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Numerical Study on Dynamic Response of Submerged Floating Tunnel Depending on Shore Connection

*Seok-Jun Kang[1], Joohyun Park[2] and Gye-Chun Cho[3]

[1), 2), 3)] *Department of Civil Engineering, KAIST, Daejeon 305-600, Korea*
[1)] *incheon@kaist.ac.kr*
[2)] *joohyun.park@kaist.ac.kr*
[3)] *gyechun@kaist.ac.kr*

ABSTRACT

The shore connection of the submerged floating tunnel (SFT) has a great influence on the dynamic behavior of the submerged floating tunnel because it acts as a boundary condition of the tunnel. In this study, numerical methods for simulating the shore connection of the submerged floating tunnel is introduced. The dynamic response of the submerged floating tunnel and the ground behavior according to various shore connection design are analyzed with the proposed numerical method. The shore connection is designed by modeling that the tunnel segments are connected elastically with the springs at every node of interface of segments between the submerged floating tunnel and the bored tunnel. The dynamic characteristics of the submerged floating tunnel, such as the natural frequency and mode shape, is changed due to the different design of shore connection, and the characteristics affected the dynamic behavior of the submerged floating tunnel. The dynamic response according to the external loads excitation with various frequency is also analyzed to estimate the dynamic behavior of the submerged floating tunnel with the wave load excitation.

1. INTRODUCTION

Submerged Floating Tunnel (SFT) is a type of tunnel operated while floating the tunnel structure in water at a specific depth with allowing a certain level of displacement. Since it has the advantages of not being limited by the depth of the seabed and not being influenced by weather condition, it has been proposed as an alternative to the previous methods for providing maritime routes. There has been no actual construction of an underwater tunnel yet, and basic research has been carried out on various factors for underwater tunnel construction according to the growing interest on SFTs. Since the SFT needs to access to continents or islands, it must be connected to the underground

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[1)] Ph.D. Candidate
[2)] Graduate student
[3)] Professor

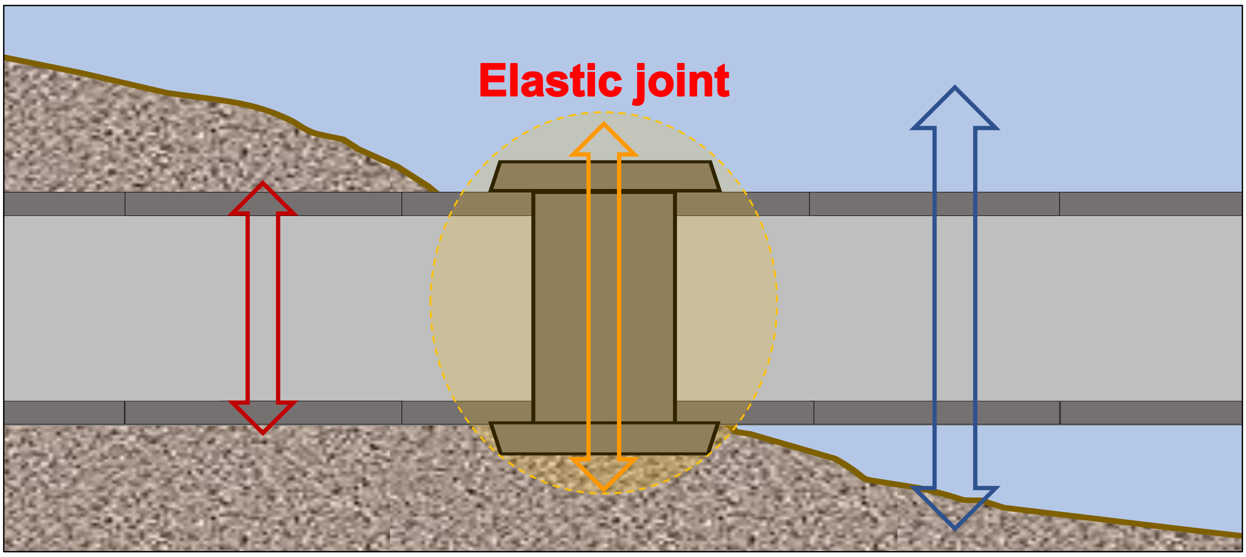


Fig. 1 Conceptual diagram of the elastic joint at shore connection

bored tunnel. There is a risk of stress concentration at the connection part of the two tunnels because the SFT and the bored tunnel have different constraint conditions. Therefore, when designing the shore connection of the SFT, it is necessary to consider special design so that stress concentration does not occur in the surrounding ground and tunnel at shore connection.

