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Seismic analysis of a SFT solution for the Messina Strait crossing

G. Martire[a], B. Faggiano[a], F.M. Mazzolani[a,*], A. Zollo[b], T.A. Stabile[b]

[a]*DIST – Department of Structural Engineering, University of Naples Federico II, P.le Tecchio 80, 80125, Naples, Italy*
[b] *Department of Physic Sciences, University "Federico II" of Naples, Naples, Italy*

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Abstract

In this paper the seismic behaviour of a Submerged Floating Tunnel (SFT) solution for the Messina Strait Crossing is investigated. The Submerged Floating Tunnel (SFT) is an innovative structural solution for the realization of waterway crossings, which features several advantages from the structural, economic and environmental impact points of view. In particular, it seems to be a suitable system for waterway crossings in high seismicity zones, thanks to the deformability of the overall structure. Moreover the interaction with the water provides additional damping and inertia to the structural motion.

In order to evaluate the SFT structural response to seismic events, time domain dynamic analyses are carried out considering a ground multi-support excitation scenario determined through the generation of synthetic accelerograms by simulating the fault breaking mechanism. This is important due to the distance among the tunnel supports, also because it can lead to significant excitation of tunnel vibration modes featuring a negligible participating mass, which would not be excited in case of synchronous ground motion. Moreover the propagation of the vertical ground motion into the water and the fluid-structure interaction are taken into account in the analyses. Different structural solutions are considered, mainly differing for the cable system configuration. The dynamic properties of the considered solutions and the main aspects of their structural response are illustrated. The obtained results, although they cannot lead to definitive conclusions, give useful indications about the seismic response of Submerged Floating Tunnels and confirm that such an innovative structural solution for waterway crossings feature great potentialities, in particular when large spans have to be surpassed, such as in the Messina Strait crossing.

Keywords: submerged floating tunnel; multi-support ground motion; fluid-structure interaction

1. Introduction

The Submerged Floating Tunnel (SFT) is an innovative structural solution for waterway crossings. It essentially consists of a tubular structure placed underwater at an appropriate depth, fixed in position through anchorage groups linked to the seabed. Owing to a positive residual buoyancy (i.e. the buoyancy overcomes the weight of the tunnel) the anchorages, which can be made up of cables or tethers, are in tension, thus effectively restraining the tunnel when it is subjected to environmental actions, such as the hydrodynamic and seismic ones.

Several advantages from the structural, economic and environmental impact points of view can be addressed to such a structural solution [1]. In particular, SFTs seem to be particularly suitable to cross waterways located in high

* Corresponding author. Tel.: +39-081-768-2443; fax: +39-081-593-4791.
E-mail address: fmm@unina.it

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seismicity zones. As a matter of fact, due to large transversal flexibility of the anchorage system and to the additional damping and inertia guaranteed by the water-structure interaction, a low amount of the earthquake input energy can be transferred to the tunnel, provided that its connections with the shores are properly conceived.

This paper provides a further advancement of the study of the seismic behaviour of SFTs under multi-support excitation [2]: the water-structure interaction is more deeply investigated, considering the propagation into the water of the vertical ground motion, and a line source model is considered to simulate the fault ground breaking.

2. Case studies

The Messina Strait crossing is considered as a case study. However, since the aim of the study is to generally investigate the seismic behaviour of SFTs, 2 crossing lengths are assumed to define the case studies. Moreover, 2 cable system arrangements and 2 cable groups inter-axis are considered, thus giving a total number of 8 case studies.

The considered case studies feature two values of the crossing length (L), namely 500 m and 3000 m. These values adequately represent standard cases of short and long SFT crossings. The seabed profile, being a relevant characteristic of the crossing, as it defines the length of the cable groups, is assumed to be flat in the central part of the crossing, whereas sloped segments, whose length is set equal to 20% of L, are considered at the shore connections. The seabed depth is set equal to 250 m, i.e. the average water depth of the Messina Strait (Fig. 1).

