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Transverse earthquake response and design analysis of submerged floating tunnels with various shore connections

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Abstract

The study investigates the seismic response of the Submerged Floating Tunnel (SFT) with different types of connection between the ends of SFT and the shore, including the rigid connection, hinged connection, elastic bearing connection, bi-linear elastic bearing connection, and passive isolation connection. In addition, the influence of various design parameters of the different types of shore bearings on the dynamic behavior of SFT is studied, involving the elastic stiffness of the elastic bearing, the secondary stiffness and turning force of stiffness of the bi-linear elastic bearing, plastic stiffness and yield shear force of the passive isolation bearing. An effective design method for the parameters of the bearing is proposed. The transverse stiffness of the cable which represents the stiffness of the whole structure is introduced as a reference of the bearing design. The seismic response of SFT can be significantly reduced by choosing proper parameters of the bearing based on the principle of redistribution of stiffness.

Keywords: submerged floating tunnel; seismic response; shore connection

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1. Introduction

Submerged Floating Tunnel (SFT) is an innovative crossing-strait transportation which is usually suspended above the sea floor and anchored by the support system of either pontoons at the surface or the anchors fixed in the sea bed. Although quite a few attentions have been paid to the design and analysis of SFT so far, there exists no real SFT built in the world. One of the main factors is how to design the structure so as to ensure its safety.

Earthquake is one of most important environmental factors that may induce the failure of the whole structure and so it is indispensable to investigate the behavior of the structure under earthquake. SFT is suspended in the water and made up of reinforcement concretes which may crack under the extreme load. Therefore, the plastic property of reinforcement concretes applied in the seismic design of the conventional structures is not suitable to SFT and then improving the earthquake resistance capacity is an especially important issue for the design of SFT.

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Several meaningful researches have been done about the earthquake analysis of SFT. Two different types of SFT, such as short span with cable anchors and long span with rigid pier supports, have been studied by Brancaleoni to investigate the earthquake response of SFT [1], in which the definition of fluid motion generated by seismic effects was also proposed. The works of Fogazzi et al. [2] and Di Pilato et al. [3] considered the multiple support seismic effort and developed a simplified procedure to model the fluid-structure and soil-structure interaction effects. They also presented an "ad hoc" finite element for modeling the behavior of anchor elements.

According to previous study, remarkable increase of transverse bending moment and shear force are shown near the shore connection when the connection is rigid. The intensive response may be due to the unreasonable stiffness distribution along the tunnel. The length of SFT will be usually more than 1 kilometer and the anchor systems, like cables, can be simplified as elastic bearing. If the shore connection is rigid, the stiffness of the whole structure will dramatically change near the shore connection. The investigations of the damage of buildings and bridges under earthquake show that structures are more likely to failure at the site where the stiffness changes dramatically [4].