The research on the dynamic behavior characteristics of the SFT has been treated as the most important topic because the SFT floats in water and shows continuous dynamic behavior under various types of loads (Cifuentes et al., 2015). Most studies on the SFT conducted the parametric study considering structural design, such as the fixation for SFT, tunnel length, depth, and BWR by numerical method (Long et al., 2009; Lin et al., 2018). However, in most studies on the dynamic behavior of SFT, the restraints at both ends of the SFT are assumed to be fixed, and studies considering the shore connection of the SFT are very scarce. Kang et al. (2020) performed numerical analysis considering the stress concentration that may occur at the shore connection of SFTs, but it has a limitation in that it does not consider the effect of the dynamic load characteristics. Therefore, a study that can evaluate the influence of the dynamic characteristics of applied loads and shore connection design on the dynamic behavior of the SFT is needed.

In this study, a connection method using an elastic joint (Fig. 1) was proposed as a method for connecting the SFT and the bored tunnel at the shore connection, and the effectiveness of the method was evaluated. The end constraint conditions of the SFT, which had not been considered in previous studies, were simulated numerically with simulating elastic connections of various stiffnesses, and the dynamic characteristics of the SFT were analyzed according to the stiffness of the elastic connections. As a result, it was confirmed that the natural frequency of the SFT was changed when an elastic connection was used to connect the shore connection of the SFT, and the dynamic behavior characteristics of the SFT could be adjusted by setting the stiffness of the elastic connection. As the connection stiffness of the shore connection was decreased, the displacement difference between the SFT and the underground bored tunnel decreased, and the natural frequency for the dynamic behavior of the SFT showed a tendency to decrease. In the case of simulating the dynamic load with various frequencies acting on the SFT, it was shown that a large displacement occurred due to resonance when a load of a frequency close to the natural frequency of the tunnel was applied. If the elastic connection proposed in this study is utilized in the design stage, it is expected that the design avoiding resonance can be performed considering the load frequency of the target area where the SFT is constructed.

2. DANYMIC CHARACTERISTICS OF SFT DEPENDING ON SHORE CONNECTION

The main dynamic characteristic of the SFT is the natural frequency. The natural frequency is determined not only by the structural parameters, such as elastic modulus, moment of inertia, cross section area and density, but also by the boundary condition which constrains the tunnel at the edge. The effect of elastic connection as the constraint condition of the SFT was analyzed with theoretical and numerical method in this study.

2.1 Theoretical approach on natural frequency of SFT

The SFT and the boundary condition was simplified for the theoretical approach as shown in Fig. 2. The boundary condition was simplified with the rotational and normal springs to simulate the elastic stiffness of the joint. The SFT was assumed to behaves as Euler-Bernoulli beam (Bauchau and Craig, 2009) to express its dynamic behavior effectively. Also, the tunnel length in consideration was set as the length of single span of SFT module without a tension leg.

The dynamic behavior of the SFT during free vibration can be expressed as Eq. (1) where ρ is density, A is cross section area, E is elastic modulus, and I is moment of inertia of tunnel.

$$\rho A \frac{\partial^2 y}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} = 0 \tag{1}$$

The dynamic behavior of Euler-Bernoulli beam can be assumed as Eq. (2) and Eq. (3) for simplification of the main equation, where $y(x,t)$ is vertical displacement of the SFT, φ_n is modal shape function, $T(t)$ is function for time-dependent parameters, and $\left(\frac{\lambda}{L}\right)^4 = \frac{\omega_n^2 \rho A}{EI}$.
.

$$y(x,t) = \sum_n^\infty \varphi_n(x) T(t) \tag{2}$$

$$\varphi_n(x) = c_1 \cosh\frac{\lambda}{L}x + c_2 \sinh\frac{\lambda}{L}x + c_3 \cos\frac{\lambda}{L}x + c_4 \sin\frac{\lambda}{L}x \tag{3}$$

As the boundary condition, the left edge was assumed as elastic boundary with rotational stiffness of k_r and normal stiffness of k_n and right edge was assumed as the free boundary condition (Eq. (4) – Eq. (7)).

