KSCE Journal of Civil Engineering (2015) 19(7):2029-2034

DOI 10.1007/s12205-015-0136-3

Geotechnical Engineering

pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Global Response of Submerged Floating Tunnel against Underwater Explosion

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Received March 14, 2014/Revised May 26, 2014/Accepted September 25, 2014/Published Online January 21, 2015

Abstract

Submerged Floating Tunnels (SFT) for transportation must be designed to secure passengers' safety in case of accidental events. Underwater explosion is the most critical event to long submerged structures. In this paper, first, shock waves and impulse pressures generated by an explosive away from the SFT are expressed by the formulas coming from the experimental results. Second, the SFT tethered by mooring lines and anchors is modeled as a simply supported uniform beam with continuous elastic springs. Finite element analysis for the beam model subjected to the impulse loading from the experimental formulas is conducted by using a commercial code so that the response of the SFT can be investigated. For design purpose, theoretical analysis is also conducted for the same model. Simple equations to show the response of the SFT due to underwater explosion attack were deduced. Time dependent displacements were calculated by these equations. The calculated results were compared with the previous numerical results and proved to give good agreement with them. Theoretical analysis using the simple equations yields solutions so rapidly that they can be applied for parametric study of the response of SFT against underwater explosion during initial design stage.

Keywords: *Submerged Floating Tunnel (SFT), underwater explosion, dynamic response analysis, classical beam theory, finite element analysis*

1. Introduction

Submerged Floating Tunnel (SFT) is a floating transport infrastructure which maintains the balance with exceeding buoyancy in the water by the tension of mooring system. A long-distance SFT is appropriate to a railway system in terms of safety, but to make it transport infrastructure for railway operation, safety verification under various load conditions is necessary.

SFT is also named as Archimedes Bridge, of which concept was proposed more than 150 years ago. A realistic SFT was proposed for Messina Strait Crossing in Italy in 1969, consisting of concrete tubes and steel shells (Martire, 2010) as shown in Fig. 1. In Norway, in 1987, Norwegian Public Road Administration also promoted the preliminary design of SFT in Høgsfjord. After that, research projects were followed so that efforts to spread SFT could increase in Italy, Japan and Norway. However, no SFT has been constructed until now. The reason for no SFT is that safety against spectacular accidents hasn't been verified (Østlid, 2010). Therefore, safety case against accidental loads is the prerequisite condition for actual start of SFT.

Load which may be working on SFT includes wave load, tidal load or seismic load, and further load in emergency situation would possibly give rise to fatal damage (Hong and Ge, 2010). Included in such loads in emergency situation are earthquake, collision and underwater explosion. Particularly the load by underwater explosion, among others, may cause a critical risk which could split the floating structure into two pieces as seen in Fig. 2 and the sinking of Cheonan Naval Vessel 3 years ago in Korea (Yoon *et al*., 2010). Before SFT is widely used as transport infrastructure linking the lands in the coming days, design in preparation for such risk is a must. This study is intended to develop the analysis method for designing the structure in dealing with such fatal risk while carrying out the conceptual design of SFT.

Naval vessels and submarines are designed to survive against attack of underwater explosion. Design requirements for survival condition are expressed by shock factor (= charge weight in pound divided by square root of stand-off distance in feet). Phenomena of underwater explosion have been clarified since World War II so that shock response analysis could be made (Keil, 1961). Shock design guidelines for structures and shipboard equipments have also proposed. Recently, detailed structural analysis of ships and submarines against underwater explosion taking into account of fluid-structure interaction could be conducted by using the advanced theory such as Doubly Asymptotic Analysis and software tools (Mair, 1999).