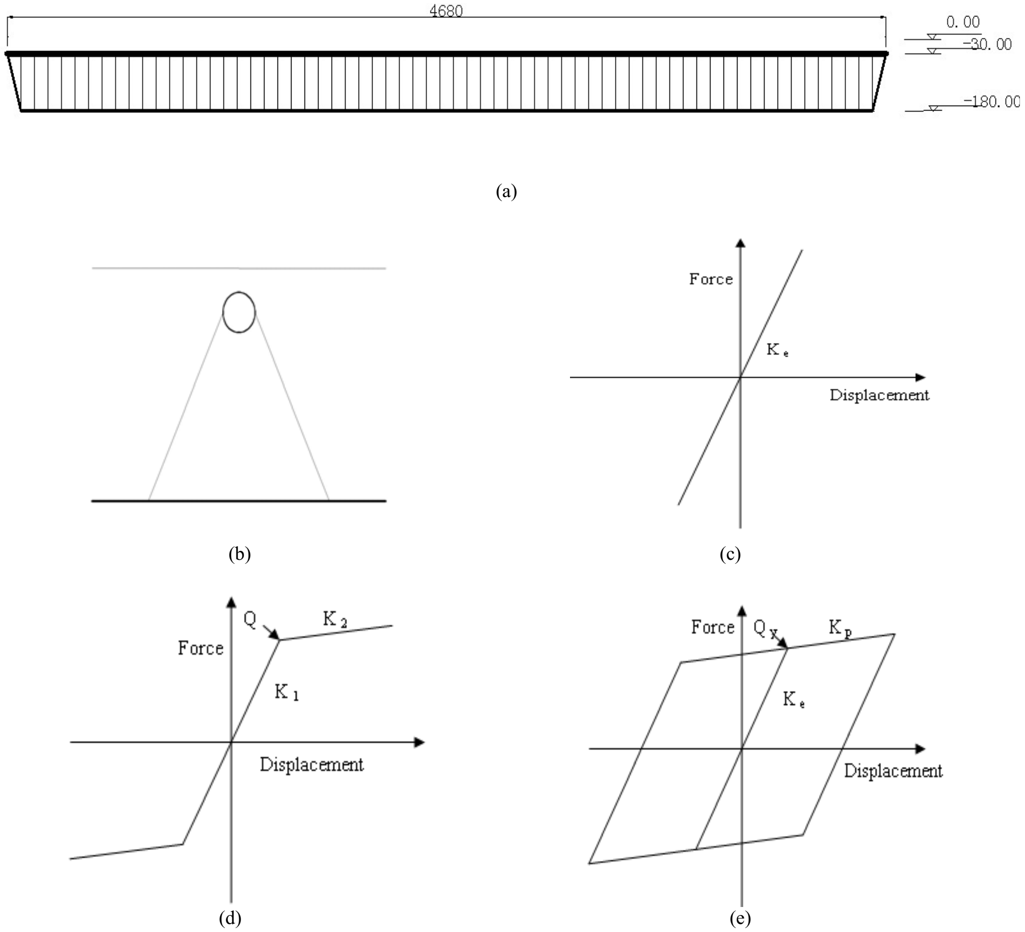
The elastic, bi-linear elastic and passive isolation (or elastoplastic) bearings are proposed in this paper to adjust the stiffness distribution, aiming to seek for an effective way to reduce the dynamic response of SFT subjected to seismic excitation. The design of the elastic bearing considers the stiffness of the cables. Two dimensionless parameters R_1 and R_2 are introduced, which are the ratios of transverse stiffness of elastic bearing and transverse plastic stiffness of the passive isolation bearing over the transverse stiffness of the cables, respectively. They represent the characteristics of stiffness distribution of the structure. It is shown that they greatly influence the dynamic response of SFT and are the most important factors in the design of the shore connection of the bearings. Although the internal force of SFT under earthquake can be reduced by using flexible elastic bearing, it may produce larger vibration in SFT during day-to-day performance. Therefore, a bi-linear elastic bearing is introduced in this paper. Its behavior remains stiffer during the usual service load and should be flexible under extreme load such as earthquake. Passive energy absorption devices such as lead-rubber bearings are commonly introduced as an isolation system to improve the damping of structures such as cable-stayed and highway bridges. It can successfully mitigate the vibration and internal force of structures under earthquake [5-9]. It is also applied as an alternative of shore connections for SFT. However, its design method and influence of the different parameters varies with the type of structures, since an important design principle of the isolation system for SFT is to adjust the stiffness distribution, besides energy dissipation as for bridges and buildings. The aim of this paper is to compare the five different types of connections and to determine the influence and design method of bearing parameters for SFT. Considering that SFT is a long-span structure and its bending stiffness is in general much less than longitudinal one, we confine our attention to the transverse earthquake response of SFT at present.

2. Modeling of SFT and shore connections

The effect of different types of shore connections on the seismic response and the influence of the bearing parameters are studied by the numerical simulation of Messina Strait (4680m) SFT which had been considered to put into construction before (Fig. 1(a) and (b)). A three dimensional beam element and a cable element are utilized to model the behaviors of the tunnel and cables, respectively. Internal rigid constraints are imposed on the end nodes of the cables and the master nodes of the beam of the tunnel.

The tunnel section is a thick steel-concrete pipe with the external diameter 15.95m, the internal diameter 13.95m and the equivalent moment of inertial $1637m^4$. The span of the cables is 72m and the weight per unit length of the tunnel is 1800kN/m. The assumed difference between buoyancy and weight is equal to 455kN/m. The water depth is 181m, corresponding to the deepest site over the crossing, and the tunnel is 30m below sea level. The anchor system is modeled through equivalent elements which have the same total area and slenderness with the real bar. The anchor bar is about 1m in diameter and 0.04m in thickness.

