Seismic wave passage effect on dynamic response of submerged floating tunnels

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Abstract

In this paper, a numerical analysis is performed to investigate the dynamic characteristics of submerged floating tunnels (SFTs) under seismic wave passage effect. The large mass method is examined firstly and then used to simulate numerically the dynamic response of SFTs. It is found that the dynamic response of SFTs is influenced remarkably by the multi-support excitation with the seismic wave passage effect and varies with the velocity of seismic waves in a non-monotone way. The numerical results show that the response under the multi-support excitation is much larger than that under the simultaneous excitation except for the displacement response in some velocities, and there exists a peak velocity of seismic waves that corresponds the maximum response of the structure. In addition, for every velocity, the most remarkable response appears near the shore connection corresponding to output end of the seismic wave. This finding reflects the unique behavior of SFTs under the multi-support excitations and is meaningful to the seismic design of SFTs as well as other periodic long-span structures.

Keywords: submerged floating tunnels; multiple support excitations; wave passage effect; large mass method; resonance

1. Introduction

Submerged floating tunnels (SFTs or Archimedes Bridges) are a new type of structural concept proposed for crossing lakes, sea-straits and fjords (Fig. 1) [1]. It consists of several linked cylindrical tubes stayed at a certain depth under water, anchored either by cables connected to the sea bed or floating pontoons to the surface of the sea depending on site conditions and different buoyancy weight ratios. As compared with the conventional bridges, a SFT is a more environmental-friendly and economical structural type as it does not bother to dig under seabed, as did usually for the conventional tunnels, and is relatively more convenient to build.

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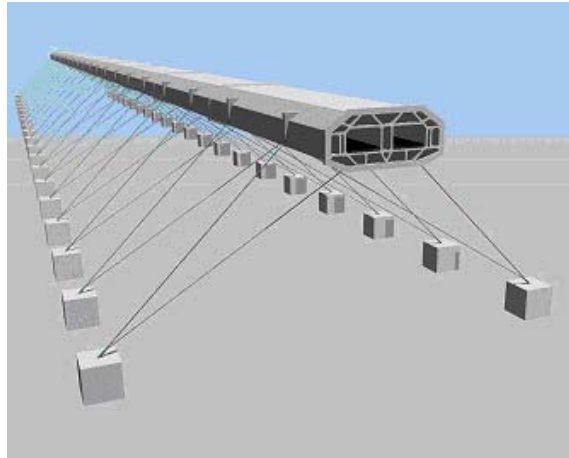E-mail address: ghuang@imech.ac.cn

Fig. 1. Overview of SFT

However, none of SFTs has been built in the world from its initial conception in the 20th century till now despite its promising future. A main concern is about the complexity of its dynamic response under environmental forces. One of the issues is the dynamic response under seismic excitation. Several research work has been done to resolve this issue. Brancaleoni et al. [2] studied the dynamic response of different types of tunnels under seismic excitation. Satoshi Morita's research [3] revealed that the compressibility of water can not be ignored without causing inaccuracy in computing the seismic response. In Di Pilato et al.'s work [4], an ad hoc nonlinear five-degree of freedom finite element was developed to model the anchor bar and implemented in a numerical procedure to analyze the 3D dynamic response of SFT under multiple support seismic excitation. Xiao and Huang studied the dynamic behavior of submerged floating tunnels under uniform seismic excitation and the seismic characteristics of an SFT with different bridge-shore connection types [5]. Since SFTs are used for crossing lakes and fjords, they are usually long-span structures. Time delays caused by the arrival of earthquake waves on the different excitation sites may play an important role in their dynamic characteristics, which is called wave passage effect. The previous analyses on conventional long-span bridges such as cable-stayed bridges have shown that the seismic wave passage effect can not be neglected while considering the dynamic response of this kind of structures [6, 7].