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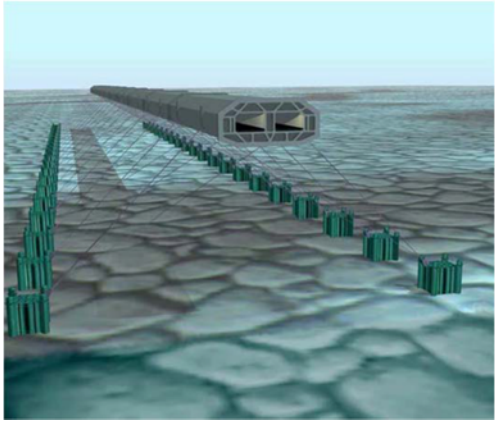

Fig. 1. Initial Concept of Submerged Floating Tunnel for Messina Strait Crossing

Fig. 2. Surface Naval Vessel Subjected to Underwater Explosion Attack

However, in the initial design stage of novel structure, a simple and reasonable approach to understand the behavior is needed.

The shock pressure induced from under explosion on SFT was calculated based on empirical formulas and the response was analyzed based on beam theory. Analysis results were compared with the calculation using finite element analysis approach.

2. Underwater Explosion

When explosive is burst up in the water, shock wave with high pressure spreads in the water, which is followed by spherical bubble caused by high pressure explosion. Fig. 3 shows shock wave, bubble pulse pressure and bubble growth development over the time. Initial speed of shock wave by underwater explosion spreads very fast at early stage in spherical wave form and the speed gets reduced to the level of sound speed as getting distance from the explosion point. As shock wave spreads, peak pressure is reduced while waveform is extended. Thus the pressure of shock wave in the water is represented as follows (Yoon *et al.*, 2010):

$$P(R, W, t) = P_m(R, W)\exp\left[\frac{-(t-t_0)}{\theta(R, W)}\right] \quad (1)$$

$$P_m(R, W) = K\left(\frac{W^{1/3}}{R}\right)^{\alpha} \quad (2)$$

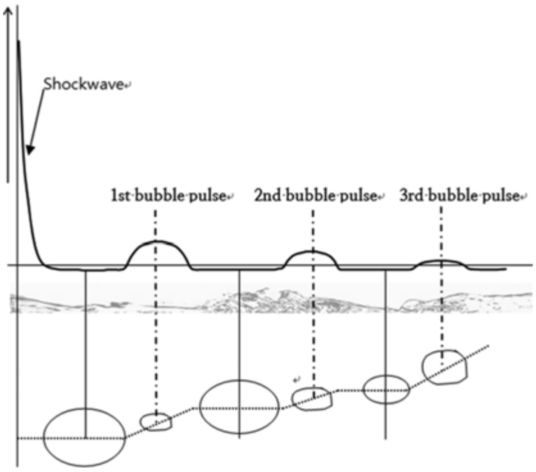

Fig. 3. Shock Wave Generated by Underwater Explosion

$$\theta(R, W) = W^{1/3}K'\left(\frac{W^{1/3}}{R}\right)^{\alpha'} \quad (3)$$

where,

K, K' = Explosive constant
$P(R, W, t)$ = Shock pressure
$P_m(R, W)$ = Peak pressure
R = Stand-off distance between body and explosive
W = Weight of explosive
α, α' = Explosive index
$\theta(R, W)$ = decay time

Bubble pulse following the shock wave as shown in Fig. 3 is the pressure waveform discharged when bubble generated by gaseous product is expanded, which has lower pressure than shock wave but very slow. Bubble with high pressure and temperature at early stage pushes the water toward outside the spherical wave and stops by inertia beyond pressure equilibrium point and when water pressure around bubble exceeds the pressure inside bubble, bubble tends to contract.

3. Submerged Floating Railway

The concept of submerged floating railway for high speed railway operation is illustrated in Figs. 4 and 5. Subsea tunnel from Honam to Jeju has been proposed for high speed railway by Jeollanamdo Province, but economic feasibility study revealed less benefit than cost (Lee, 2010). A breakthrough to the economic feasibility problem can be the submerged floating railway for some sections in this line. The concept design of a prototype submerged floating railway is based on the severest environment conditions of Honam-Jeju line. The sea level is 120 meters below the free surface, while the tunnel structure is floating 40 meters below the surface. Its inner diameter along the long axis is 15 meters and along the short axis 12 meters as shown in Fig. 6. It is designed to sustain the tunnel structure which tends to rise by buoyancy with tension force of mooring system. For complete water-tightness, outer (22 mm thick) and inner (10 mm thick)