Fig. 1(c) depicts the mechanical property of the usual elastic bearing with the elastic stiffness, K_e. A bi-linear elastic model is introduced to model the transverse mechanical behavior of the bi-linear elastic bearing with the force-displacement relationship shown in Fig. 1(d), where K_1, K_2 and Q are the first and second stiffness and the turning force of stiffness, respectively. Meanwhile, a bi-linear hysteretic model element is introduced to model the behavior of the passive isolation bearing and a typical hysteretic loop for the bearing is shown in Fig. 1(e) [6] which is different evidently from the bi-linear elastic bearing, where K_e, K_p and Q_y are the first and second stiffness and the turning force of stiffness, respectively. The other shore connections are rigid and hinged ones, respectively.



(a)

(b) (c)

(d) (e)

Fig. 1. Sketch of Messina Strait SFT and mechanical characterization of various bearings: (a) Side view of SFT; (b) Front view of SFT; (c) Force-displacement relationship of elastic bearing; (d) Force-displacement relationship of bi-linear elastic bearing; (e) Force-displacement relationship of passive isolation bearing

3. Equations of motion and solution strategies

The structure is discretized by finite element method in time domain and modeled by beam elements and cable elements. Each element has two nodes at its ends and the mass is assumed to be lumped at the nodes. The beam element has six degrees of freedom at each node, including translations in x, y, and z directions and rotations about the x, y and z axes. The cable element has three degrees of freedom at each node including translations in x, y, and z directions. The cable element considers only the tension-compression behavior of the element. Soil-structure interaction effect and multi-support effect are not considered in this paper.

The equations of motion for SFT under uniform seismic excitation are expressed as

$$[M]\{\ddot{s}(t)\}+[C]\{\dot{s}(t)\}+[K]\{s(t)\}=-[M]\{a_g\}+\{F(t)\} \qquad (1)$$

where $[M]$ is the mass matrix of the structure; $[C]$ is damping matrix of the structure; $[K]$ is the stiffness matrix of the structure; $\{\ddot{s}(t)\},\{\dot{s}(t)\},\{s(t)\}$ are the acceleration, velocity and dynamical displacement vectors of the structure respectively; $\{a_g\}$ is the vector of ground motion, $\{F(t)\}$ is the hydrodynamic force under earthquake.

The water is assumed to be at rest at beginning and incompressible and inviscous. Then, the motion of water under earthquake is the same as that of the ground in the vertical direction and not affected by the transverse motion of the ground. The added mass effect to the vibration of the tunnel is considered in this model and the hydrodynamic force is simplified by Morison equation:

$$\mathbf{F} = C_M \frac{1}{4}\pi D^2 \rho \ddot{\mathbf{w}} - \rho\left(C_M - 1\right)\frac{1}{4}\pi D^2 \ddot{\mathbf{s}} + C_D \frac{1}{2}\rho\left|\dot{\mathbf{w}} - \dot{\mathbf{s}}\right|\left(\dot{\mathbf{w}} - \dot{\mathbf{s}}\right) \tag{2}$$

where $\mathbf{F}$ is the hydrodynamic force vector; C_M is the added mass coefficient; C_D is the drag force coefficient; $\ddot{\mathbf{w}}$ and $\dot{\mathbf{w}}$ are the acceleration and velocity vectors of water particle, respectively; $\ddot{\mathbf{s}}$ and $\dot{\mathbf{s}}$ are the acceleration and velocity vectors of the structure nodes, respectively; D is the diameter of the structure element.

In the seismic analyses, the motion of the tunnel based on the dead load deformation and the nonlinear dynamics analyses is solved with Newmark method. The structure damping matrix is assumed to be a Rayleigh type and the damping ratio is assumed to be 2%. The earthquake record of EI-Centro in vertical and transverse direction is adopted in the analysis and the Peak Ground Acceleration (PGA) is 341.7 cm/s^2 in transverse direction.

The commercial explicit finite element analysis program ANSYS LS-DYNA is utilized to model the different components of the structure and to analyze the dynamic responses of SFT. The time-history method with Newmark algorithm is used to solve the dynamic function.

4. Earthquake responses of SFT with different types of shore connections

The response of SFT under earthquake is highly dependent on the manner in which the tunnel is connected to the shore foundation. A rigid connection will result in reduced displacement in the connection and higher forces during earthquake. In contrast, a soft connection will induce larger displacement in the connection and keep the seismic forces at lower levels. In the analysis, the parameters of the five types of the shore connection are as follows:

A: The tunnel is rigidly connected to the shore foundation;

