Influences of Structural Damping and Buoyancy-Weight Ratio on Dynamic Responses of Submerged Floating Tunnel

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ABSTRACT: The recent progress of submerged floating tunnel (SFT) investigation and SFT prototype (SFTP) project in Qiandao Lake (Zhejiang Province, P.R. China) is the background of this research. Structural damping effect is brought into present computation model in terms of Rayleigh damping. Based on the FEM computational results of SFTPs as a function of buoyancy-weight ratio (BWR) under hydrodynamic loads, the effect of BWR on the dynamic response of SFT is illustrated. In addition, human comfort index is adopted to discuss the comfort status of the SFTP.

1 BACKGROUND

Submerged floating tunnel (SFT), also named Archimedes Bridge, is a novel type of traffic solution for waterway crossings. The alternative choice of SFT has been taken into consideration in some strait crossing projects in the past two decades. However, there is still no practical SFT project in action in the world.

Compared with traditional bridges and tunnels, SFT possesses promising advantages. From the structural point of view, SFT is less influenced by water and current, even tsunami. SFT also has the unique merit of minimizing the environmental impact resulted from construction. From the economical point of view, the construction cost of SFT is just linearly proportional to the tunnel length, while the construction cost per meter of suspension bridge grows exponentially with the length (Ahrens 1996). Moreover, SFT is with small road slope between tunnel section and shores compared with the immersed tunnel, such that the passing cars will exhaust less gas emission.

SFT is submerged at a certain depth under water surface. The difference of Archimedes buoyancy and tunnel self-weight is balanced by the cable systems connected between tunnel tube and waterbed foundation. In general, an SFT consists of four parts (Huang et al. 2002): (1) tunnel tube, which allows traffics and pedestrians to get through water area, and its self-weight stabilizes the whole SFT system; (2) cable system, which is designed to tether the tunnel tube to the foundation; (3) waterbed foundation, which provides supports for cable system and consequently supplies the downward tension for tunnel; and (4) tunnel-shore connection, which creates the extremity constraints for SFT.

Since Alan Grant proposed the SFT solution for Messina Strait Crossing in 1969 (Faggiano et al. 2005), some other projects and relevant studies have been reported, especially in the following aspects: structural analysis and dynamic response of tunnel tube under hydrodynamic loads (Kunisu et al. 1994, Venkatramana et al. 1996, Paik et al. 2004), seismic load (Pilato et al. 2008), accidental load (Hui 2007), temperature load (Dong et al. 2006) and cable system scheme optimization under specific water environment (Mazzolani et al. 2008).

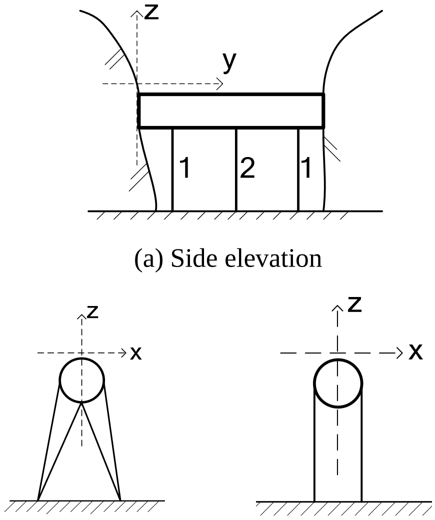
Buoyancy-weight ratio (BWR) is defined by the ratio of Archimedes buoyancy to the self-weight of SFT. As for the basic feature of SFT type with BWR larger than unity, Archimedes buoyancy must be larger than the self-weight of SFT. Considering the in-service situation of SFT, equipment load and traffic and pedestrian loads will change BWR in a certain extent. It is identified that BWR is one of the most important factors in the design of SFT, which influences not only the geometrical design of the tunnel tube, but also material choice, safety design, integral stiffness, etc. However, since the studies of SFT for Messina Strait crossing in 1970s, numerical computations and model experiments have been mainly focused on SFTs with pre-fixed BWR. Thus, in the feasibility analysis concerning SFT, it is an urgent challenge to find an appropriate BWR range to better the general behaviour of SFT.