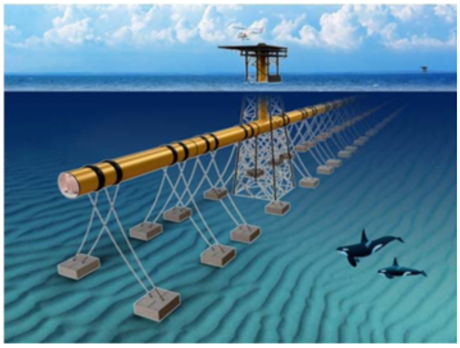

Fig. 4. Submerged Floating Railway Shaped as Pipe Line

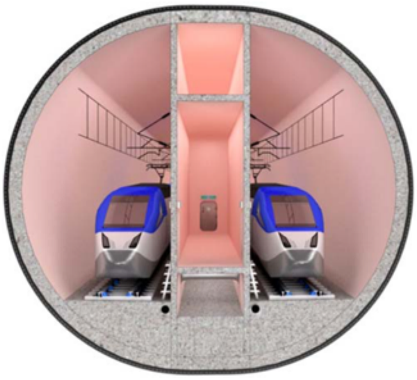

Fig. 5. Section of Submerged Floating Railway

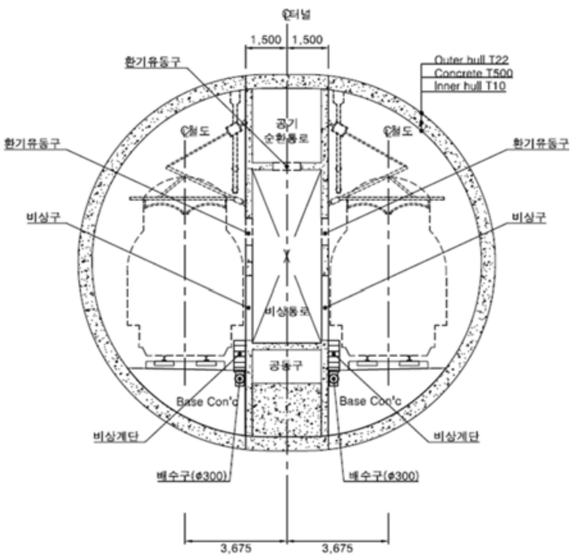

Fig. 6. Details of Section

shells are made of steel materials and to maintain the buoyancy at certain level the space between shells is filled with concrete (500 mm thick). Inner shell also contributes to achieving the dual watertight system. A module is fabricated at intervals of 100m and outer shell is fastened with bolts on free surface and pre-assembled before assembling completely in the water. Fixed-type structure for evacuation and ventilation is prepared at certain interval (Seo, 2012). Mooring system is linked to gravity

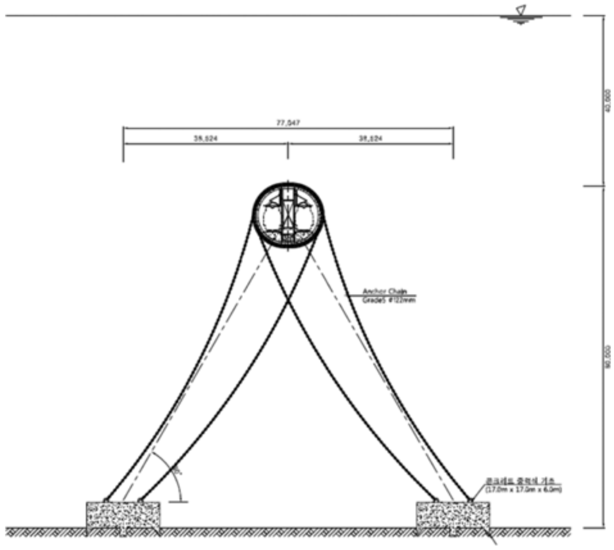

Fig. 7. Mooring Lines for Submerged Floating Railway

concrete block on sea-bed so as to convey the tension force to deal with exceeding buoyancy as shown in Fig. 7. Fixed jackets are designed to be placed at a certain interval for passenger evacuation and ventilation purpose.