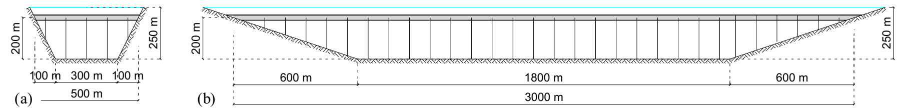


Fig. 1. Geometrical configuration of the SFT location site considered: (a) L=500 m; (b) L=3000 m

The tunnel has a composite r.c-steel multi-cellular structure: an external steel sheet (t=30 mm) encloses the main r.c tube, having inner walls and slabs which give the multi-cellular arrangement (Fig. 2a). The r.c. structure provides good strength capacity, large stiffness and stabilizing weight, whereas the external steel sheet guarantees waterproofing, protection against external impacts and ductility. The internal multi-cellular arrangement allows for accommodating traffic and escape ways; moreover the external cells can hold additional ballast and act as a further barrier against water penetration inside the traffic cells. Furthermore, the cross-section is designed such that the buoyancy ratio (i.e. the ratio between the buoyancy and the gravity loads) is enclosed between 1.2 and 1.3 in order to assure enough tension to the anchorage system and to limit the permanent stress in the structure [2].

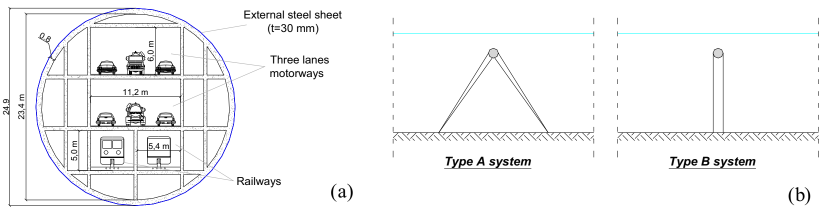


Fig. 2. (a) SFT cross-section; (b) Cable group configurations

Two configurations of the anchoring system are considered: type A, with four inclined cables in a W-shaped arrangement. restraining the tunnel against the vertical and lateral motion, and type B, with two vertical cables and providing only vertical stability to the tunnel (Fig. 2b). Two kinds of longitudinal arrangement for the cable systems are also considered: the first one, namely CW, features only type A cables systems, whereas the second one, namely CH, is an hybrid solution featuring the alternation of type A and type B systems along the tunnel lay-out. The latter solution could represent a good compromise, considering both the effectiveness and the cost of the cable system.

One or two anchoring groups restrain each tunnel module, 100 m long, thus corresponding to an inter-axis of 50 m and 100 m, respectively. The cables diameter adopted in each configuration described are given in Table 1.

Each cable group is linked to the seabed by means of piled foundation blocks.

The shore connection design represents a critical issue of the SFT design, involving the complex interaction between the buoyant tunnel and the land bored tunnels. In this study it is assumed, for the sake of simplicity, that free rotations in the vertical and horizontal plane are allowed at both tunnel ends; axial displacement is set free at one of the shore connections, whereas at the other SFT end is rigidly restrained.

Table 1. Diameter of the cables for the assumed anchorage system configurations

	Type A system		Type B system	
	(i=100 m)	(i=50 m)	(i=100 m)	(i=50 m)
D [cm]	35.0	26.0	41.0	29.0

3. SFT seismic analyses

3.1. Finite elements analysis

The performed analyses consist of five steps, allowing for the modelling of the SFT configuration under permanent loads, the identification of its dynamic characteristics and, finally, the evaluation of its dynamic response to a multi-support seismic excitation: (step 1) pre-tension step, free axial movement is allowed between the cables and the tunnel and the cable design pre-tension forces are applied; (step 2) permanent condition step, the permanent residual buoyancy is uniformly applied to the tunnel, the cables-tunnel connection is fixed and the pre-tension cables forces are released, thus achieving the permanent stress condition of the structure (Fig. 3a); (step 3) traffic loading step, the traffic loads (20% of the nominal value) are applied to the structure; (step 4) vibration modes extraction, the vibration modes are extracted through a linear perturbation step; (step 5) seismic analysis step, the (synchronous and asynchronous) ground motion is imposed to the tunnel supports and a dynamic non-linear analysis is carried out.