This paper studies in detail the behavior of SFTs under seismic wave passage effect with an emphasis on the influence of different seismic wave velocities. Time domain analysis is performed by using commercial code ANSYS11.0. For the sake of simplifying the procedure, soil-structure interaction is ignored and the large mass method is incorporated in ANSYS11.0 in conducting the computation. Hydrodynamic force due to Fluid-structure interaction is considered by using the Morison's equation and thus the problem is a non-linear one. The time history record of acceleration from El Centro earthquake is used as an excitation source and the structural dynamic responses under various seismic wave velocities are computed and compared. From the results, some distinguishing features of the response are revealed, showing a unique resonance effect, which hopefully would be of some value for the aseismic design of SFTs and similar periodic long-span structures.

2. Computational model

2.1. Modeling of tunnel and environmental loadings

The tunnel module of an SFT is modeled by the three-dimensional PIPE59 element [8] with the pipe option activated, while anchoring system is modeled by the same element with the cable option activated. The constraints where anchoring bars are connected to tunnel structure and ground are hinge joints, which are also assumed to be same as the tunnel-shore connections.

The aim of the analysis is to simulate the dynamic behavior of submerged floating tunnels under transverse seismic wave excitation. The seismic loading is the dominating excitation. In spite of that, buoyancy and the earthquake-induced hydrodynamic loading due to fluid-structure interaction are also considered. The latter is simply expressed by the modified Morrison's equation [9, 10]. The force per unit length acting in the direction normal to the element axis is given as:

$$\overline{\mathbf{q}} = C_D \rho \frac{D}{2} |\dot{\mathbf{u}} - \dot{\mathbf{x}}| (\dot{\mathbf{u}} - \dot{\mathbf{x}}) + C_M \rho \pi \frac{D^2}{4} (\ddot{\mathbf{u}} - \ddot{\mathbf{x}}) \tag{1}$$

where the following symbols are introduced:

ρ is the density of water;
D is the element diameter;
C_D is the drag force coefficient;
C_M is the inertia force coefficient;
$\dot{\mathbf{x}}$, $\ddot{\mathbf{x}}$ are the velocity and acceleration vectors of the structure, respectively;
$\dot{\mathbf{u}}$, $\ddot{\mathbf{u}}$ are the velocity and acceleration vectors of water, respectively;
$\overline{\mathbf{q}}$ is the hydrodynamic force vector.

Initial state of surrounding water is assumed to be still, i.e., wave and current effects are not considered. For inviscous water, the state of still water will remain during transverse earthquake. C_D and C_M are functions of Reynolds number and cylinder roughness, which are, however, defined as constant values in this paper, for convenience.

2.2. Equation of motion and solution strategy

For the afore-mentioned SFT model under multi-support excitation, the governing equation, based on structural dynamics [11], is

$$\begin{bmatrix} \mathbf{M}_{ss} & \mathbf{M}_{sb} \\ \mathbf{M}_{bs} & \mathbf{M}_{bb} \end{bmatrix} \begin{pmatrix} \ddot{\mathbf{X}}_s \\ \ddot{\mathbf{X}}_b \end{pmatrix} + \begin{bmatrix} \mathbf{C}_{ss} & \mathbf{C}_{sb} \\ \mathbf{C}_{bs} & \mathbf{C}_{bb} \end{bmatrix} \begin{pmatrix} \dot{\mathbf{X}}_s \\ \dot{\mathbf{X}}_b \end{pmatrix} + \begin{bmatrix} \mathbf{K}_{ss} & \mathbf{K}_{sb} \\ \mathbf{K}_{bs} & \mathbf{K}_{bb} \end{bmatrix} \begin{pmatrix} \mathbf{X}_s \\ \mathbf{X}_b \end{pmatrix} = \begin{pmatrix} \mathbf{P}_f \\ \mathbf{P}_b \end{pmatrix} \tag{2}$$

in which $\mathbf{M}$, $\mathbf{K}$ and $\mathbf{C}$ stand for mass, stiffness and damping matrices; $\mathbf{X}$, $\dot{\mathbf{X}}$ and $\ddot{\mathbf{X}}$ are vectors of dynamic displacement, velocity and acceleration of the structure, respectively. The subscripts *s* and *b* denote the unconstrained degree of freedoms and constrained degree of freedoms, respectively. Here, they are corresponding to structural and ground ones, respectively. $\mathbf{P}_f$ and $\mathbf{P}_b$ are the load vectors on the unconstrained and constrained degree of freedoms, specifically the force vectors caused by hydrodynamic and seismic excitation, respectively.