4. Response Analysis Model by Underwater Explosion

When underwater explosion occurs by accident or on purpose by terrorist, submerged floating railway is fatally affected by impulse pressure of shock wave (Seo *et al.*, 2013). To secure the safety in preparation for underwater explosion, structural response of submerged floating railway under shock pressure was analyzed in theoretical method.

The body of submerged floating railway is in the form that the tunnel on uniform section supported by mooring line is continuously connected between fixed jackets. Since the body has uniform section and the interval of fixed jacket is longer than the width of the body, the body can be idealized to beam, mooring line to elastic support and fixed jackets to supporting boundary. In case of underwater explosion under the body as shown in Fig. 8, behavior of the body is identified with response of a simply supported beam with elastic springs subjected to impulse pressure.

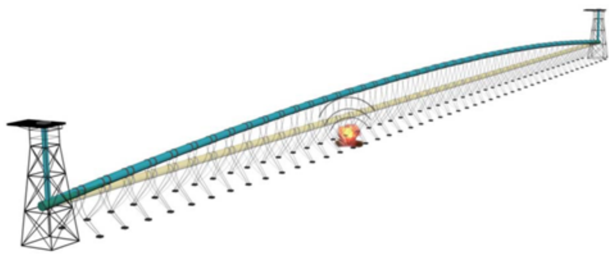

Fig. 8. Body of Submerged Floating Railway Attacked by Underwater Explosion

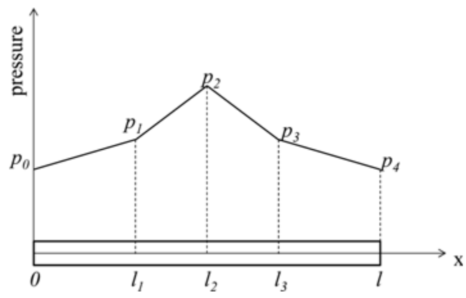

Fig. 9. Beam Subjected to Partial Linear Load

Shock pressure by underwater explosion, as indicated in Fig. 3 and Eq. (1), varies depending on exponential function. To simplify the analysis, however, it may be idealized into piecewise linear functions as indicated in Fig. 9.

Figure 9 is represented by equations as follows:

$$0<x<l_1\,,\; p(x) = \frac{P_1-P_2}{l_1}x + P_0 \tag{4}$$

$$l_1<x<l_2\,,\; p(x) = \frac{P_2-P_1}{l_2-l_1}x + \frac{-P_2l_1+Pl_2}{l_2-l_1} \tag{5}$$

$$l_2<x<l_3\,,\; p(x) = \frac{P_3-P_2}{l_3-l_2}x + \frac{-P_3l_2+P_2l_3}{l_3-l_2} \tag{6}$$

$$l_3<x<l\,,\; p(x) = \frac{P_4-P_3}{l-l_3}x + \frac{-P_4l_3+P_3l}{l-l_3} \tag{7}$$

The pressure over the time is assumed to decrease linearly as indicated in equations below:

$$0<t<t_1\,,\; p_1(x,\,t) = p(x)\left(1-\frac{t}{t_1}\right) \tag{8}$$

$$t_1<t\,,\; p_1(x,\,t) = 0 \tag{9}$$

where,

$p_1(x,\,t)$ = Pressure at a time on a point

t_1 = Time on zero pressure

Governing equation of the beam is as follows (Clough and Penzien, 1975):

$$EI\frac{\partial^4 w}{\partial x^4} + M\frac{\partial^2 w}{\partial t^2} + kw = p_1(x,\,t) \tag{10}$$

where, EI = Bending rigidity of beam

k = Spring constant per unit length

M = Mass of beam per unit length

w = Deformation of beam

Deformation of the beam which is simply supported on both ends is expanded with sinusoidal series satisfying the boundary condition which is represented by the following equation:

$$w = \Sigma_{n=1}^{\infty}\sin\frac{n\pi x}{l}q_n(t) \tag{11}$$

Substituting Eqs. (8), (9) and (11) into Eq. (10) and multiplying both sides by $\sin\frac{m\pi x}{l}$ which is then integrated, the followings are obtained:

$$\frac{d^2q_n(t)}{dt^2} + \omega_n^2 q_n(t) = R_n\left(1-\frac{t}{t_1}\right) \tag{12}$$

$$\begin{aligned} R_n = \frac{2}{M}\Big[& -\frac{P_1}{n\pi}\cos\frac{n\pi}{l}l_1 + \frac{P_0}{n\pi} + \frac{P_1-P_0}{n^2\pi^2}\frac{l}{l_1}\sin\frac{n\pi}{l}l_1 \\ & -\frac{P_2}{n\pi}\cos\frac{n\pi}{l}l_2 + \frac{P_1}{n\pi}\cos\frac{n\pi}{l}l_1 + \frac{P_2-P_1}{n^2\pi^2}\cdot\frac{l}{l_2-l_1}\left(\sin\frac{n\pi}{l}l_2-\sin\frac{n\pi}{l}l_1\right) \\ & -\frac{P_3}{n\pi}\cos\frac{n\pi}{l}l_3 + \frac{P_2}{n\pi}\cos\frac{n\pi}{l}l_2 + \frac{P_3-P_2}{n^2\pi^2}\cdot\frac{l}{l_3-l_2}\left(\sin\frac{n\pi}{l}l_3-\sin\frac{n\pi}{l}l_2\right) \\ & -\frac{P_4}{n\pi}\cos n\pi + \frac{P_3}{n\pi}\cos\frac{n\pi}{l}l_3 + \frac{P_4-P_3}{n^2\pi^2}\cdot\frac{l}{l-l_3}\sin\frac{n\pi}{l}l_3\Big] \end{aligned} \tag{13}$$

$$\omega_n^2 = \left[\frac{EI}{M}\left(\frac{n\pi}{l}\right)^4 + \frac{k}{M}\right] \tag{14}$$

Solution of Eq. (12) can be obtained as follows:

$$0<t<t_1,\; q_n(t) = \frac{R_n}{\omega_n^2}(1-\cos\omega_n t) + \frac{R_n}{\omega_n^3 t_1}(\sin\omega_n t-\omega_n t) \tag{15}$$

$$t_1<t,\; q_n(t) = -\frac{R_n}{\omega_n^2}\cos\omega_n t + \frac{R_n}{\omega_n^3 t_1}(\sin\omega_n t-\sin\omega_n t(t-t_1)) \tag{16}$$

where,

l_1, l_2, l_3, and l = Lengths defined in Fig. 9

n = Integer for summation

P_0, P_1, P_2, P_3 and P_4

= Pressures along the length defined in Fig. 9

ω_n = Natural frequency of the structure defined in Eq. (14)

5. Result of Response Analysis

The response of the body of submerged floating railway under shock pressure is expressed by Eqs. (11) to (15). Fig. 10 shows the analysis model in underwater explosion. The length of model is short enough to verify the proposed theoretical solution. If it becomes large, the bending rigidity of the body is so negligible that the system can be a single-degree-of-freedom vibration system. This is discussed in the next chapter. The shape and distribution of shock pressure by underwater explosion is shown in Figs. 11 and 12. Fig. 11 shows the shock pressure variation over the time according to Eq. (1) and for simplifying analysis, it was idealized in triangular pulse as indicated in Eqs. (8) and (9). Fig. 12 is the result of idealizing the distribution of shock pressure lengthwise based

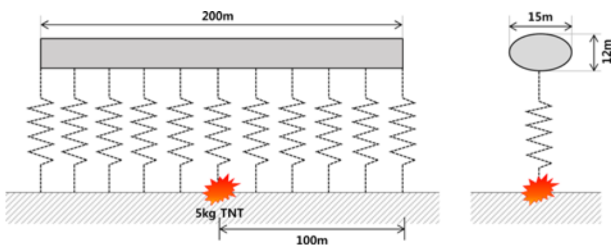

Fig. 10. Analysis Model of Submerged Floating Railway Subjected to Underwater Explosion