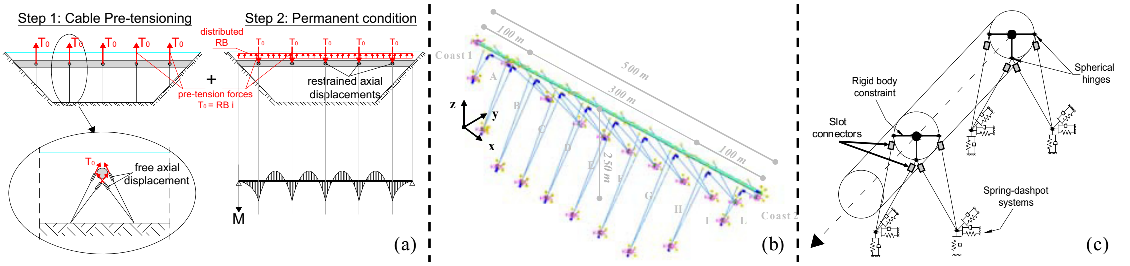


Fig. 3. (a) SFT permanent stress condition modelling; (b) F.E model; (c) Detail of the cables modelling

The structural analyses are performed through the finite element software ABAQUS 6.7 [3]. A simplified three-dimensional model of the structure is set up (Fig. 3b). The tunnel is modelled by means of 20 quadratic beam elements per tunnel module. Rigid connections between the tunnel modules are assumed. Cables are modelled through quadratic beam hybrid elements, which are specifically provided to adequately represent the behaviour of flexible elements with pre-dominant axial stiffness in geometrically non linear analyses. The cable groups and the corresponding tunnel sections are connected through a rigid body constraint and slot connector elements, allowing free relative rotations and cable axial displacements, are placed at the cable anchorage points, so that cables pre-tensioning of the cables can be properly introduced in the model as described above.

The dynamic behaviour of the ground-piled foundation system is also modelled, through a simple Lumped Parameters Model (Fig. 3c), able to reproduce the dynamic impedance of the ground-foundation system in the frequency range of interest (0-10 Hz). More details about the F.E. structural analysis carried out can be found in [2].

3.2. Environmental actions

3.2.1. Ground motion simulations

As in the case of classic bridges, the ground supports of SFTs are located at large distances from each other, so that the assumption of synchronous ground motion is unrealistic. Therefore it is necessary to determine the ground motion at each support location during the design seismic event. The multi-support seismic excitation scenario is here determined by simulating the 1908 Messina earthquake (M=7.1) recorded for a floating tunnel deployed in the Messina Strait along the West-East direction (Fig. 4a). The simulations are carried out using the method proposed by Lancieri and Zollo [4], describing the ground rupture process with an along-strike, line source model (red line, Fig. 4a) and complete wave field Green's functions computed for a flat-layered P,S velocity and attenuation model.

In this study a line source model is used instead of the most commonly used point source model [2], in order to reproduce the correct signal duration and to take into account the effects of rupture directivity and of fault length finiteness that can significantly affect the seismic records and the inferred damage.

The propagation model is an anelastic 1D flat-layered medium having 13 interfaces. Each layer has been characterized by different physical properties in terms of density (ρ), compressive wave (P-wave) velocity (V_P), shear wave velocity (V_S), P-wave quality factor (Q_p), S-wave quality factor (Q_s) and thickness. Below 1 km depth the model is equivalent to the one obtained [5] for the Calabro-Peloritan area, whereas 8 superficial thin layers are introduced in order to simulate the complex shallow sedimentary structure of the Messina Strait. The first layer is modelled as a water layer, its P-velocity being set equal to the mean sound velocity in seawater and considering sea water density. In proximity of the coasts a new velocity model having a thinner water layer has been used, according to seabed profile assumed (Fig. 2). The soil layer characteristics considered are omitted due to lack of space.

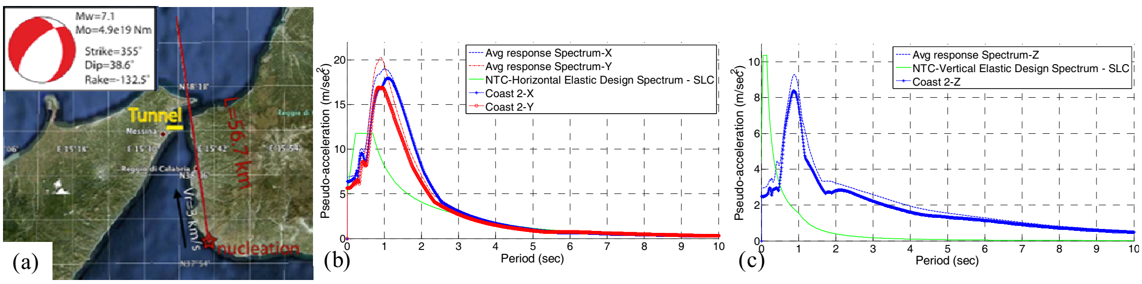


Fig. 4. (a) Plane view, showing tunnel and fault positions for the seismic scenario considered; comparison of the Elastic Response Spectra given by the Italian National Code [8] and by the simulated earthquake in the (b) horizontal and (c) vertical plane

Source parameters have been derived by several works carried out for 1908 Messina earthquake [6, 7]; The simulated event has a seismic moment M_o=4.9e19 N m, corresponding to a moment magnitude M_w=7.1.

