TRANSIENT RESPONSE ANALYSIS OF A SUBMERGED FLOATING TUNNEL UNDER SEISMIC AND WAVE EXCITATIONS

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ABSTRACT: In this study, a numerical procedure is described for the transient response analysis of a submerged floating tunnel with reference of a designed tunnel in Japan. Tension legs seizing the tunnel are simply modeled by a spring elements and the tunnel itself is assumed by two rigid bodies between which a flexible joint is used. A recorded seismic excitation is used while the wave load is calculated under a specific design condition. Hydro-damping and added mass are considered for numerically modeling the underwater condition. A numerical procedure is validated with compared to the previous results of the designed tunnel. Some modifications are proposed through the validating process in terms of modeling and analysis procedure. Eventually, the modified numerical procedure will be used in analyzing the transient response of a newly designed tunnel.

Keywords: Submerged floating tunnel, transient response analysis, seismic excitation, wave load.

INTRODUCTION

Submerged floating tunnels (SFT) have been researched as a new promising technology for strait crossing since it is superior to conventional crossing structures. The research society of SFT in Hokkaido, Japan was established in 1991 to realize SFT through experimental and analytical researches with feasibility studies. Funka bay crossing was the first feasibility study for the society (Kanie, 2010). The research group in KIOST, Korea has started the study of SFT since 2010 supported by a project "Development of core techniques for submerged floating tunnels". China and Italy have also been interest in the study on SFT.

Transient analysis is a powerful approach in estimating the dynamic responses of structures under seismic and wave load, which are critical in judging the safety of the structures. In this study, a numerical procedure is described for the transient response analysis of a submerged floating tunnel with reference of a designed tunnel in Funka bay.

PROBLEM DEFINITION & MODELING

The total length of a targeted tunnel, which is designed in Funka Bay, Japan, is 7km and it is consist of 200m tubes. The tubes are located at 30m below a water surface. The water depth is 90m in the first domain from 0m to 2km, 80m in the second domain from 2km to 3.8km, and 70m in the third domain from 3.8km to 7km. The outer diameter of the tube is 23m and its inner diameter is 21m. So, the length of the tension leg in the first domain is 48.5m, that in the second domain is 38.5m, and that in the third domain is 28.5m. The both ends of the tunnel are connected to a ventilation structure.

The tubes of the tunnel are floating and strained by the tension legs. Among the types of tension legs, a simplest type is utilized and it is consisted of single cable and straightly aligned along vertical axis to an anchor on the ground. The initial tension of the tension leg is 4.9e7 N and its area is 0.1120m^2 (RS-SFT).

Recovery forces in horizontal and vertical axes are calculated by

$$K_x = K_y = 2\frac{P_V}{L_V}$$
$$K_z = 2\frac{EA}{L_V} \tag{1}$$

in which L_v is the length of the tension leg, P_v is initial tension, E is young's modulus, and A is the area of the section of the tension leg. The tension leg is coupled with another one, so the final values are doubled. From the equation, (K_x, K_y, K_z) for each domain are calculated as follows.

First domain: (2.02e6 N/m, 2.02e6N/m, 9.0e8 N/m)

Second domain: (2.55e6 N/m, 2.55e6 N/m, 11.4e8 N/m)

Third domain: (3.44e6 N/m, 3.44e6 N/m, 15.5e8 N/m)

In order to analyze the dynamic response of the whole tunnel quickly, the real model is simplified as shown in the Fig. 1.

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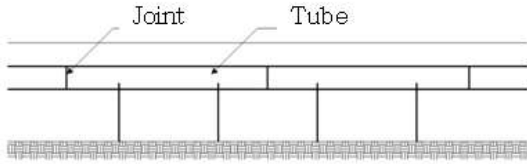
Fig. 1 Simplified model and corresponding terminologies.

As a further simplification, the tube is separated into two rigid bodies and the joint of the tube is used for connecting between them as shown in the Fig. 2. The tension leg and the joints are actually modeled by a spring element in a corresponding finite element model.
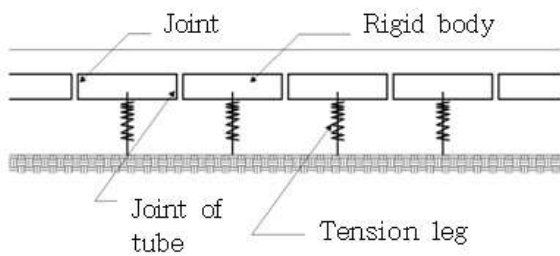

Fig. 2 Further simplified model and corresponding terminologies.