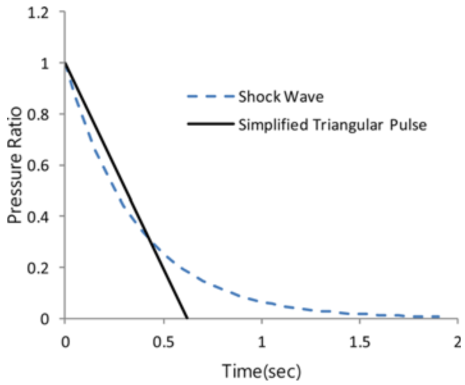

Fig. 11. Variation of Shock Wave over Time

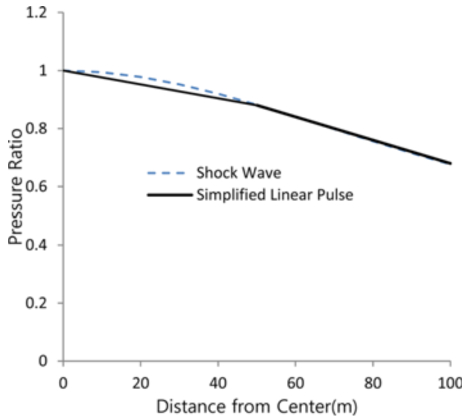

Fig. 12. Distribution of Shock Pressure Lengthwise

on the center of the body as shown in Eqs. (4) to (7).

The model for finite element analysis is shown in Fig. 13 below. Modeling the body with beam element and modeling the mooring system with distributed spring element were carried out (LSTC, 2003). The data for finite element analysis is indicated in Table 1. The shock pressure at each nodal point given by Eq. (1) is multiplied by the diameter of body so that it can be applied to

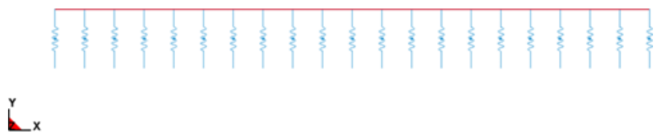

Fig. 13. Finite Element Analysis Model (20 beam elements and 21 spring elements)

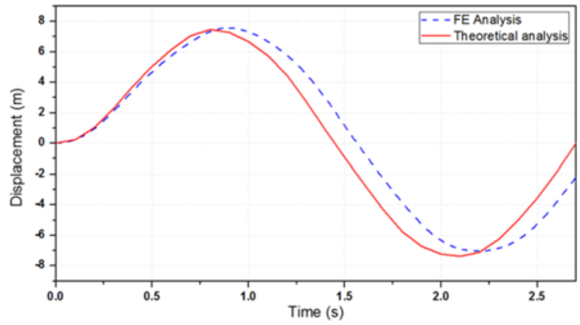

Fig. 14. Variation at the Center of the Body over Time

each element. The time varying loads defined at each time are acting on each element for transient response analysis. The load distribution along the length is plotted in dotted line as shown in Fig. 12 and time variation at each point in Fig. 11. Responses are given after calculation at the predefined time interval.

Figure 14 is the calculated result of displacement with time variation at the center where maximum displacement occurred. Also, Figs. 15 and 16 show the distribution of displacement and bending moment, respectively lengthwise at certain time. Fig. 14 shows a little difference in the periods of peak displacement. In theoretical analysis, damping terms were neglected, but in finite element analysis damping effects were taken into accounts. Damping effects contribute to time delay of the maximum displacement and decay of peak displacements. Generally, the damped period of vibration is a little longer than the undamped period of vibration. Figs. 15 and 16 show that the maximum

Table 1. Data for Analysis

Item	Value	Remarks
Bending rigidity, EI (N·m^2)	6.7×10^{12}	Young's modulus of Steel 2.0×10^{11}Pa, Wall Thick. 20 mm
Mass per unit length (including virtual mass), m (kg/m)	1.4×10^5	
Stiffness of mooring system, k (N)	4.8×10^5	Steel Chain Dia. 122 mm
Length of the body (m)	200	
Diameter of the body along long axis (m)	15	
Diameter of the body along short axis (m)	12	
Weight of explosive (kg)	5	Small charge for test (Shock Factor 0.1)*
Distance between the body and explosive (m)	10	
Explosive constant, K	52.5	Constants given by similitude relation for TNT (Yoon *et al.*, 2012)
Explosive constant, K'	0.084	
Explosive index, α	1.13	
Explosive index, α'	-0.23	
Maximum shock pressure (Pa)	5.3×10^5	
Maximum shock load (N/m)	7.93×10^6	

*Shock Factor 0.3 is the survival condition for shipboard equipments in naval vessels (Keil, 1961). For sample calculation, Shock Factor 0.1 is taken into account for structure in this study.