The line source model is built by positioning a series of equally spaced, double couple point sources along the line, each of them having the same source duration and focal mechanism. The sum of point source seismic moments (each of them varies along the line according to the slip distribution obtained from [6]) is set to be equal to the final event seismic moment. The simulations are carried out using the AXITRA code as described in [3].

The synthetic accelerograms show very large values of the PGA, ranging from 0.4 g to 0.85 g in the horizontal plane and from 0.2 to 0.45 in the vertical one. These large values are due to the great amount of energy released by the fault rupture concentrated in a small time period (≈10 seconds). Fig. 4b and 4c show the comparison between the elastic response spectra of the synthetic accelerograms (the average ones and at one of the coast approaches) and the design elastic spectrum provided by the Italian National Code [8] for the Messina Strait (return period T_R=2475 years, soil type D; PGA_H=0.482 g; PGA_V=0.452 g).

3.2.2. Hydrodynamic actions

The forces F_h per unit length arising from the water-SFT interaction, due to their relative motion, during a seismic event can be evaluated through the Morison's equation [9]:

$$F_h(t) = \rho_w \cdot \frac{\pi \cdot D^2}{4} \cdot \left[(C_I - 1)\cdot(a_w(t) - a_S(t)) + a_w(t)\right] + \frac{1}{2}\cdot C_D \cdot D \cdot \left(v_w(t) - v_s(t)\right)\cdot\left|v_w(t) - v_s(t)\right| \tag{1}$$

where ρ_w is the water density, D is the external diameter of the structural element (i.e. tunnel or cable), C_I is the inertial coefficient, C_D is the drag coefficient, a_w and a_s are the water particle and structure acceleration, respectively,

v_w and v_s are the water and structure velocity, respectively. Here C_D=1.0 and C_I=2.0 are assumed.

This equation is commonly used to compute the hydrodynamic forces induced by wind waves and currents on offshore structures but it can be used to roughly estimate hydrodynamic loadings during seismic events, once the water velocities and accelerations due to seaquake are determined. Neglecting the water motion due to the propagation of vertical seismic waves, the first term of Eq. (1) becomes the so-called added mass, that is, the mass of water surrounding the tunnel and moving along with it, thus noticeably increasing the tunnel inertia, and the second term of Eq. (1) represents the hydrodynamic damping, which therefore increases the overall damping.

Here the effect of the vertical motion of the water during a seismic event is assessed, using kinematics water data recorded during the fault rupture simulation at a grid of stations located in the water layer.

4. Results of the analyses

4.1. Dynamic properties

The first 300 vibration modes are extracted for all case studies considered. This number of vibration modes feature a total participant mass always larger than 95% of the total structural mass.

A large number of vibration modes regard only transverse oscillations of the cables. In shorter SFTs (L=500 m), the vibration modes involving transversal oscillations of the tunnel are similar to those of a simply supported beam. The first vibration mode always involves horizontal oscillations of the tunnel whereas the second one regards its vertical oscillations; the corresponding vibration periods range from 4.48 to 7.40 sec, the larger ones being related to horizontal vibration modes of SFT solutions featuring CH cable systems. The participating mass of the first modes is about 80% of the total mass of the system.

Similar considerations can be made for longer crossings but some differences from the shorter crossings can be pointed out. The tunnel bending vibration modes feature a progressively increasing number of waves, whose shape is clearly affected by the presence of the stiffer cable groups located at the sloped part of the seabed close to the shores. As a matter of fact part of the ends of the tunnel do not participate to the first vibration modes; this leads also to a reduction of the participating mass of the first modes to 50-60% of the total mass. The length of this part progressively reduces in higher modes, which feature larger frequency, thus involving also stiffer cable groups. Moreover, SFTs with larger crossing length feature a considerable lower difference between vibration frequencies related to successive vibration modes with respect to shorter crossing cases.