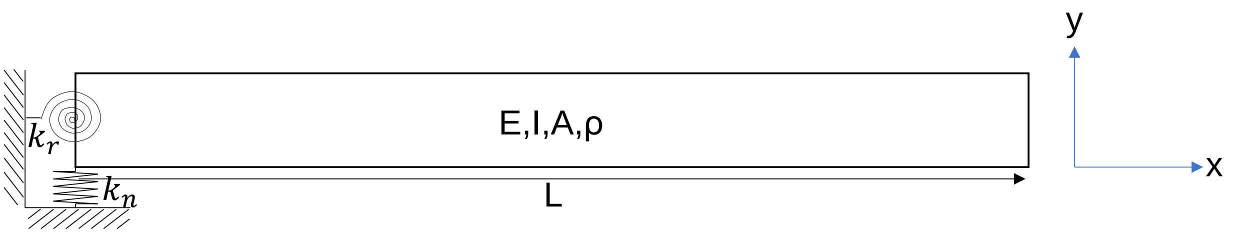


Fig. 2 Conceptual diagram of the elastic joint at shore connection

$$EI\frac{\partial^3 y(0,t)}{\partial x^3} = k_n y(0,t) \tag{4}$$

$$EI\frac{\partial^2 y(0,t)}{\partial x^2} = k_r y(0,t) \tag{5}$$

$$EI\frac{\partial^3 y(L,0)}{\partial x^3} = 0 \tag{6}$$

$$EI\frac{\partial^2 y(L,0)}{\partial x^2} = 0 \tag{7}$$

By substituting Eq. (2), Eq. (3) and the boundary conditions into Eq. (1), the dynamic behavior of the SFT can be expressed as Eq. (8). Using the equation, the natural frequency can be obtained with various elastic stiffness of joint as shown in Fig. 3.

$$\left(\lambda^4 - \frac{k_n L^3}{EI}\frac{k_r L}{EI}\right)(1-\cosh\lambda\cos\lambda) - \lambda\left[\left(\lambda^2\frac{k_r L}{EI} + \frac{k_n L^3}{EI}\right)\sin\lambda\cosh\lambda + \left(\lambda^2\frac{k_r L}{EI} - \frac{k_n L^3}{EI}\right)\cos\lambda\sinh\lambda\right] = 0$$

(8)