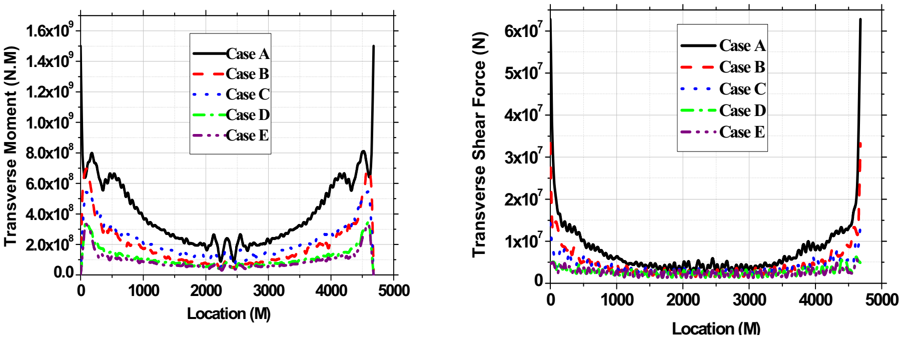
B: The tunnel is hinged at the shore foundation;

C: The tunnel is connected to the shore foundation with an elastic bearing and the transverse stiffness of the bearing is $2k_h$ ($k_h = k\sin^2\theta$; k_h is the transverse stiffness of cables; k is the axial stiffness of cables; θ is the initial angle between the cables and the vertical direction);

D: The tunnel is connected to the shore foundation with a bi-elastic bearing. The first transverse elastic stiffness of the bearing is $2k_h$; the second transverse elastic stiffness of the bearing is $0.2k_h$ and the turning force of stiffness is 0.1W where W is the portion of the deck weight carried by the bearing;

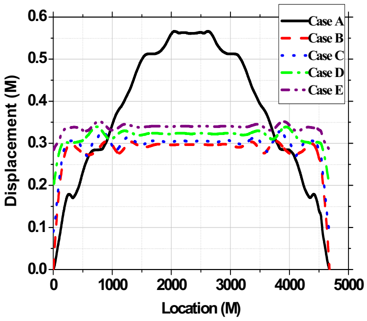
E: The tunnel is connected to the shore foundation with an elastoplastic bearing. The transverse elastic stiffness of the bearing is $2k_h$; the transverse plastic stiffness of the bearing is $0.2k_h$ and the yield force of the bearing is 0.1W.

The seismic responses are shown in Fig. 2. It can be seen that free of the moment restraint (case B) will greatly reduce the seismic response, as compared with the rigid connection (case A). The maximum response is reduced approximately to 47.6% in the transverse moment, to 55.6% in the transverse shear force, and to 54.1% in the transverse displacement. With changing of the stiffness distribution of the whole structure by using the elastic bearing (case C) and bi-linear elastic bearing (case D) as shore connections, the responses can be reduced to 42.9% and 21.0% in the transverse shear force and to 79.9% and 51.4% in the transverse moment, respectively, as compared with the response of the hinged connection. Furthermore, the passive isolation connection can reduce the responses to 18.9% in the transverse shear force and to 49.1% in transverse moment, as compared with those of the hinged connection, slightly more effective than bi-linear elastic bearing with the same parameters.



(a) Transverse Moment

(b) Transverse Shear Force



(c) Transverse Displacement

Fig. 2. Comparison between the envelopes as the seismic responses of SFT with different shore connections

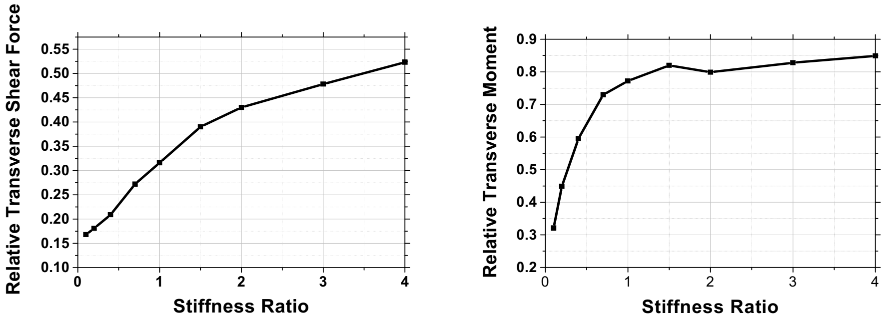
5. Parametric design of elastic bearing and their effects on seismic response

The design principle of the elastic bearing is to change the stiffness distribution of whole structure. The transverse stiffness of the elastic bearing affects the dynamic behavior and, accordingly, the seismic performance of SFT. The aim of this section is to investigate the seismic behavior of SFT with the changing of the stiffness of elastic bearing. It can provide a simplified design method and some advice for the connection design.