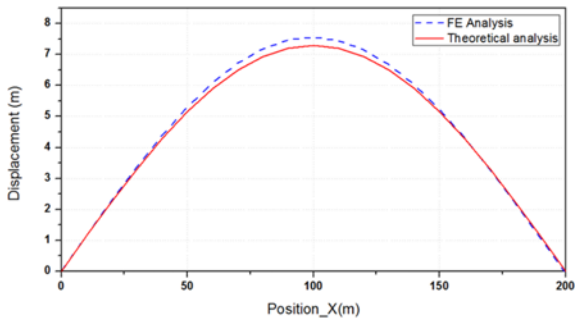

Fig. 15. Displacement of Body Lengthwise at Time 0.9 sec

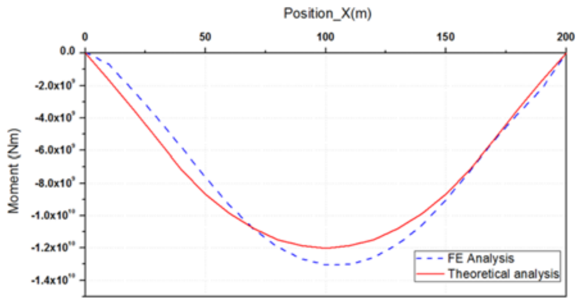

Fig. 16. Moment of Body Lengthwise at Time 0.9 sec

displacement and bending moment by theoretical analysis are a little less than those by finite element analysis. These differences seem to be caused by the small difference of shock pressure shown Fig. 8. In spite of the little differences in period of vibration and maximum values, the results by theoretical analysis give good correlation with those by finite element analysis. They verify that the theoretical analysis results can reveal the behavior of SFT under shock loading.

6. Simplified Response Analysis for Long Body

In case that the interval of fixed jacket is so far that the body of submerged floating railway can be a very long beam, the bending rigidity of the body is negligible and only mooring lines resist to lateral movement. This assumption is verified by Eq. (14) to give the natural frequency of the body. It can be modified as the following equation:

$$\omega_n = \sqrt{\frac{k}{m}\left[1+\frac{EI}{k}\left(\frac{n\pi}{l}\right)^4\right]} \cong \sqrt{\frac{k}{m}} \tag{17}$$

The larger stiffness of mooring line k or length l is, the more negligible the second term of Eq. (14) is. In this case, the natural frequency of the body becomes that of mass-spring system of one-degree of freedom. Shock responses of one-degree of freedom system are given similar to Eqs. (15) and (16), in which only one mode is used (Seo *et al.*, 2014).

7. Conclusions

In this study, response analysis of the body of submerged floating railway to underwater explosion was carried out in an effort to secure the safety of a long-distance submerged floating railway. Shock pressure by underwater explosion was assumed to be piecewise linear and theoretical solution of the governing equation was obtained for the simply supported beam with elastic springs under impulse pressure. Calculation results were compared with the results of finite element analysis. As a result of comparing, the calculated displacement was acceptably coincident. A little difference in the periods of peak displacement seems to be caused by the damping effect taken into accounts in finite element analysis. Also, the small differences in the maximum displacement and bending moment seem to be caused by the small difference in the shock pressure which comes from idealization of loading. In spite of the small differences in the results, theoretical analysis gives good solution to describe the behavior of SFT during impact loading process. When the length of the body is extended and natural frequency of the body itself is much smaller than that of mooring system accordingly, response of the body could be obtained using one dimensional model considering the mooring system only. Theoretical simple solution is very useful for repeated analysis of design parameters needed at early design stage.

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