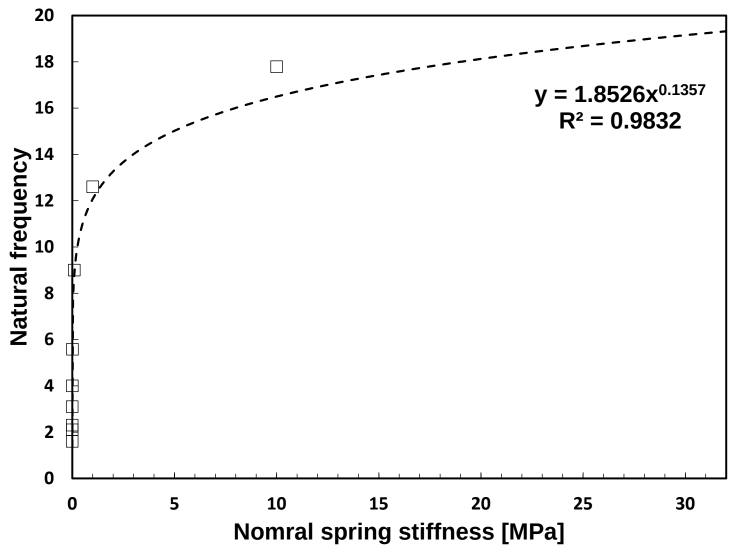


Fig. 3 Natural frequency variation depending on stiffness of elastic joint

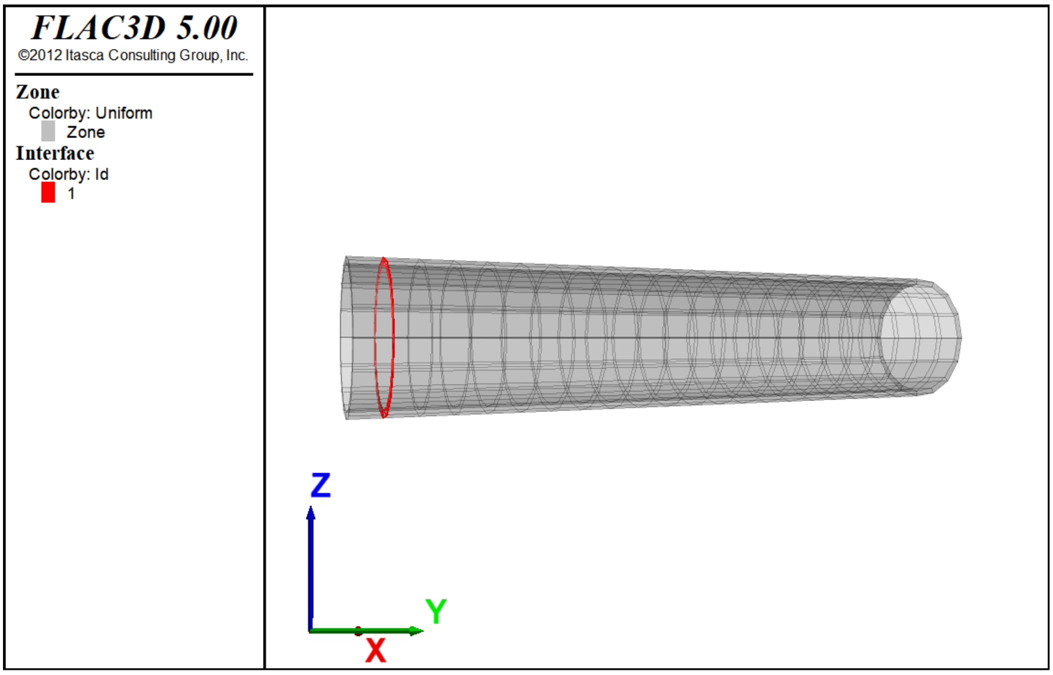
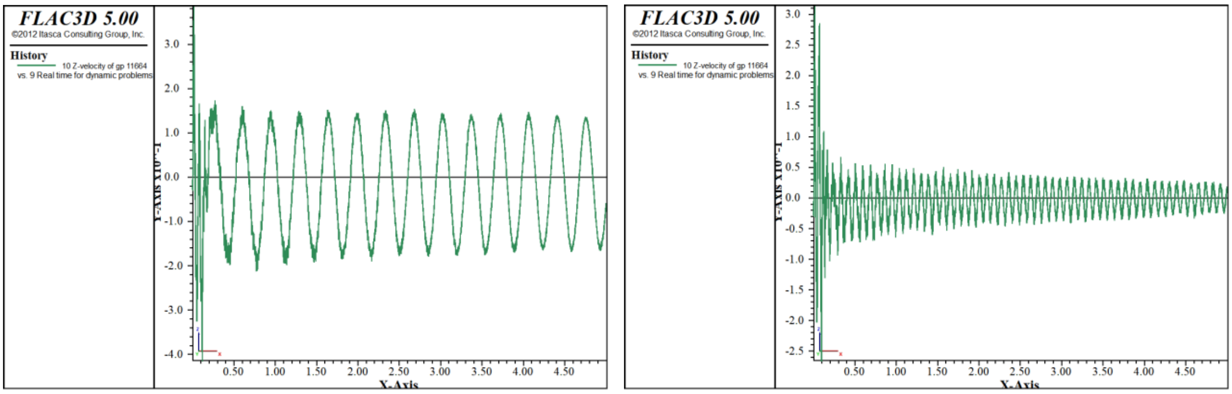


Fig. 4 Numerical model for SFT and elastic joint

2.2 Numerical simulation for obtaining natural frequency of SFT

The theoretical approach on free vibration of the SFT was carried out, but there were many assumptions and simplifications. Numerical analysis simulating the free vibration of the SFT was conducted to evaluate the natural frequency depending on the elastic joint in more general conditions. The SFT and boundary conditions were assumed identically with the case of the theoretical approach, but the numerical model was formed with three-dimensional consideration as shown in Fig. 4. The numerical software is FLAC 3D based on the finite difference method.