Seismic wave passage effect is simulated by introducing time delays with reference to different wave velocities between various support points of the structure; the computation is realized by large mass method [12]. Before the simulation, a numerical experiment is carried out to validate this method. As will be seen in the next section, the depicted SFT model above is computed under simultaneous seismic excitation with and without using large mass method, and the two results fit well, almost indistinguishable, verifying this method.

3. Case study

3.1. Modeling parameters

A SFT model (Fig. 2) based on published data and design criteria about crossing of the Messina Strait between Punta S. Ranieri and Catona is constructed [13]. The computation conditions are as follows:

- The tunnel structure is 4680 meters long and fixed at a depth of 30 meters below the surface of the sea where the water depth is a constant value of 210 meters and water density is 1000kg/m³. The tunnel section is a steel-

concrete composite pipe with external and internal diameter of 15.95 meters and 13.95 meters, respectively. The equivalent elastic modulus is 3.0×10^{10} Pa.

- The anchoring bars are considered to have a fixed length and spread with a constant spacing span of 72 meters along the tunnel structure (See Fig. 2). Also, it is considered that the anchoring system lies in the plane normal to the axis of tunnel structure and is inclined with a constant angle of 45°. The section of the anchoring system is a pipe with external and internal diameter being 1.85 and 1.72 meters, respectively. The elastic modulus is assumed to be 2.1×10^{11} Pa.
- Soil-structure interaction effect is neglected. Constant values of 1.0 and 2.0 are adopted as the drag force coefficient and inertia force coefficient respectively in the generalized Morison's equation. A damping ratio of 0.05 is assumed for the structure.
- As regard to the direction of seismic excitation, only transverse one is considered. Seismic wave goes from the left end to the right end in the model (See Fig. 2), which means the wave is taken as shear wave and only its horizontal component is considered. A 50-second-long El Centro earthquake time history record (Fig. 3) of acceleration is used as input excitation, with PGA being 0.32g. Various seismic wave velocities are considered.
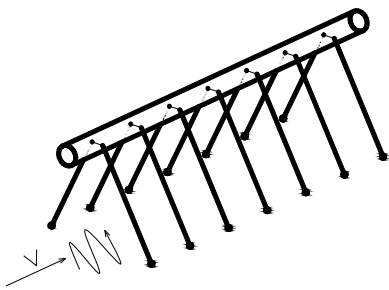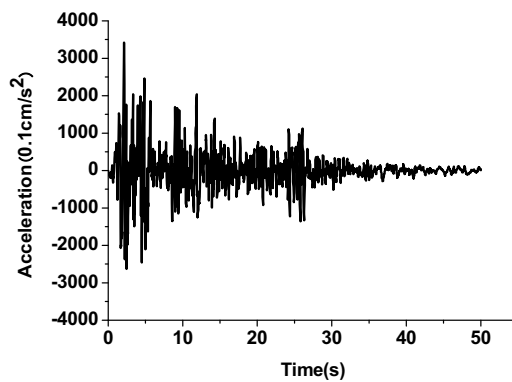

Fig. 2. SFT model

Fig. 3. Time history of El Centro seismic wave

3.2. Results and discussion

Some results of the analysis are shown below. Table 1 shows the first 50 modal frequencies of the SFT model. Figs. 4 and 5 are mainly for the purpose of validating the large mass method. In these figures, the envelopes of the transverse moment, transverse shear force and time history of transverse moment at middle section of tunnel computed with and without large mass method are compared. It can be easily found that the two curves in each graph coincide well, thus validating the use of large mass method.