In this paper, SFT prototype (SFTP) designed by SIJLAB (Chinese Team of SIJLAB 2007, Italian

Team of SIJLAB 2007) is taken as the background in terms of environmental condition and tunnel design scheme. Total cross-section simplification method is proposed and an FEM computational scheme is set up in connection with the commercial code ANSYS. The dynamic responses with and without structural damping of SFTs with different BWRs under hydrodynamic loads (wave and current) are analyzed.

2 FEM MODEL

The design length of SFTP is 100m and the tunnel tube is submerged 4.2m under water surface. The tunnel-shore connection with transversal constraint is applied at one end, while the other three translational degrees of freedom are constrained at the other end. The configuration and the distribution of cable systems are schematically shown in Fig. 1, where the two ends of cable are connected to the tunnel and to the foundation with spherical hinges, respectively. Considering corrosion resistance, collision protection, tunnel weight balance, etc., the cross-section of SFTP tunnel tube is design as shown in Fig. 2 (Italian team of SIJLAB, 2007). With total cross-section simplification method based on stiffness equivalent principle (Long 2008), the parameters of simplified SFTP structure are listed in Table 1. The Fluid environment condition where the SFT prototype is planned to be established is also listed in Table 1 (Chinese team of SIJLAB, 2007).



(a) Side elevation

(b) Cable system 2 (c) Cable system 1

Figure 1. Schematic diagram of SFTP.

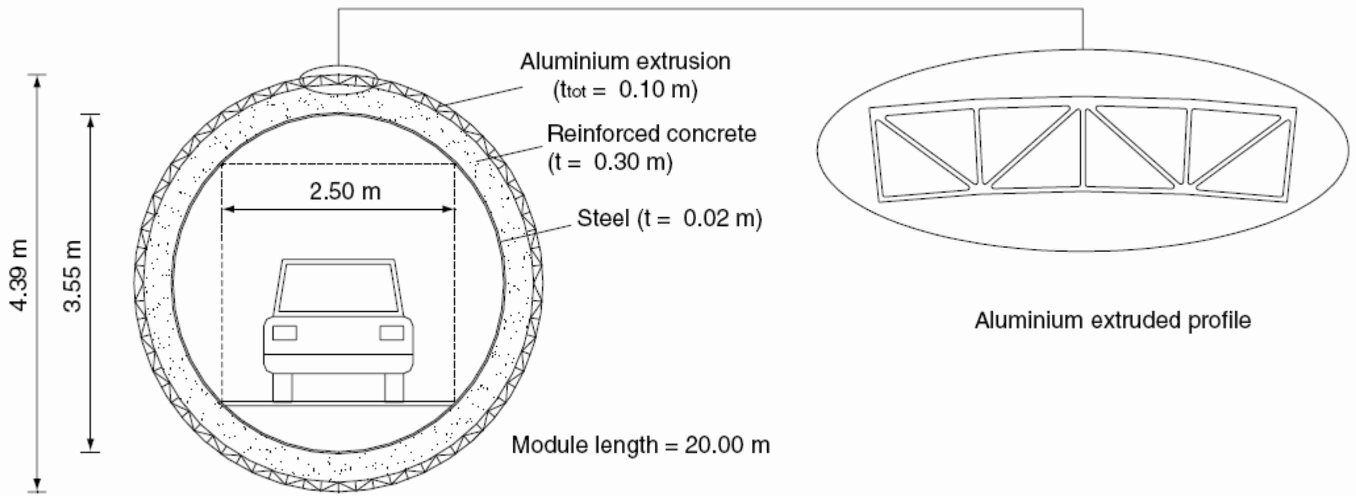


Figure 2. Cross-section of SFTP tunnel tube.