Fig. 5 shows the examples of numerical result simulating free vibration of the SFT with two elastic joint, low and high stiffness. The raw results show that the lower stiffness of joint cause the larger displacement during vibration and lower natural frequency. Fourier fast transform was used to obtain the natural frequency of each case and the numerical results are summarized as shown in Fig. 6. The tendencies of variation of the natural frequency depending on the stiffness of elastic joint obtained from theoretical and numerical method were similar as the power function. It is expected that the difference between two results is caused from different dimension. The natural frequency changes with the joint stiffness with lower changes in higher stiffness, and it may converge at specific stiffness which is same with fixed condition. The coefficient of the equation from trend liner means the natural frequency with free boundary condition and the exponent means the increasing rate. The coefficient and exponent are affected by the structural parameters of the SFT, so the trend of natural frequency with various joint stiffness could be obtained when the specific design of SFT is determined.



(a) Low stiffness (2 MPa) (b) High stiffness (32 MPa)

Fig. 5 Displacement of SFT during free vibration

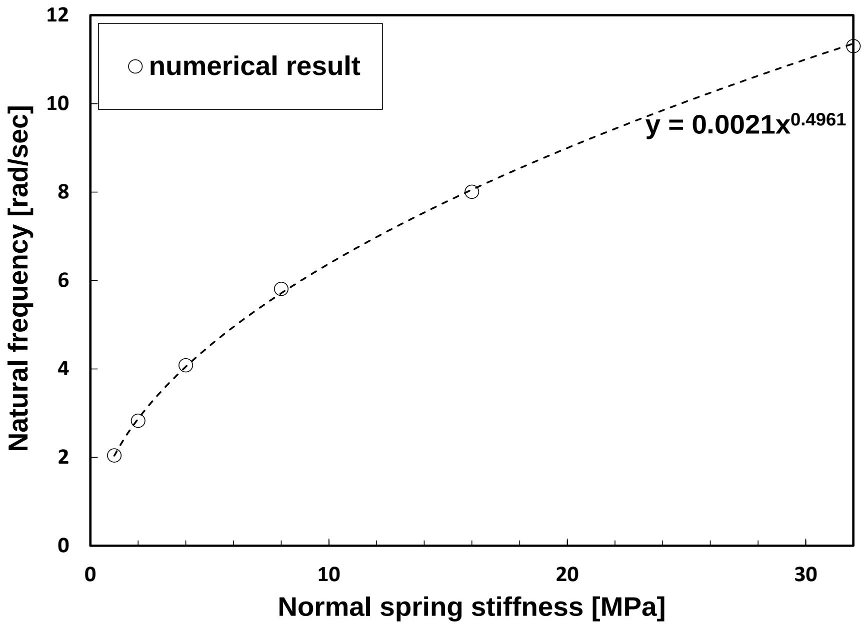


Fig. 6 Natural frequency of SFT depending on stiffness of elastic joint

3. DYNAMIC RESPONSE OF SFT WITH CONSIDERATION OF RESONANCE

The natural frequency varying with the joint stiffness affects the dynamic behavior of the SFT. If the dynamic load with a frequency close to the natural frequency is applied on the SFT, the resonance can occur and cause large displacement. Numerical simulation to evaluate the occurrence of resonance according to the stiffness of the elastic joint at shore connection was conducted. The numerical model was formed as shown in Fig. 7. The ground was assumed as homogenous granite, and tunnels were assumed that they have general modulus of concrete.