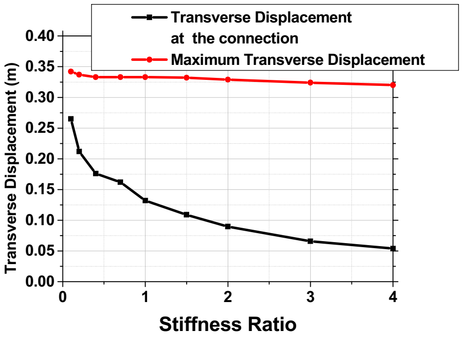
A dimensionless parameter R_1 is introduced to represent the stiffness distribution of SFT, which is the ratio of the transverse stiffness of the elastic bearing over the transverse stiffness of cables. The seismic responses of SFT with different transverse stiffnesses ($0.1\,k_h$, $0.2\,k_h$, $0.7\,k_h$, $1\,k_h$, $1.5\,k_h$, $2\,k_h$, $3\,k_h$, $4\,k_h$) are investigated to provide detailed information for designing. The results are shown in the Fig. 3.

The maximum transverse shear force increases with the increasing stiffness of the bearing in an approximately linear way. The influence of transverse moment which may induce the failure of the tunnel is more complex and important in the design of the elastic bearing. When the transverse stiffness is smaller than $1\,k_h$, the transverse moment reduces dramatically with the reduction of the transverse stiffness. The relative transverse moment (as compared with the responses of the hinged connection) ranges from 32.1% to 77%. While, when the transverse stiffness is between $1\,k_h$ and $4\,k_h$, there is not a dramatically change of the transverse moment reduction, with the relative value ranging from 77% to 85%. The transverse displacement of the connection decreases with the increasing transverse stiffness of the bearing.

According to the analysis, the stiffness ratio R_1 is one of the most important parameter to the design of elastic bearing of SFT. The choice of the stiffness ratio R_1 for elastic bearing should achieve a balance between control of the displacement in the connection and reduction of the seismic response along SFT. Although more detailed information about theoretical and experimental tests is needed, the analysis in this paper suggests that the transverse stiffness of the bearing should be lesser than $0.5\,k_h$ and the lesser the better as long as it satisfies the requirement of service load.



(a) Maximum Transverse shear Force (b) Maximum Transverse Moment



(c) Transverse Displacement

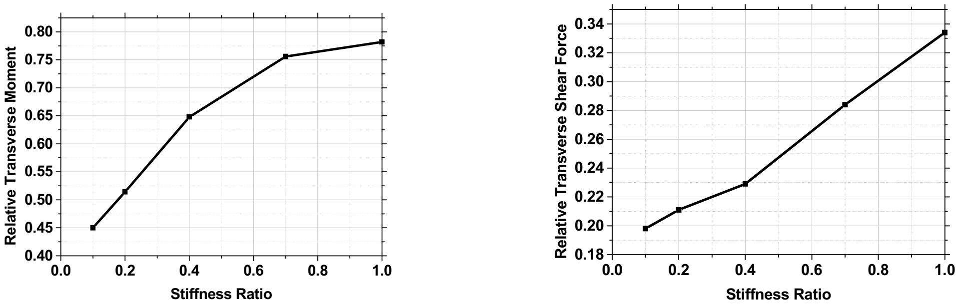
Fig. 3. Seismic response of SFT with different stiffness ratios, R_1, of elastic bearing (w.r.t. the hinged connection)

6. Parametric design of bi-linear elastic bearing and their effects on seismic response

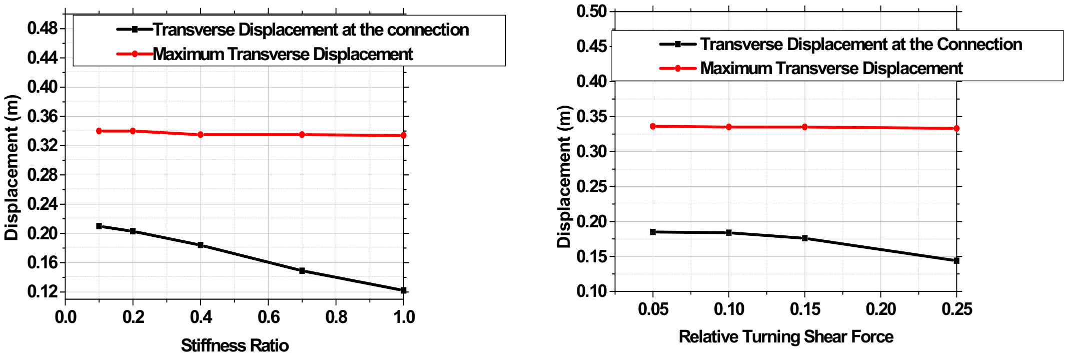
According to the analysis in Section 5, the stiffness of elastic bearing should be small enough to reduce the earthquake-induced internal force effectively. However, it may cause larger displacement and vibration in the connection under the action of wave, current, breaking force, and small conventional earthquakes. Therefore, a bi-linear elastic bearing is introduced to satisfy the objective of being stiff enough under service load and flexible enough under extreme loads such as earthquakes.