Properties of the rigid body and joints are listed in Table 1. Highlighted values indicate that original values are modified.

Table 1 Properties of each part (RS-SFT).

Part	Properties	Value
Rigid body	Mass (ton)	33670
	Rotational inertia moment (x axis: ton-m²)	8360
	Rotational inertia moment (y axis: ton-m²)	2.80E+06
	Rotational inertia moment (z axis: ton-m²)	2.80E+06
Joint	Shear spring (tf/m)	1.01E+06
	Rotational spring (tf-m)	4.33E+08(y, z) 1.01E+08(x)
	Axial spring (tf/m)	3.57E+06
Joint of tube	Shear spring (tf/m)	1.01E+06
	Rotational spring (tf-m)	1.30E+08

Finite element model, in which the high stiffness is given for implementing the rigid body model, is depicted in Fig. 3.

MSC/NASTRAN is used for the transient analysis from

seismic and wave dynamic loads.

A Rigid body is modeled by two NASTRAN CBAR linear elements, and the middle node is then connected to spring element. The section of the tube is defined in NASTRAN PBAR.

So the bar element has 50m length and the number of the elements is 140. Mass in the table 1 is adjusted by giving a corresponding density, but inertia moments are not adjusted well because of the fore-mentioned simplifications. The middle node of the rigid body is connected to ground by using NASTRAN CELAS1 elements of which number is 70. The joint and joint of the tube are also modeled by NASTRAN CELAS1 elements of which number are 70 and 69, respectively. Fixed point constraints are imposed to the both ends of the tunnel, which are connected to the ventilation structure, and the low end of every spring for modeling the tension legs. In case of seismic analysis, the loading is imposed at the end of every spring for the tension legs as well.
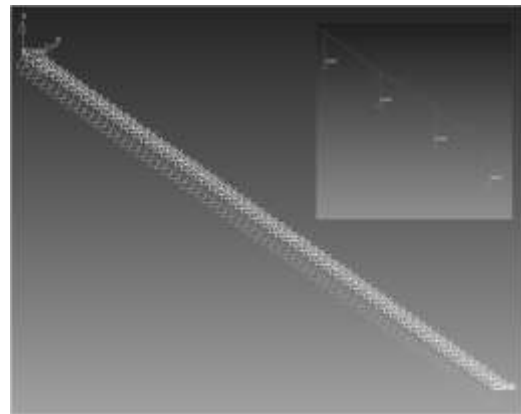

Fig. 3 Finite element model and boundary condition.

Added mass and hydrodynamic damping should be considered in analyzing an underwater structure because of high density water effect in a transient analysis. Newmark et al. (1971) introduced a simple calculation of the added mass in water as

$$m_{added} = \rho_w \pi r^2 \sin\theta, \tag{2}$$

in which ρ_w is the water density, r is a radius of object, and θ is angle between flow direction and longitudinal direction of the tunnel. Calculated added mass is applied in imposing the material properties. The hydrodynamic damping is calculated by following 4 terms.

$$D_{add,offsh} = D_{radiation} + D_{vis,hydro} + D_{steel} + D_{soil}$$
with : $D_{radiation}$ *damping from wave creation due to structure vibration*
$D_{vis,hydro}$ *viscous damping due to hydrodynamic drag*
D_{steel} *material damping of steel*
D_{soil} *soil damping due to inner soil friction*

Cook (1982) introduces the ranges or the values of the four terms as follows:

$$D_{radiation} = 0.22\%, \quad D_{vis,hydro} = 0.15\%, \quad 0.2\% \leq D_{steel} \leq 0.3\% \quad D_{soil} = 0.53\%$$