Dynamic load was assumed to form trigonometrical function with single frequency to evaluate the effect of the frequency on dynamic behavior of the SFT. The load frequencies were set as 2 Hz, 5 Hz, 10 Hz, and 20 Hz. The stiffness of the elastic joint were set as two cases, soft and hard joints. The SFT with soft elastic joint has the natural frequency of 0.8 Hz, and the SFT with hard elastic joint has the natural frequency of 9.4 Hz. As the result applying the dynamic loads with various frequency, the results showed that the case with soft elastic joint does not undergo resonance, since the natural frequency is not close to the load frequency. On the other hand, the results from case with hard elastic joint show that the dynamic load with frequency close to the natural frequency causes the resonance as shown in Fig. 8. It was confirmed that as the load frequency approaches the natural frequency, resonance occurs and the magnitude of the displacement increases. Displacement was more than doubled in the case of resonance compared to the case where a load having a large difference from the natural frequency was applied.

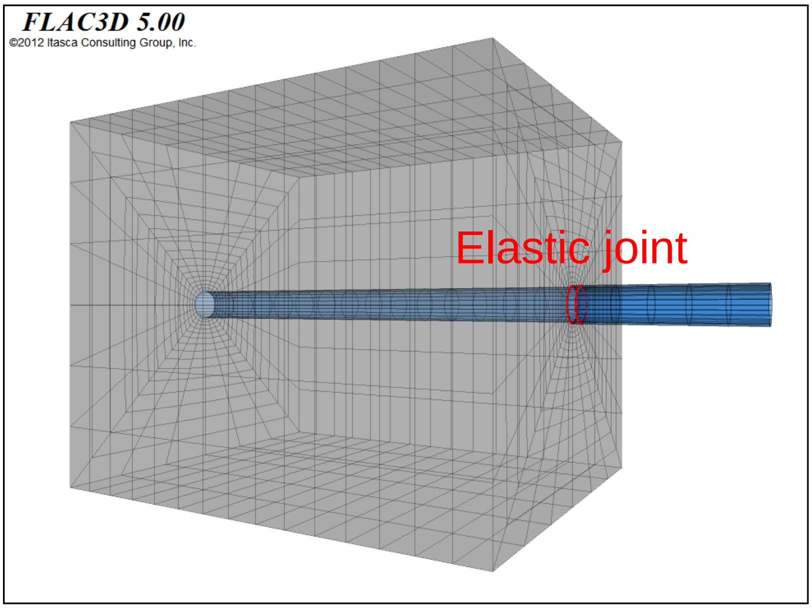
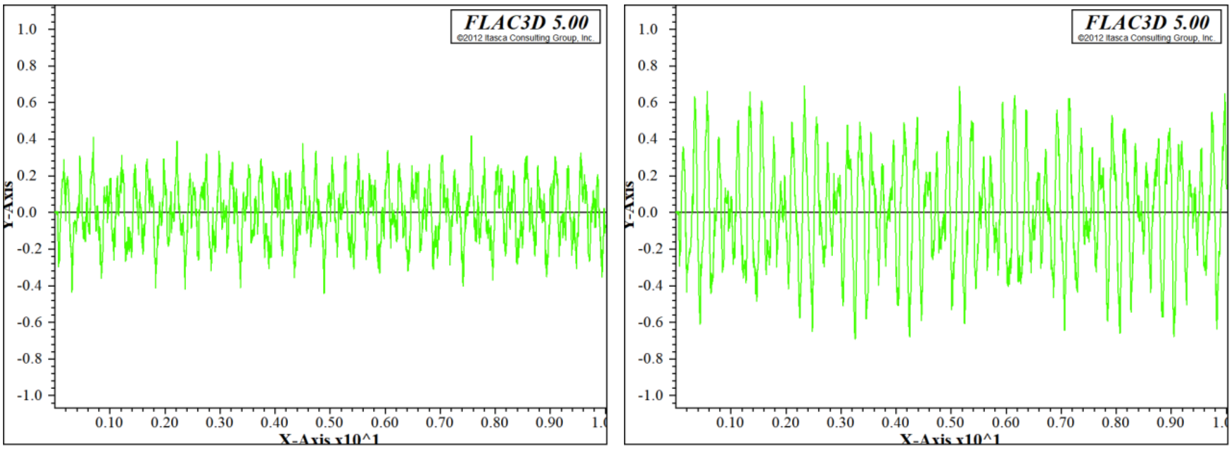
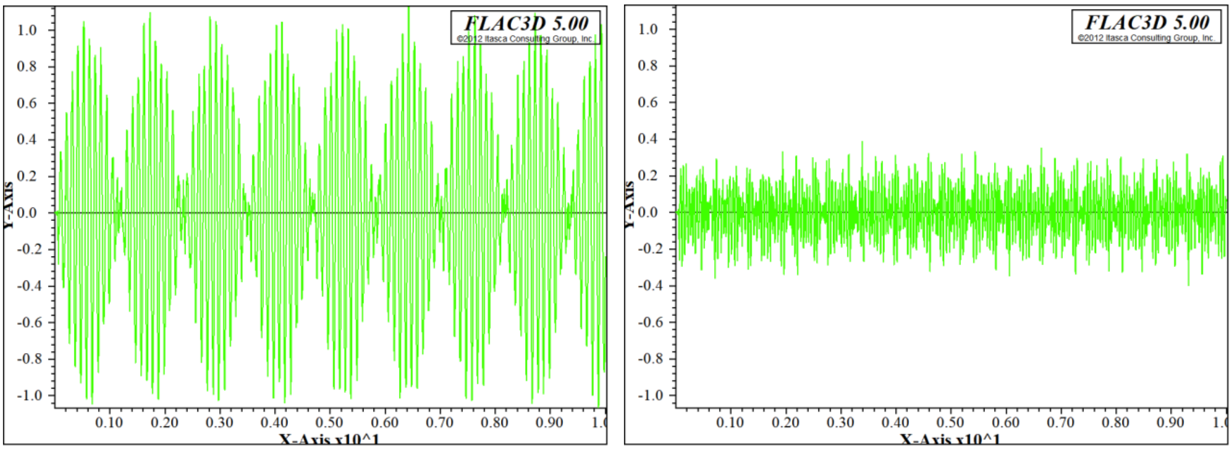