The efficiency of the bearing mainly depends on the secondary stiffness and the turning shear force, which control the stiffness distribution of SFT and the force transmitted to the tunnel. The aim of this section is to investigate the seismic behavior of SFT with changing of the secondary stiffness and the turning shear force of the bi-linear elastic bearing. It can provide a simplified design method and instructions for the connection design.

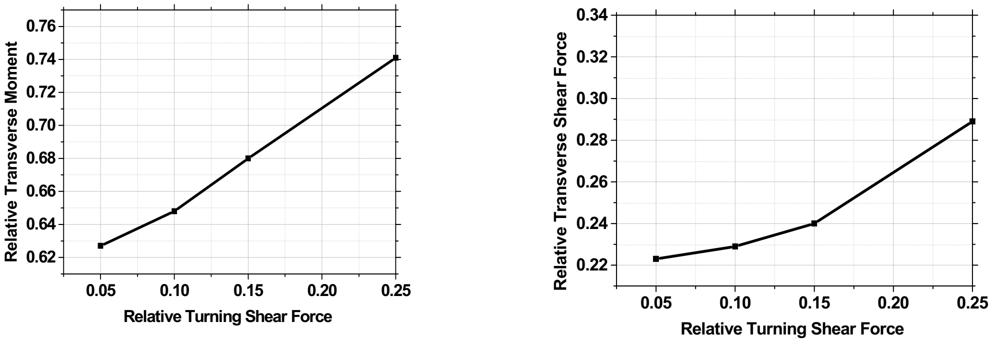
The secondary transverse stiffness of the bearing is one of most important factors that influence the stiffness of the connection under extreme loads, and accordingly influence the dynamic behavior and seismic response of the tunnel. A dimensionless parameter R_2, which is the ratio of the secondary transverse stiffness of the bearing to the transverse stiffness of cables, is introduced to represent the transverse stiffness distribution of SFT. The seismic responses of SFT with different secondary transverse stiffness ($0.1\,k_h$, $0.2\,k_h$, $0.7\,k_h$, $1\,k_h$) are investigated. The first elastic stiffness of the bearing is assumed to be 1 k_h and the turning shear force is assumed to be 10% of W, which is the weight undertaken by the bearing at the connection.



(a) Maximum Transverse Moment (b) Maximum Transverse Shear Force



(c) Transverse Displacement (d) Transverse Displacement



(e) Maximum Transverse Moment (f) Maximum Transverse Shear Force

Fig. 4. Seismic response of SFT with the different secondary stiffness ratios, R_2, and turning shear forces of the bi-linear elastic bearing (w.r.t. the hinged shore connection)

The maximum value of the responses for the different cases are normalized with respect to that of the tunnel with the hinged shore connection and shown in Fig. 4(a-c). The results indicate that the maximum transverse shear force increases approximately linearly with the increases of secondary stiffness of the bearing. When the secondary stiffness ranges from 0.1 k_h to 0.7 k_h, the transverse moment reduces dramatically with the reduction of the secondary stiffness, with the relative value ranging from 45% to 76%. When the secondary stiffness is between

$0.7\,k_h$ and $1\,k_h$ there is not a dramatically change of the transverse moment reduction, ranging from 76% to 78%. The transverse displacement of the connection decreases with the increase of the secondary stiffness.

The turning shear force of stiffness is another important factor that influences the seismic behavior of SFT. The design of the turning shear force is to satisfy the requirement of day-to-day performance and to make the connection functions satisfactory. The seismic response of SFT with different turning shear forces (0.05W, 0.1W, 0.15W, 0.25W) are investigated to provide detailed information for the interest of designer. The first elastic stiffness is assumed to be $2\,k_h$ and the secondary stiffness is assumed to be $0.2\,k_h$.