Hence, the additional offshore damping is included in the following range for a pile supporting structure (Schmidt, 2010)

$$D_{add,offsh} = 0.8 - 1.2\%, \ Best \, estimate \, 0.9\%$$

The tunnel is supported by a tension leg-anchor instead of the pile, thus D_{soil} is a little bit decreased but the damping of a concrete is larger than that of steel. Thus, we use 1% as damping ratio, *D*. In MSC/NASTRAN, the structural damping *G* is used in giving damping ratio: *G* = 2*D* = 0.02 and is calculated by the following equation (Rose, 2001).

$$[B_{total}] = [B] + [K] G/w_3 + \sum Ke \, Ge/W_4 \, ,$$

in which w_3 is dominant frequency of the response in radians per second. In the equation, [*B*] is viscous damping matrix, [*K*] is global stiffness matrix, [*Ke*] is element stiffness matrix, *Ge* is element structural damping, and W_4 is the dominant frequency of each element. w_3 is obtained as 0.178 from the eigensolution in Fig. 4. *Ge* is given by zero.
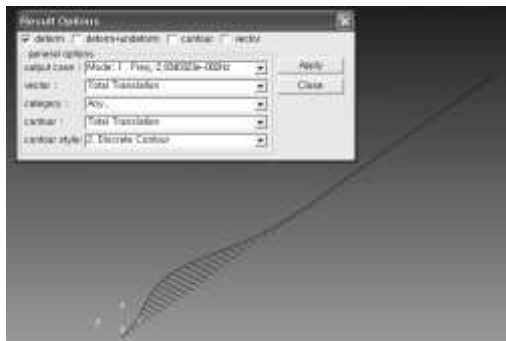

Fig. 4 First natural frequency and normal mode.

DYNAMIC LOAD

(1) Seismic load
The seismic load is assumed to be same at all supporting points. In our model, the both ends of the tunnel and the low ends of the tension legs are considered as the supporting points. The seismic loads are reproduced from the previous work (RS-SFT) as shown in Fig. 5.
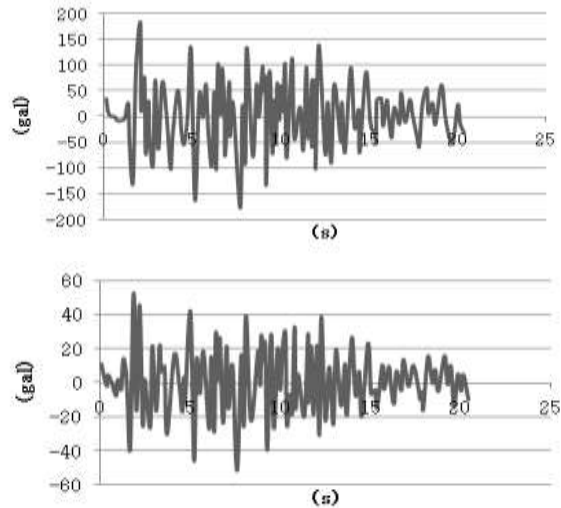

Fig. 5 Horizontal(top) and vertical(bottom) seismic loads.

(2) Wave load

A worst condition, in which the wave height is 23.4m and the period is 13 second, is chosen for design purpose. The wave loads are calculated in an in-house code, CADMAS-SURF 3D for every domain of the tunnel. Fig. 6 shows the horizontal and vertical loads in the third domain where water depth is 70m.
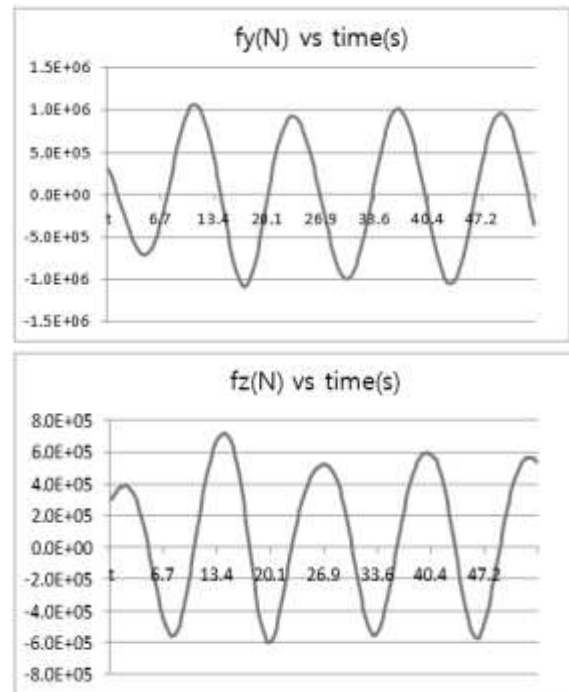

Fig. 6 Horizontal(top) and vertical(bottom) wave loads in 70m depth.