Fig. 7 Numerical model of SFT at shore connection



(a) load frequency: 2 Hz　　(b) load frequency: 5 Hz



(c) load frequency: 10 Hz (d) load frequency: 20 Hz

Fig. 8 Numerical results of dynamic behavior of SFT with hard elastic joint

4. CONCLUSIONS

In this study, theoretical and numerical analysis were conducted to understand the effect on the dynamic behavior of the submerged floating tunnel according to the connection stiffness of the joint connecting the underground bored tunnel and the submerged floating tunnel at the shore connection. The main conclusions obtained from conducting the study are as follows.

- The natural frequency of the SFT is affected by the boundary condition which is determined by the stiffness of elastic joint.
- The stiffer the elastic joint, the higher the natural frequency of the SFT.
- The tendency of the relationship between the natural frequency and the joint stiffness can be expressed as the power function including two parameters related to the natural frequency in free boundary condition and structural characteristics.
- Intensive displacement occurs when the loading frequency is close to the natural frequency.
- The elastic joint at the shore connection can be utilized during design process to avoid the resonance by considering loading frequency at the construction site.

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REFERENCES

Bauchau, O. A., & Craig, J. I. (2009). Euler-Bernoulli beam theory. *In Structural analysis* (pp. 173-221). Springer, Dordrecht

Cifuentes, C., Kim, S., Kim, M. H., & Park, W. S. (2015). “Numerical simulation of the coupled dynamic response of a submerged floating tunnel with mooring lines in regular waves”, *Ocean Systems Engineering*, **5**(2), 109-123.

Kang, S. J., Kim, J. T., & Cho, G. C. (2020). Preliminary study on the ground behavior at shore connection of submerged floating tunnel using numerical analysis. *Geomechanics and Engineering*, **21**(2), 133-142.

Lin, H., Xiang, Y., Yang, Y., & Chen, Z. (2018). “Dynamic response analysis for submerged floating tunnel due to fluid-vehicle-tunnel interaction”, *Ocean Engineering*, **166**, 290-301.

Long, X., Ge, F., Wang, L., & Hong, Y. (2009). “Effects of fundamental structure parameters on dynamic responses of submerged floating tunnel under hydrodynamic loads”, *Acta Mechanica Sinica*, **25**(3), 335-344.