Table 1. Parameters of SFTP Structure and Fluid Environment

Structural properties	Symbol	Unit	Value	Fluid dynamic environment	Symbol	Unit	Value
Tube equivalent density	ρ_T	kg/m^3	2018	Fluid density	ρ	kg/m^3	1050
Tube outer diameter	D	m	4.39	Water depth	h	m	30
Tube inner diameter	d	m	3.48	Wave height	H	m	1.0
Tube equivalent Young's modulus	E_T	N/m^2	3.2×10^{10}	Wave period	T	s	1.8
Cable density	ρ_C	kg/m^3	7850	Surface current velocity	U_0	m/s	0.1
Cable diameter	d_C	m	0.06	Drag coefficient	C_D	1	1.0
Cable Young's modulus	E_C	N/m^2	1.4×10^{11}	Mass coefficient	C_m	1	2.0
Kinetic viscosity coefficient	υ	m^2/s	1.067×10^{-6}	Added-mass coefficient	C_a	1	1.0

Hydrodynamic loads are brought into FEM model via Morison equation expressed as Eq.(1) and Stokes fifth order wave theory.

$$f(t)=\frac{1}{2}C_D\rho D(u_w+u_c-\dot{x}_i)|u_w+u_c-\dot{x}_i|+\frac{\pi\rho D^2}{4}\left(C_m\frac{\partial u_w}{\partial t}-C_a\ddot{x}_i\right) \quad (1)$$

where $x_i(i=1,2)$ is the displacement in X or Z direction; u_w and u_c are the fluid particle velocities on the axis of SFTP in X or Z direction; other parameters are defined in Table 1.

With all above considerations, a finite element computational model was developed by means of the FEM code ANSYS and the in-service element PIPE59.

3 STRUCTURAL DAMPING

In the FEM computational model of this paper, structural damping is considered in the form of Rayleigh damping model which is a classical method to calculate system damping matrix.

A system with multi-degrees of freedom under externally time-dependent force, the equation of motion is:

$$[M]\{X\}+[C]\{\dot{X}\}+[K]\{X\}=\{P_t\} \quad (2)$$

After the orthogonal transformation, Eq.(2) is reduced to a number of uncoupled equations:

$$\{\ddot{\xi}\}+2\varsigma_j\omega_j\{\dot{\xi}\}+\omega_j^2\{\xi\}=\{P(t)\} \quad (3)$$

According to Rayleigh damping model assumption, the damping matrix $[C]$ is the function of mass matrix $[M]$ and stiffness matrix $[K]$, i.e.

$$[C]=\alpha[M]+\beta[K] \quad (4)$$

where α and β are the Rayleigh damping coefficients. Then the following equation is derived.

$$\{\phi\}^T[C]\{\phi\}=\alpha\{\phi\}^T[M]\{\phi\}+\beta\{\phi\}^T[K]\{\phi\} \quad (5)$$

where $\{\phi\}$ is the normalized eigenvector of the system.

Comparing Eq.(3) with Eq.(5) in the system with two degrees of freedom, we find that

$$2\varsigma_1\omega_1=\alpha+\beta\omega_1^2 \qquad 2\varsigma_2\omega_2=\alpha+\beta\omega_2^2 \quad (6)$$

However, for systems with a great number of degrees of freedom, in the beginning of analysis, it does not make sense to guess the Rayleigh damping coefficients α and β. Thus, the coefficients were estimated and a constant damping ratio for all modes was assumed (Chowdhury & Dasgupta 2003).

Different interpolations are adopted to find the best-fit one for the values of α and β with different order choices:

$$\varsigma_i=\frac{\varsigma_m-\varsigma_1}{\omega_m-\omega_1}(\omega_i-\omega_1)+\varsigma_1 \quad (7)$$

where ω_i and ς_i are natural frequency and damping ratio for the *i*th mode in the structural analysis, respectively.