The first three vibration modes having a non-negligible participating mass (i.e. with an even number of waves) are depicted in Fig. 5 for two case studies. Their periods and participating mass is indicated too.

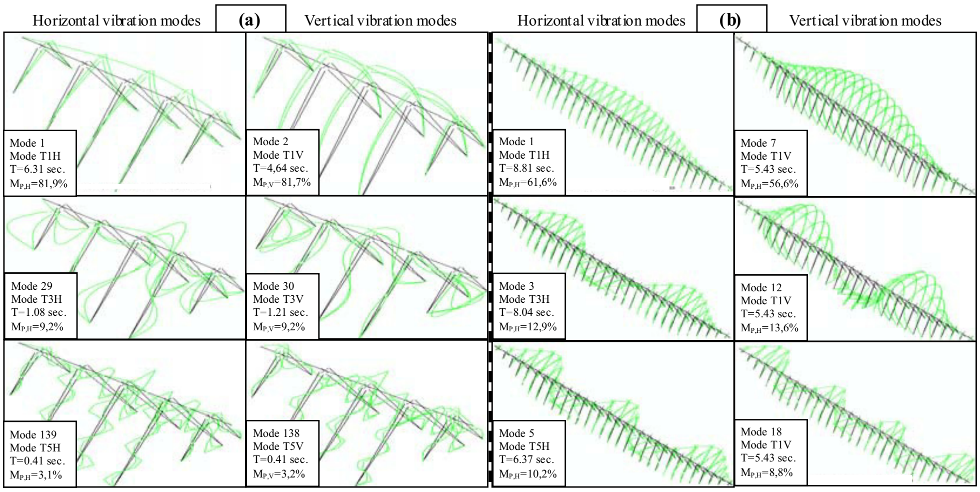
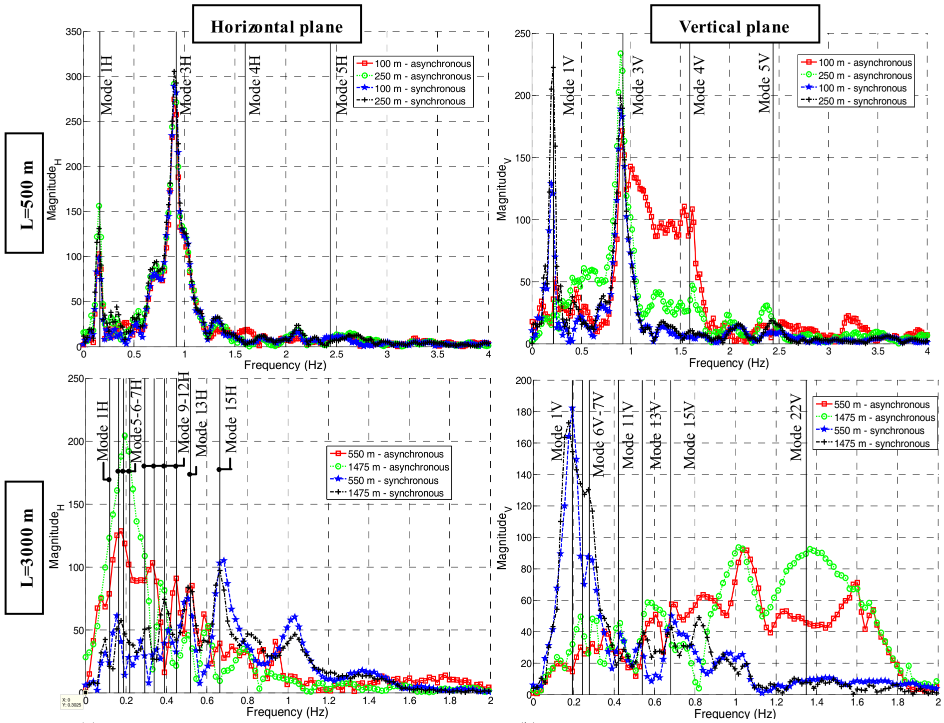


Fig. 5. Most relevant tunnel vibration modes for CW cable system, i=100m (a) L=500 m; (b) L=3000 m

