to their corresponding traditional solutions.

First of all, as the tunnel would be placed 20 to 50 meters below the water surface, the water velocities taking place during a storm event would be considerably lower than the wind velocities occurring at the height where the deck of cable supported bridges are usually located. Thus the aerodynamic stability problem, representing the major issue for long span cable supported bridges, should be of minor concern for immersed bridges. Furthermore, the realization of a spatial cable systems providing also a lateral support to the tunnel is more easily feasible (see §3.1).

The pylons could also be realized with a significant material saving. As a matter of fact, given a certain seabed profile, in a traditional solution the overall pylon height would be equal to the sum of the seabed depth and the relative pylon height over the water surface whereas for the immersed solutions the pylon height would be lower than the seabed depth and, if the seabed depth allows it, the pylon can be substituted by a more economic cable group (see §3.1). Moreover, in CSIB the own weight of the pylon has a positive effect, as this counterbalances the vertical upward force transmitted to the pylon itself by the cable system. At the same time, the pylon weight reduces the tension force to be transmitted to the ground, thus reducing also the foundation costs.

CSIBs do not interfere with the vessel traffic over the water surface, so that the geometry of the system, i.e. the length of the main span and of the side spans, is only influenced by structural reasons, besides of the seabed profile.

Cable Supported Immersed Inversed Bridges are invisible structures, so that the problem of the visual environmental impact of the crossing would be totally resolved in those locations where the natural landscape has to be protected. Moreover, also the air pollution production can be faced in a more effective way considering that inside a tunnel the gas emissions due to vehicular traffic can be treated by means of modern air purification plants.

Clearly, also some specific issues must be faced, such as the attention to the hydrostatic pressure permanently stressing the tunnel and the need for various submarine operations during the construction phases and for maintenance during the service life.

Concerning the comparison with the “classic” Submerged Floating Tunnel solution, in crossings cases featuring intermediate water depths (i.e. lower than 200 m) and very large distances, SFT is still the most convenient solution, this being a modular structure which is therefore quite unaffected by the variation of the crossing length. In crossing cases with very deep waters the length of the cables composing the cable system would noticeably increase, leading to a large increment of the costs and also to a reduction of the efficiency of the cables. Moreover, the use of the cable system of traditional cable supported bridges would also imply a drastic reduction of the foundation blocks to be realized. For the aforementioned reasons, in the latter cases the Cable Supported Immersed Inversed Bridge solution seems to be more competitive than the SFT one.

4. Conclusive remarks

The research activities in the field of strait crossings are currently still of great importance. These activities are in a large part devoted to the enhancement of the structural solutions already available such as Cable Supported Bridges (CSBs). It is nevertheless true that in recent years many researches dealing with the study of new and more competitive solutions are taking place. Among the proposed innovations, the Submerged Floating Tunnel (SFT) is a very promising one. In this paper an overview of the main aspects of Cable Supported bridges, which are of interest for Submerged Floating Tunnels is given, such as the cable system and the tunnel/girder arrangement, discussing similarities and differences with the SFT proposals developed in previous years.

In this context the combination of some of the structural solutions commonly adopted in the field of Cable Supported Bridges with the concept of an immersed floating bridge seems to be absolutely feasible. In particular, due to the similarities between the wind loading and current and wave loading, the advancement in the aerodynamic shaping of the stiffening girder of CSBs can be exploited in the field of SFTs with similar solutions.

The new version Cable Supported Immersed Inversed Bridge, featuring the cables systems traditionally used in Cable Supported Bridges mirrored with respect to the water surface, exploit this challenging idea. This solution seems to be convenient in intermediate to deep waters, featuring several advantages with respect to traditional Cable Supported Bridges under the economic and the environmental impact point of view. In case of deep waters and crossing length belonging to the range of feasibility of Cable Supported Bridge, this new solution features some important advantages also with respect to the “classic” SFT.

Therefore more studies are needed to investigate peculiar aspects of CSIBs, such as their hydroelastic behaviour, so that they could represent a competitive and available solution for waterway crossings in the next future.

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