In the calculation, first we set ς_1 as 2.5% and ς_m as 10%. Then we considered the damping ratio with respect to the first 10 order range, 25 order range, and the average value of the first 10 range and first 25 range differential values. Therefore, the results of damping ratios are obtained and shown in Fig. 3.

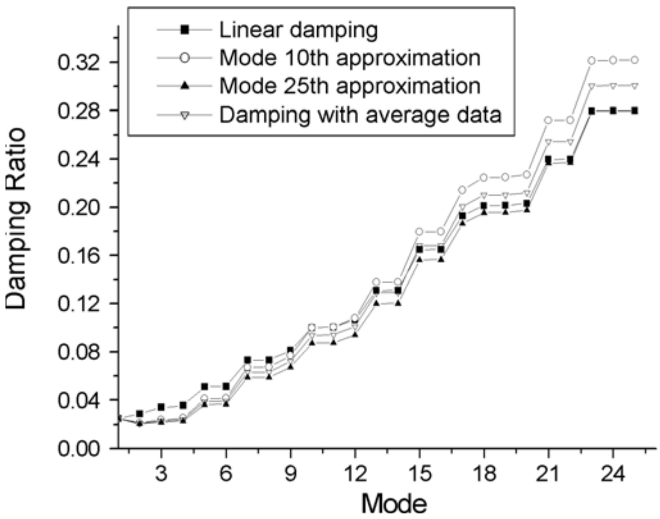


Figure 3. Comparison of damping ratio with different interpolation methods.

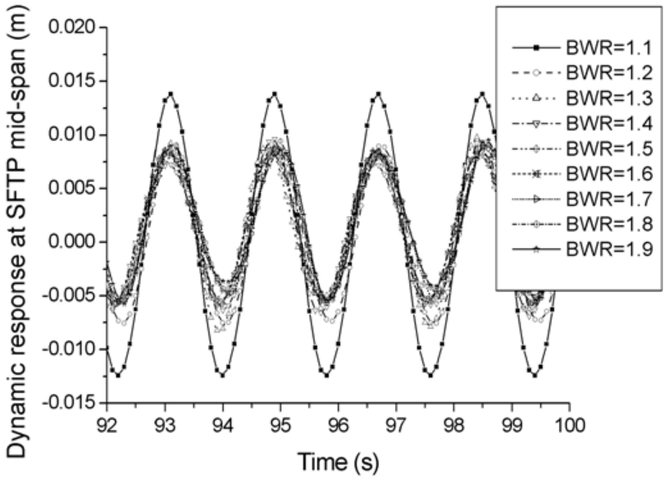
Obviously, Rayleigh damping coefficients in Fig. 3 from the first 10 order range and the first 25 order range are a little less than that from linear interpolation method. The most important is that the damping ratios of first several modes are almost the same and does not vary with the increasing of modes.

Since only the first order mode is excited under the environmental loads, the effective natural frequency of vibration would be the first several ones. In addition, the mass fraction of the first two vibration modes is over 65% and is the majority of the mass participating in the SFTP system vibration. Thus, one may use the same damping ratio and the first two natural frequencies to compute SFTP in dynamic analyses under hydrodynamic loads.

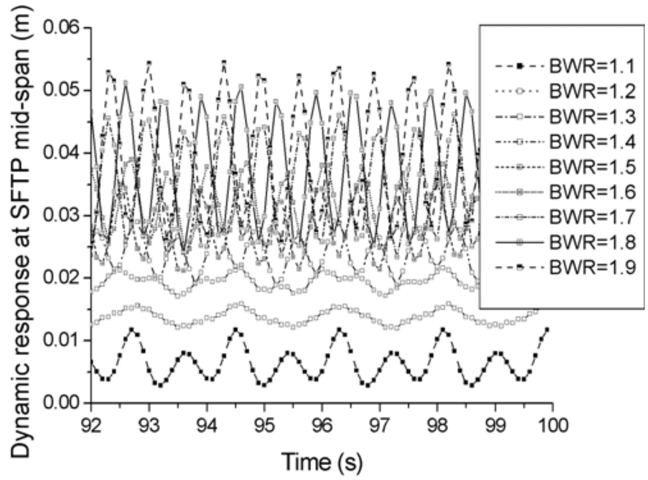
4 BUOYANCY-WEIGHT RATIO (BWR)