The maximum value of the response for different cases are normalized with respect to that of the tunnel with the hinged connection and shown in Fig. 4 (d-f). The results indicate that the maximum transverse shear force increases with the increasing turning shear force and the increase will be more significant when the turning shear force is more than 0.15W. The transverse moment increases with the increasing turning shear force in an approximately linear manner when the secondary shear force is smaller than 0.25W. The relative transverse moment ranges from 62.7%-74.1%. The transverse displacement of the connection will decrease with the increase of the turning shear force.

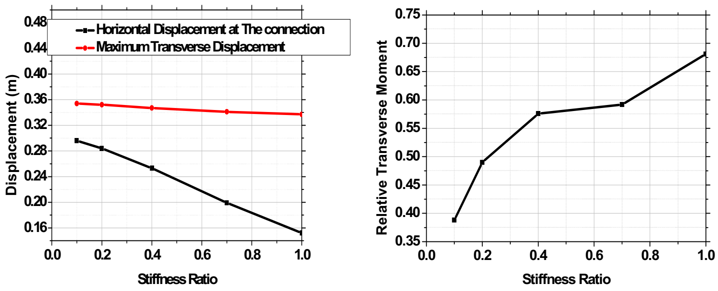
7. Parametric design of passive isolation bearings and their effects on seismic response

Passive energy absorption devices such as lead-rubber bearings are introduced to improve the damping of structures, they can successfully control the vibration and force under earthquake. A bi-linear hysteretic model is introduced to mode the behavior of the isolator such as LRB and a typical hysteretic loop for the bearing is shown in Fig. 1.

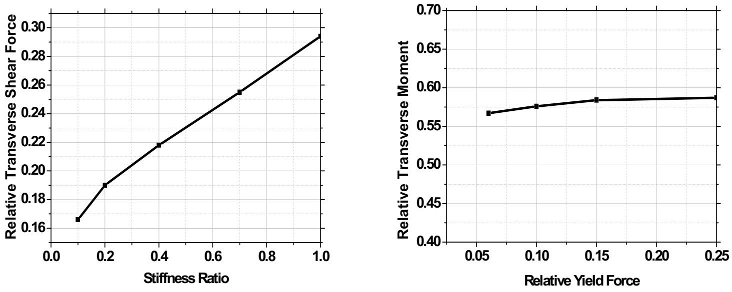
The design method and principle is similar to the bi-linear elastic bearing in Section 6. However the dynamic behavior and sensitivity to the design parameter of SFT with LRB bearing are different from those with bi-linear elastic bearing. The objective of this section is to investigate the seismic behavior of SFT with the changing of the plastic stiffness and yield shear force of LRB as shore connections.

The seismic responses of SFT with the different transverse plastic stiffness ($0.1\,k_h$, $0.2\,k_h$, $0.4\,k_h$, $0.7\,k_h$, $1\,k_h$) of the bearing are investigated to provide the detailed information for the interests of designers. The elastic stiffness of the bearing is assumed to be $1\,k_h$ and the yield force is assumed to be 10% of W, which is the weight undertaken by the bearing at the connection. The results shown in Fig. 5(a-c) indicate that the maximum transverse shear force increases nearly linearly with the increasing plastic stiffness of the bearing. When the plastic stiffness ranges from $0.1\,k_h$ to $0.4\,k_h$, the transverse moment reduces dramatically with the reduction of the plastic stiffness, with relative values (as compared with the response of the hinged connection) ranging from 39% to 58%. When the plastic stiffness is between $0.4\,k_h$ and $1\,k_h$, there are not considerable changes of the transverse moment reduction, being from 58% to 68%. The seismic response is smaller than that with bi-linear elastic bearings when the corresponding design parameters are coincided. However, the difference is not significantly. The transverse displacement of the connection decreases with the increase of the plastic stiffness.

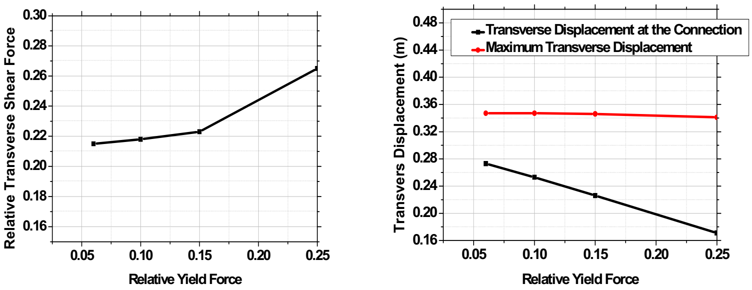
The seismic responses of SFT with the different transverse yield force (0.05w, 0.1w, 0.15w, 0.25w) are also investigated. The elastic stiffness is assumed to be $2\,k_h$ and the plastic stiffness is assumed to be $0.2\,k_h$. The maximum response values of the different cases are normalized with respect to that of the tunnel with the hinged connection and shown in Fig. 5 (d-f). The results indicate that the transverse moment is not sensitive to the change of the yield force. The transverse shear force increases with the increase of the yield force. However, it is not as much as that of the bi-linear elastic bearing.