ANALYSIS RESULTS

The structural responses for the given seismic loads are extracted on center nodes of all rigid bodies in Fig. 2. In this paper, we showed only our results due to a copyright issue. The further information and

supplementary data will be given in the presentation.

(1) Seismic load

From the dynamic response, the peak values in acceleration curves along in axial direction are plotted in Fig. 7. Maximum acceleration in the horizontal direction is observed in the both ends of the tunnel and its value is similar to the previous work. Maximum acceleration in vertical direction is also observed in the both ends of the tunnel as well. Its value is lower than the values in the previous work.
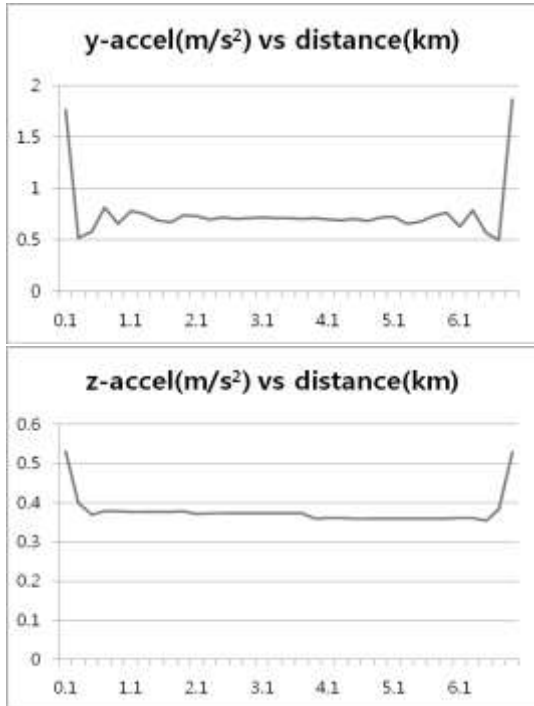

Fig. 7 Maximum horizontal(top) and vertical(bottom) accelerations along axial direction.

(2) Wave load

From the dynamic responses, the peak values in displacement and acceleration curves along in vertical direction are plotted in Fig. 8. Maximum displacement and acceleration are observed near the left end of the tunnel as same as the previous work. Their values are also similar to the previous work.

CONCLUSION

In this study, a numerical procedure is investigated for the transient response analysis of a submerged floating tunnel with reference of a designed tunnel in Japan. The chosen results from our model by using the numerical procedure are similar to those of the previous model. However, the model is constructed based on the two-level simplifications, thus detail modeling will be required for acquiring more reliable results. Our future work is a flexible modeling for satisfying it and quick
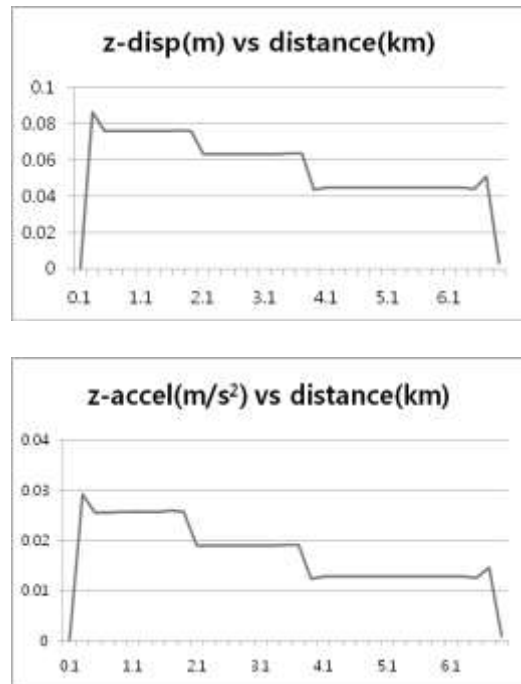
solution techniques.

Fig. 8 Maximum displacement(top) and acceleration(bottom) in the vertical axis.

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