4.1 Dynamic response without structure damping

Under the hydrodynamic loads, dynamic responses at the mid-span of SFTP tunnel as a function of time variable without the consideration of structural damping are shown in Fig. 4. The results indicate that in the current direction, the tunnel vibration amplitude decreases with increasing BWR value from 1.1 to 1.9, which is in accordance with the experiments regarding the specific gravity tunnel range between 0.51 and 0.76 (BWR range between 1.32 and 1.96) under similar mooring systems and environmental loads reported by Mizuno et al. (1994).



(a) Current Direction



(b) Vertical Direction

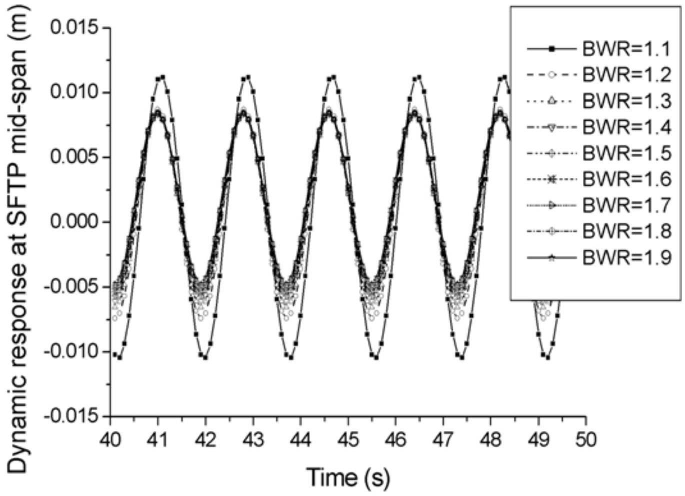
Figure 4. Dynamic responses without structural damping at mid-span of SFTP tunnel.

On the other hand, in the vertical direction, the amplitude is more obviously influenced by BWR and in the adjacent region where BWR is 1.2, the tunnel vibration amplitude arrives at its minimum value. This phenomenon is an example to verify the theoretical analysis concluded by Clough & Penzien (1975), for which the vibration system without damping under impressed excitation will have a deleterious effect if it is too stiff.

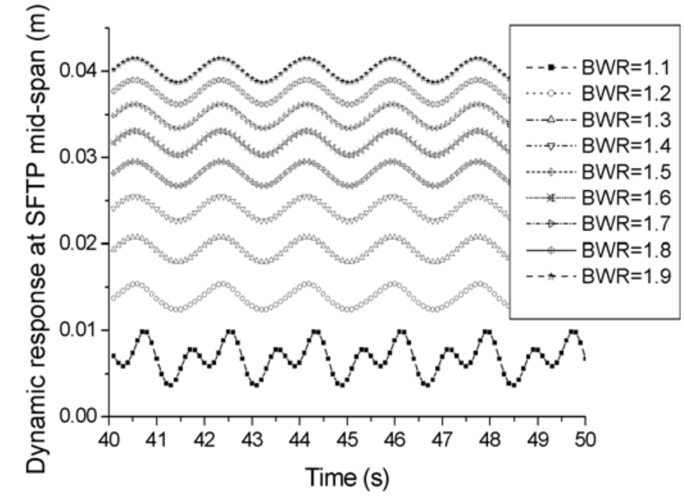
4.2 Dynamic response with structure damping

The dynamic responses with structural damping at the mid-span of SFTP tunnel as a function of time variable are shown in Fig. 5. With the mathematical treatment of standard deviation (STDEV), the dynamic responses with structural damping at the mid-span of SFTP tunnel as a function of BWR value are shown in Fig. 6.