4.2. Structural response

The Fourier transform of horizontal and vertical acceleration time-history of some tunnel sections (100 m, 250 m for L=500 m; 550 m, 1475 m for L=3000 m) is calculated, in order to assess the frequency content of tunnel vibrations. For SFTs featuring shorter crossing length (500 m) the first (Mode T1H, T1V) and the third (Mode T3H, T3V) tunnel vibration modes are the most excited ones (Fig. 6a), whereas for longer crossings, a larger number of modes contribute to the tunnel vibrations (Fig. 6b). The multi-support excitation gives rise to a significant excitation of the tunnel vibration modes whose deformed shape features an even number of sinusoidal waves, thus a participating mass equal to zero; these modes are clearly not excited in case of synchronous ground motion (Fig. 6). Moreover in the vertical plane the multi-support excitation seems to excite the vibration modes having larger frequency more than the synchronous excitation (Fig. 6).



(a) (b)

Fig. 6. Fourier transform of acceleration time history for relevant tunnel sections in the horizontal and vertical planes (cable system CW, i=50 m)

The tunnel stress state occurring during the earthquake is monitored; in particular the attention is focused on the bending moments, representing the most onerous stress condition. Fig. 7 shows the maximum values of the bending moments attained along the tunnel during the analyses (asynchronous-w are the diagrams related to asynchronous ground motion including the vertical water motion). The results of the analysis show that the shorter SFTs, being stiffer, are subjected to larger bending moments, whose maximum values are generally attained close to the mid-span section (Fig. 7a). For longer crossing cases the maximum values are lower and in many cases do not occur close to the mid-span section, as the contribution of higher vibration modes is more relevant (Fig. 6b). Increasing the number of cable groups per tunnel module leads to unnoticeable variations of the maximum bending moments, thus giving as the only advantage the reduction of permanent stress acting in the tunnel. Similarly, CW cable systems do not lead to important variations in the maximum values of the tunnel bending stress and sometimes offer slightly worse performance than CH ones when synchronous ground motion is considered. Synchronous ground motion often represents the most onerous excitation, in particular for longer crossing cases (Fig. 7b). However this condition should be caused by the fact that for the synchronous excitation scenario the ground motion relative to the east coast of the tunnel has been used, where the larger values of the PGA are attained.

The contribution of the propagation of vertical ground motion proves to be beneficial, especially for longer SFTs, as the vertical bending moments substantially reduces in the central part of the tunnel (Fig. 7b). This result can be explained by observing that the hydrodynamic force due to the water motion is in phase with the water motion itself, whereas the seismic effective forces are out of phase with the ground motion generating them; since the vertical water motion and the ground motion given by the simulations are in phase, the hydrodynamic and seismic effective forces turn out to be out of phase and thus the vibrations induced by the latter ones are reduced by the former ones.

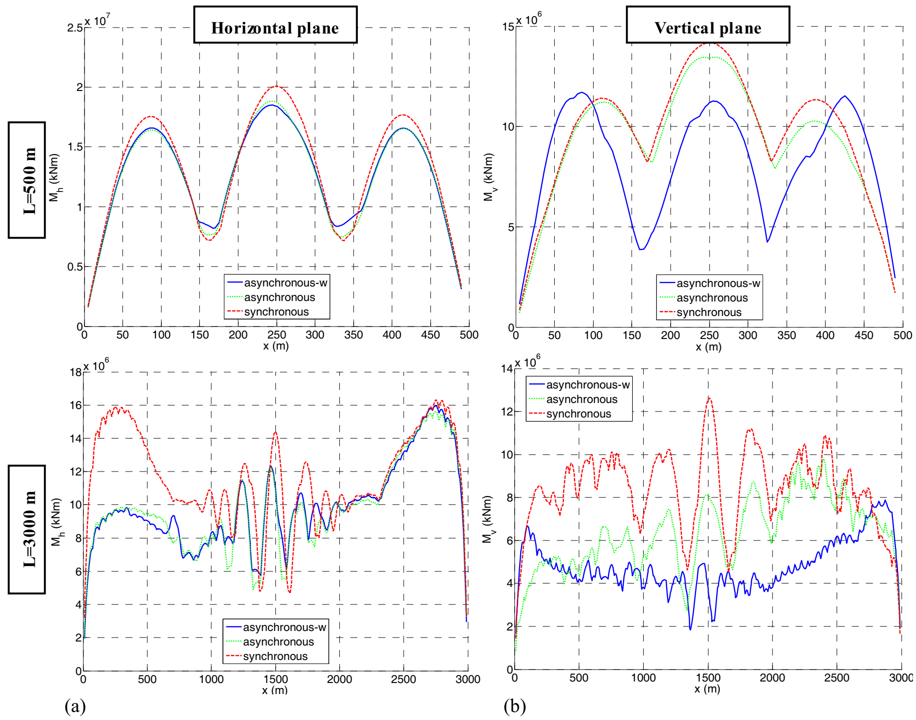


Fig. 7. Distribution of the maximum values of tunnel bending moments in the horizontal and vertical planes (cable system CW, i=50 m)