Figs. 6 and 7 illustrate the envelopes of the transverse moment, transverse shear force and transverse relative displacement. The latter is acquired by subtracting the displacement of base point from the displacement of the corresponding point at the tunnel structure, under wave passage effect and simultaneous excitation. From these figures, the characteristics of dynamic response of SFT under wave passage effect can be summarized as follows:

- Dynamic responses of SFT are generally magnified with the wave passage effect with some exceptions in the relative transverse displacement. Note that simultaneous excitation corresponds to the infinite velocity in the figures.
- The dynamic response, no matter whether it is the transverse moment, transverse shear force or relative transverse displacement, reaches its peak at various sections of the tunnel, when subjected to the wave passage effect with the velocity span of about 240m/s to 260m/s. The maximum transverse moment at the velocity of

260m/s is nearly three times that of simultaneous excitation, as shown in Fig. 6(a). Similar results can be found in both Fig. 6(b) and Fig. 7.

- Maximum response usually occurs at the right end of the tunnel structure, or the output end of seismic wave. It seems that the response is accumulating with the traveling of the seismic wave along the tunnel structure until it reaches the peak near the right end, especially as shown in Fig. 7.

Table 1. First 50 modal frequencies (Hz) of the SFT model

| No. of modes	1	2	3	4	5	6	7	8	9	10
Frequency(Hz)	0.20240	0.32125	0.40479	0.42508	0.42510	0.42518	0.42537	0.42575	0.42642	0.42749
No. of modes	11	12	13	14	15	16	17	18	19	20
Frequency(Hz)	0.42908	0.43134	0.43442	0.43848	0.44370	0.45023	0.45825	0.46789	0.47931	0.49262
No. of modes	21	22	23	24	25	26	27	28	29	30
Frequency(Hz)	0.50792	0.52529	0.54478	0.56642	0.59023	0.60719	0.61621	0.63680	0.63681	0.63685
No. of modes	31	32	33	34	35	36	37	38	39	40
Frequency(Hz)	0.63696	0.63719	0.63761	0.63830	0.63934	0.64082	0.64251	0.64286	0.64433	0.64558
No. of modes	41	42	43	44	45	46	47	48	49	50
Frequency(Hz)	0.64909	0.65353	0.65904	0.66575	0.67378	0.67457	0.68328	0.69436	0.70689	0.70714
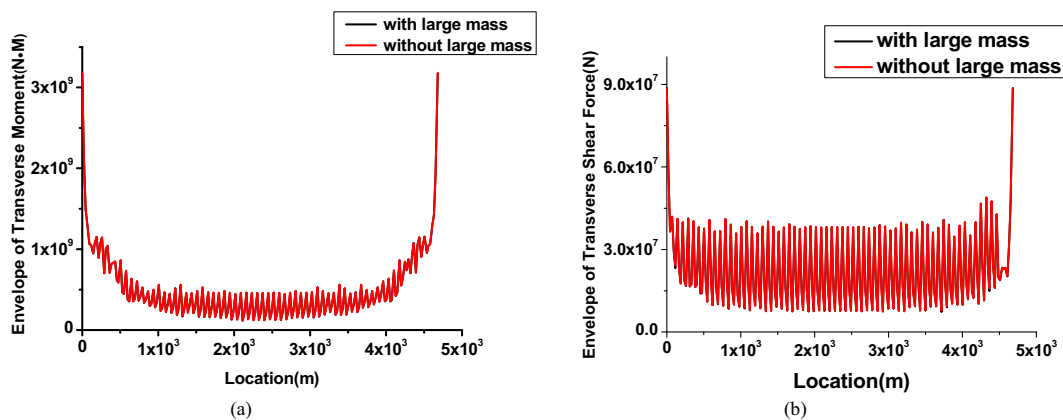
Fig. 4. Dynamic response of SFT under simultaneous seismic excitation computed with and without large mass method. (a) Envelope of transverse moment; (b) Envelope of transverse shear force
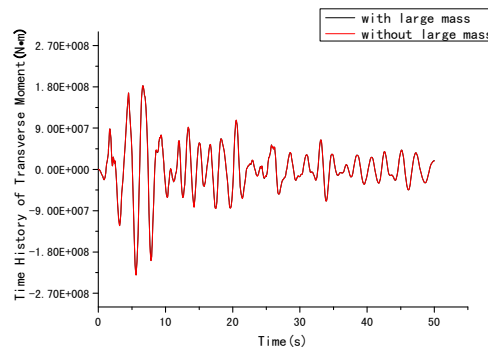