Fig. 5(a) shows the similar changing pattern with the value of BWR in the current direction of SFTP. But according to the dynamic response in the vertical direction of SFTP tunnel [Figs. 5(b) and 6(b)], the vibration amplitude decreases and then tends to a stable value with the increasing value of BWR from 1.1 to 1.9. This distinct feature means that it is possible to optimize the value of BWR in future engineering design and construction.



(a) Current Direction

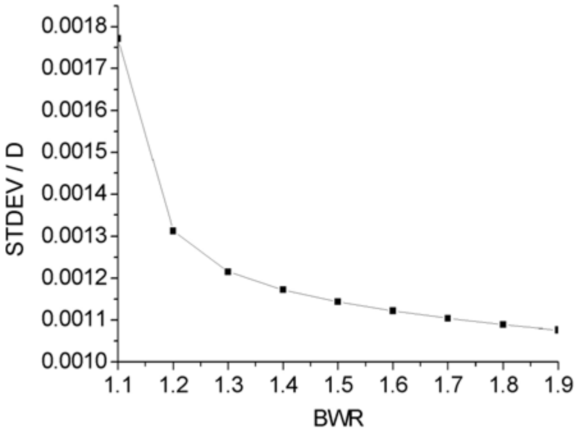


(a) Vertical Direction

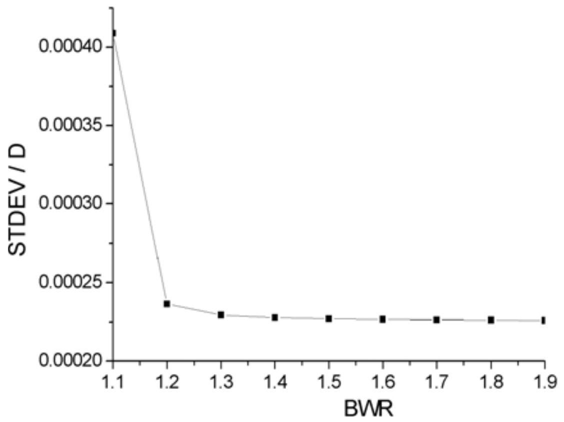
Figure 5. Dynamic responses with structural damping at mid-span of SFTP tunnel.

In the structural modal analysis for natural frequencies and Rayleigh coefficients, it is noted that damping coefficient α increases while β decreases as BWR increases from 1.1 to 1.9. Note also that, in the damping matrix of Eq.(4), α and β are the weight coefficients for mass matrix and stiffness matrix, respectively. Thus, under such an SFTP circumstance, the influence of the mass matrix on structural damp increases, while the influence of the stiffness matrix on structural damp decreases, resulting in the importance of structural damping in SFT problem which should be paid more attention.

In general, as a structural parameter, BWR is efficient to optimize the vertical vibration stability than the horizontal one.



(a) Current Direction



(b) Vertical Direction

Figure 6. Dynamic responses at mid-span of tunnel with structural damping.

5 SFT COMFORT INDEX

Comfort index is also an importance factor for vehicles and bridges. In this study, Sperling comfort index (W_z) (Wu & Yang 2003), based on the acceleration amplitude and the frequencies of vibration components identified by Fast Fourier Transform (FFT), is referred as the comfort standard of SFTP under hydrodynamic loads, which is described in Table 2.