The maximum cables axial force is always lower than the cables design strength for shorter crossing cases (Fig. 8a), whereas very large values can occur for longer SFTs in cable groups located close to the shores on the sloped parts of the seabed (Fig. 8b), which feature larger axial stiffness.

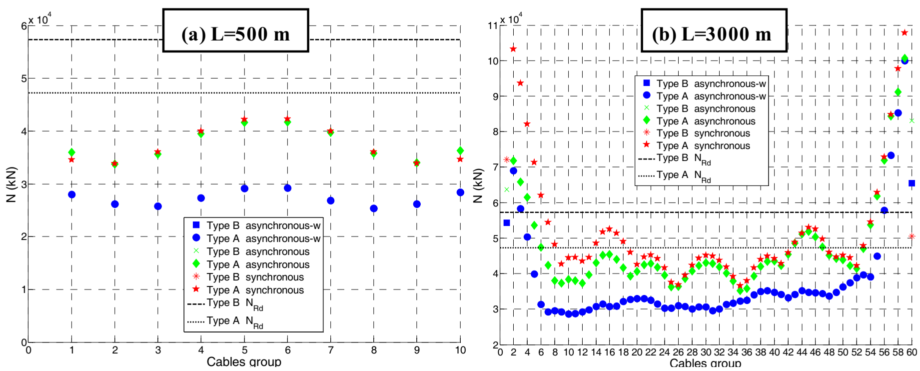


Fig. 8. Distribution of the maximum values of inclined (Type A) and vertical (Type B) cables axial force (cable system CW, i=50 m)

In case of longer SFTs, the axial force time history in the cables feature huge peaks, sometimes exceeding the cable strength, generally right after the slackening of the cable occurs; this behaviour seem to be caused by the high intensity of the ground shaking in both the horizontal and vertical plane. Therefore two additional analyses were performed, increasing the residual buoyancy permanently acting on the tunnel (considering a Buoyancy Ratio equal to 1.4) and increasing the cables diameter (approximately 50% larger) to satisfy the cables strength checks. Increasing the residual buoyancy did not prove to be effective, as it did not prevent the slackening of the cables not reducing their maximum axial force, whereas increasing the cables diameter the maximum axial forces didn't increase noticeably, thus allowing for the cables strength checks to be satisfied for almost every cable.

5. Conclusions

The present study investigates the seismic response of SFTs, considering synchronous and multi-support excitation and taking also into account the propagation of vertical ground motion in the water.

In general the oscillations of SFTs during the considered seismic event involve several vibration modes, in particular for longer SFTs. Multi-support ground motion can lead to significant excitation of vibration modes featuring zero participating mass, which are not excited in case of synchronous ground motion. As it could be expected, the tunnel displacements and stresses are noticeably larger for the case studies with shorter crossing length, as the vibration frequencies of their fundamental modes are higher and more diffuse in the earthquake frequency content.

The contribution of the propagation of vertical ground motion proves to be beneficial, especially for longer SFTs, as the vertical bending moments substantially reduces in the central part of the tunnel. This is due to the fact that hydrodynamic and seismic effective forces acting on the tunnel are out of phase and thus the vibrations induced by the latter ones are reduced by the former ones.

For longer crossing cases large values of the cables axial force occur in the cable groups located near the shore approaches, being shorter and thus stiffer. These peak values often occur right after the slackening of the cables, probably caused by the extremely high intensity of the ground motion, whose energy is concentrated in a small time period. However this problem could be solved by increasing the cables diameter, changing the cable system configuration close to the shores, using damping devices or replacing the cables with rigid members, featuring a ductile post-yielding behaviour.

Further investigations are needed, considering other seismic scenarios, to study in more detail the role of the propagation of vertical motion into water and to understand more deeply the issue of cable groups located close to the shore approaches.

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