Fig. 5. Time history of transverse moment at middle section of SFT computed with and without large mass method, respectively
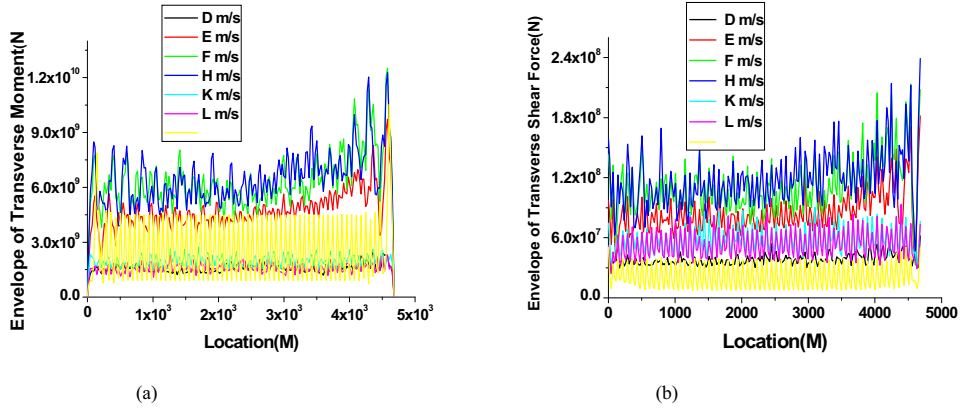
Fig. 6. Dynamic response of submerged floating tunnels under simultaneous excitation and seismic wave passage effect. (a) Envelopes of transverse moment; (b) Envelopes of transverse shear force
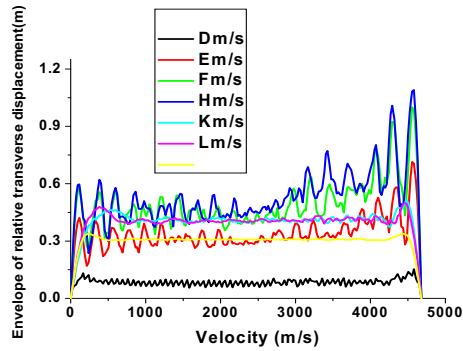

Fig. 7. Envelopes of relative transverse displacement of SFT under simultaneous excitation and seismic wave passage effect, respectively
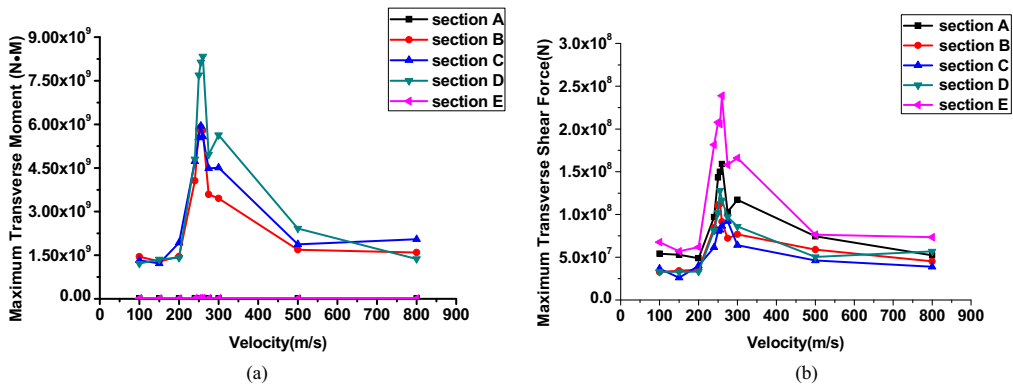

Fig. 8. Maximum transverse response of different sections on SFT under wave passage effect with various wave velocities. (a) Maximum transverse moment; (b) Maximum transverse shear force

More detailed views can be found in Figs. 8(a) and 8(b), which illustrate the maximum dynamic response of different sections against seismic wave velocities. The five sections A, B, C, D and E are defined as the left end, one-fourth, two-fourth, three-fourth and right end of the tunnel structure, respectively. In these figures, it can be clearly seen that the dynamic responses of different sections in the structure reach their peaks with nearly the same seismic wave velocity, being about 250m/s for the present model.