Table 2. Sperling Comfort Index

W_z	Comfort level
1.00	Just noticeable
2.00	Clearly noticeable
2.50	More pronounced but not unpleasant
3.00	Strong, irregular, but still tolerable

Sperling Comfort Index is defined as:

$$W_z = \left(\sum_{i=1}^{n_f} W_{z_i}^{10} \right)^{0.1} \tag{8}$$

where n_f is the total number of the discrete frequencies of the acceleration response identified by FFT and W_{z_i} is the comfort index corresponding to the ith discrete frequency:

$$W_{z_i} = \left[a_i^3 B(f_i)^3 \right]^{0.1} \tag{9}$$

where a_i denotes the amplitude of the acceleration response of the ith frequency identified by FFT and $B(f_i)$ a weighting factor:

$$B(f_i) = 0.588 \left[\frac{1.911 f_i^2 + (0.25 f_i^2)^2}{(1 - 0.277 f_i^2)^2 + (1.563 f_i - 0.0368 f_i^3)^2} \right]^{0.5} \tag{10}$$

By means of FFT and inverse transformation of FFT, dynamic responses of vibration component corresponding to every vibration frequency as a function of time variable were adopted to assess the Sperling comfort index, which is shown in Fig. 7.

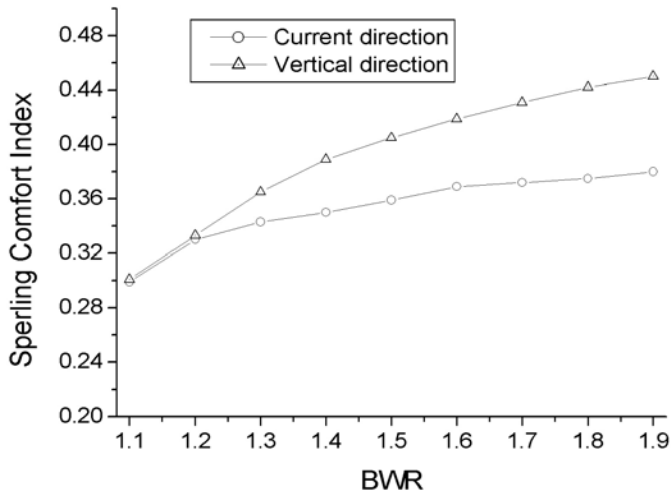


Figure 7. Sperling comfort index at mid-span of SFTP as a function of BWR.

Fig. 7 indicates that, BWR influences Sperling comfort index more obvious in the current direction as the value of BWR increases. In the BWR range between 1.1 and 1.2, the comfort indexes in both the current direction and vertical direction are almost identical and relatively small. On the whole, due to the mild fluid dynamic environment of SFTP, dynamic responses of SFTP under hydrodynamic loads bring little influence on the human comfort index which lies in the range of "just noticeable".

As shown in Fig. 7, Sperling comfort index increases with BWR increasing. For the sake of SFTP structural safety, BWR must be larger than 1.0. If BWR is equal to 1.0, the SFTP will be of free submerged under the water surface and there is no net buoyancy to ensure the tunnel location. Combined human sense of security and Sperling comfort index based on the analysis of SFTP vibration accelerations and frequencies, BWR is suggested to be around 1.2 in the practical structural design.

6 CONCLUSIONS

(1) The dynamic responses, with and without taking into account the structural damping, of SFTPs with increasing value of BWR under hydrodynamic loads are obtained, which indicate the effect of structural damping on the dynamic responses is more obvious in the vertical direction of tunnel tube .

(2) The patterns of dynamic responses for SFTPs with increasing value of BWR under hydrodynamic loads indicate the strategy of adopting the BWR value to optimize the dynamic behaviour of SFTP tunnel and cable. No matter whether the structural damping is considered, the obvious changing trend of tunnel dynamic responses with the increase of BWR happens in the adjacent region of BWR being 1.2. For the SFTP in Qiandao Lake, BWR of 1.2 is the most appropriate choice in the design.

(3) Under hydrodynamic loads, the dynamic responses in both the current direction and the vertical direction of SFTP tunnel with BWR value around 1.2, satisfy the requirement for security and comfort of human sense.

ACKNOWLEDGMENTS

This paper was supported by the National Natural Science Foundation of China (Grant no.10532070), the Knowledge Innovation Program of Chinese Academy of Sciences (Grant no. KJCX2-YW-L07) and the LNM initial funding for young investigators.

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