(a) Maximum Transverse Displacement (b) Maximum Transverse Moment



(c) Maximum Transverse Shear Force (d) Maximum Transverse Moment



(e) Maximum Transverse Shear Force (f) Maximum Transverse Displacement

Fig. 5. Seismic responses of SFT with different plastic stiffness ratios and yield force of the passive isolation bearing

8. Conclusive remarks

The dynamic behavior and seismic response can be significantly changed with the change of shore connections. The hinged connection system can greatly reduce the seismic response as compared with that of the rigid connection. Furthermore, the elastic bearing, bi-linear elastic bearing and passive isolation bearing can significantly reduce the seismic response w.r.t. that of the hinged connection by choosing proper parameters of the bearings.

The principle of stiffness redistribution can be successfully applied to the design of the parameters of the bearing. The transverse stiffness of the elastic bearing can be expressed as a ratio over the transverse stiffness of the cables.

The seismic response reduces with the reduction of the ratio, especially resulting in a remarkable efficiency when the ratio is less than 1.

The bi-linear elastic bearing can successfully reduce the response with enough first stiffness which would satisfy the day-to-day performance. The most important parameters of this bearing are the second transverse stiffness and the turning force of stiffness. The secondary transverse stiffness can be normalized as a ratio by the transverse stiffness of the cables. The seismic response reduces with the reduction of the ratio and decreases significantly when the ratio is less than 0.7. The turning force can be expressed as a ratio over the partial tunnel weight carried by the bearings. The seismic response reduces with the reduction of the turning force. However, the displacement of the connection increases with the reduction of the turning force.

The design parameter of passive bearing is similar to the design of SFT with the bi-linear elastic bearing. However, the dynamic behavior is different. The seismic response is not sensitive to the change of transverse yield force and the response is small than the bi-linear elastic with the same design parameter. However the difference is not significant.

The present study has focused manly on the dynamic performance SFT by using different shore connections from the aspect of mechanics. As to the engineering design of an actual shore connection, it is another important task. The result presented here will benefit to complete this engineering design.

Acknowledgements

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References

[1] Branchaleoni F, Castellani A, D'Asdia P. The response of submerged tunnels to their environment. *Engineering Structures* 1989; 11: 47–56.

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

[3] Fogazzi P, Perotti F. The dynamic response of seabed anchored floating tunnels under seismic excitation. *Earthquake Engineering and Structural Dynamics* 2000; 29: 273–95.

[4] Di Pilato M, Perotti F, Fogazzi P. 3D dynamic response of submerged floating tunnels under seismic and hydrodynamic excitation. *Engineering Structures* 2008; 30(1): 268–81.

[5] Ali HM, Abdel-Ghaffar AM. Seismic energy dissipation for cable-stayed bridges using passive devices. *Earthquake Engineering and Structure Dynamics* 1994; 23: 877–93.

[6] Ali HM, Abdel-Ghaffar AM. Modeling the nonlinear seismic behavior of cable-stayed bridges with passive control bearings. *Computers & Structures* 1995; 54(3): 461–92.

[7] Ali HM, Abdel-Ghaffar AM. Seismic passive control of cable-stayed bridges. *Shock and Vibration* 1995; 2(4): 259–72.

[8] Robinson WH. Lead-rubber hysteretic bearing suitable absorber suitable for the protecting structures during earthquake. *Int. J. Earthquake Engineering and Structure Dynamics* 1982; 10: 593-604.

[9] Ibrahim RA. Recent advances in nonlinear passive vibration isolators. *Journal of Sound and Vibration* 2008; 314: 317–452.

[10] Fan LC. *Earthquake Resistance Design of Bridge*. Shanghai: Tongji University Press, 1996. (in Chinese)

[11] Soneji BB, Jangid RS. Influence of soil–structure interaction on the response of seismically isolated cable-stayed bridge. *Engineering Structures* 2008; 28(4): 245–57.