The above results indicate much remarkable effect of seismic wave passage effect, as compared with that reported previously for the conventional and cable-stayed bridges. SFT features longer span and more periodic supports that may cause a resonance owing to the periodic hitting of seismic wave. When the hitting frequency coincides with the structural natural frequency of certain mode and the predominant frequency of seismic wave, the response is magnified gradually with the propagation of seismic wave. A detailed analytical study on this mechanism will be presented in another companion paper of the authors.

Intensive response with the seismic wave passage effect demonstrate that special attentions should be paid to the multiple support seismic excitation in the design of SFTs. Mitigation of the resonance is an important issue for further research. The present study is helpful to the more comprehensive understanding of the seismic dynamic response of SFTs and their aseismic design in practice.

4. Conclusion

A numerical model of submerged floating tunnel is built by using finite element method. Large mass method is incorporated and implemented to perform the study of seismic wave passage effect, which is proved to be an effective way. Time domain analysis on an example of SFTs illustrates that the dynamic response of the structure subjected to the multiple support seismic excitation is more intensive than that subjected to the uniform seismic excitation. This distinguishing feature of SFTs necessitates the special concern with the seismic wave passage effect in the aseismic design of this kind of periodic long-span structures.

Acknowledgments

References

[1] Ahrens D. Submerged floating tunnels-A concept whose time has arrived. *Tunneling and Underground Space Technology* 1997; 12 (2): 317-36.

[2] Brancaleoni F, Castellani A, D'Asidia P. The response of submerged tunnels to their environment. *Engineering Structures* 1989; 11: 47-56.

[3] Morita S, Mizuno Y, Mineta M, Kurosaki K. Earthquake response analysis of submerged floating tunnels considering water compressibility. *Proceedings of the Fourth International Offshore and Polar Engineering Conference*, 1994, Osaka, Japan, p. 20-6.

[4] Pilato MDi, Perotti F, Fogazzi P. 3D dynamic response of submerged floating tunnels under seismic and hydrodynamic excitation. *Engineering Structures* 2008; 30: 268-81.

[5] Xiao J, Huang GJ. Influence of shore-bridge connection to the seismic behavior of submerged floating tunnels. *Proc. of the 16th structural engineering conference*, 2007, p. 501-4. (in Chinese) .

[6] Bogdanoff JL, Goldberg JE, Schiff AJ. The effect of ground transmission time on the response of long structures. *Bulletin of the Seismological Society of America* 1965; 55: 627-40.

[7] Aly S. Nazmy, Ahmed M. Abdel-Ghaffar. Effects of ground motion spatial variability on the response of cable-stayed bridges. *Earthquake Engineering and Structural Dynamics* 1992; 21: 1-20.

[8] ANSYS Inc. *ANSYS Release 11.0 Documentation*. 2007.

[9] Wilson JF. *Dynamics of Offshore Structures*. New Jersey: John Wiely & Sons, Inc, 2003.

[10] Chakrabarti SK. *Hydrodynamics of offshore structures*. WIT Press / Computational Mechanics, 1987.

[11] Clough RW, Penzien J. *Dynamics of Structures*. 3rd ed. Computers & Structures, Inc; 2003.

[12] Leger P, Ide IM, Paultre P. Multiple-support seismic analysis of large structures. *Computers & Structures* 1990; 36 (6): 1153-8.

[13] RINA report. *Verification of the basic design called Archimedes Bridge for the company Ponte di Archimede Nello Stretto di Messina S.p.A.*, 1984.