수중폭발에 의한 해중터널의 동적거동

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Dynamic Behavior of Submerged Floating Tunnel by Underwater Explosion

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Abstract

In this paper, to estimate the dynamic behavior of a submerged floating tunnel(SFT) by underwater explosion(UE), the SFT is modeled and analyzed by the explicit structural analysis package LS-DYNA. The section of SFT near to explosion point is modeled to shell and solid elements using elasto-plasticity material model for concrete tubular section and steel lining. And the other parts of the SFT are modeled to elastic beam elements. Also, mooring lines are modeled as tension-only cable elements. Total mass of SFT is including an added mass by hydrodynamic effect. The buoyancy on the SFT is considered in its initial condition using a dynamic relaxation method. The accuracy and the feasibility of the analysis model are verified by the results of series of free field analysis for UE. And buoyancy ratio(B/W) of SFT, the distance between SFT and an explosion point and the arrangement of mooring line are considered as main parameters of the explosion analysis. As results of the explosion analysis, the dynamic responses such as the dent deformation by the shock pressure are responded less as more distance between SFT and an explosion point. However, the mooring angle of the diagonal mooring system can not affect the responses such as the horizontal displacement of SFT by the shock pressure.

Keywords : submerged floating tunnel, SFT, underwater explosion, UE, shock pressure, dynamic behavior, mooring force, diagonal mooring system

1. Introduction

The concepts of Submerged Floating Tunnels(SFTs) and Submerged Floating Bridges(SFBs), also known as Archimedes Bridges that are supported by buoyancy in the water, were first mentioned in the patent of Lord Edward James Reed of England in 1886, and in Norway in the early 1900s. SFTs are not significantly affected by water depth or soil of seabed because SFTs are not directly connected to

the seabed, except for the anchors that supports them, thus increasing the feasibility of intercontinental or massive ocean tunnels. In particular, if the structure is located below a certain depth in the water, it is minimally affected by weather conditions above the water surface or by waves; therefore, the structure can be stable. Many countries have supported concept designs and prototype projects based on these merits, most notably, Italy, Norway, and Japan since the mid and late 1900, because these countries

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view such structures as the future technology of mankind. Most recently, the prototype project to construct an SFT in Qiandao Lake is underway in China(Mazzolani *et al.*, 2010).

Studies(Pilato *et al.*, 2008; Martinelli *et al.*, 2007; Martinelli *et al.*, 2010) on the fundamental safety of SFTs have focused on behavior caused by earthquake loads and hydrodynamic loads, and on design concepts. In addition, fatigue load has been investigated(Li *et al.*, 2010).

However, accident loads that can cause severe damage on SFTs are collisions with Underwater Navigation Vessels(UNVs) and Underwater Explosions (UEs)(Hong and Lee, 2014). In particular, impacts by UEs like to the attack against ROK ship Cheonan by TNT equivalent of the maximum 360kg charge size are serious accident loads that can destroy entire submerged tunnel systems; however, such accidents have not been actively considered.

DNV-RP-C204, which is one of the current design standards on steel tube against impact force, explains the predominance of bending that accompanies local deformation from impact loads described in terms of a force-deformation relationship(DNV, 2010). The flexural stiffness of steel tube decreases from strain caused by local buckling; moreover, such strain induces an axial tensile force of membrane stress type. To apply this approach to an SFT analysis, it is important to evaluate the dynamic behavior of the SFT during an underwater explosion(UE).

In this paper, the dynamic behaviors of SFT by the shock wave and the bubble expansion induced by underwater explosion(UE) are analyzed. For analyzing the dynamic behaviors of SFT under the underwater explosion, the explicit structural analysis packages LS-DYNA is used.

2. Modeling of the structure

2.1 Submerged floating tunnel(SFT)

In this paper, the entire system behavior and local behavior occurred on SFTs under the underwater

explosion were identified through the detailed modeled part as shown in Fig. 1(a). The other part of the SFT was modeled as elastic beams with the cross sectional properties of the SFT. We modified the shape and data of the SFT cross section from a previous study (Seo and Kim, 2013) and applied it to our analysis.

The SFT cross section used in our analysis is shown in Fig. 1(b). This circular cross section shows an internal partition, and internal and external walls installed with a steel liner to secure water-tightness. For the detailed model part of 100m with a steel-concrete complex cross section was considered. Moreover, steel materials such as internal liner and concrete were modeled as elasto-plastic models using shell elements and solid elements, respectively.

(a) Detailed model for collision part of 100m

(b) Steel-concrete complex cross section

Fig. 1 FE model of SFT

The material properties and nonlinear behavior of the steel and concrete in the SFT model are given in Table 1 and shown in Fig. 2, respectively.

Table 1 Material properties of steel and concrete

Material	Mass density (kg/m ³)	Modulus of elasticity(Pa)	Poisson's ratio
SS400	7,850	2.0×10^{11}	0.3
Con'c(35MPa)	2,450	3.5×10^{10}	0.167

(a) Stress-strain curve for SS400

(b) Damage and failed curve for concrete(35MPa)

Fig. 2 Applied material properties

Both the detailed model and elastic beam model parts are supported by mooring. The stiffness of the mooring lines, whose tension changes with the direction of the applied force, was calculated.

The initial tension in the mooring lines, T_o , is calculated under the equilibrium condition of forces (Fig. 3) as follows: (Long *et al.*, 2009)

$$T_o = \frac{b}{n(\cos\theta_1 + \cos\theta_2)} \quad (1)$$

Where, n is the number of mooring lines and b is the buoyancy obtained by subtracting the self-weight from the total buoyancy of SFT.

The stiffness coefficient of the mooring lines that considers the amount of change in the mooring tension caused by external forces is calculated by the following relationship equations.

$$K_x \delta_x = (T_0 + \Delta T_x) \sin\theta - (T_0 - \Delta T_x) \sin\theta \quad (2a)$$

$$K_z \delta_z = \Delta T_z \cos\theta + \Delta T_z \cos\theta \quad (2b)$$

Tension of the mooring lines obtained as a result of assuming a mooring of 80m depth using Eqs. (2a) and (2b) is listed in Table 2.

(a) Equilibrium condition of forces in static state

(b) Behaviors of SFT by external forces

Fig. 3 Mooring lines of SFT(Long *et al.*, 2009)

Table 2 Stiffness coefficients for cable element

Outer(MN/m)	Inner(MN/m)	Ideal(MN/m)
55.77	57.54	109.40

Furthermore, to simulate the continuous behavior of SFTs caused by impact effects, 1km sections on the left and right were represented by elastic models (Fig. 4) using beam elements.

For the cross section properties of the elastic model idealized using beam elements, the cross sectional area and the moment of inertia were applied as given in Table 3, considering the cross sectional region of the concrete part.

To make the mass of the idealized SFT elastic beam model equal to the mass of the detailed SFT elasto-plastic model, the unit masses were set to 3,745.9kg/m³, 3,210.6kg/m³ and 2,809.4kg/m³ at buoyancy ratios(B/Ws) of 1.2, 1.4 and 1.6, respectively.

(a) Mooring line and boundary condition

(b) Global FE model of SFT

Fig. 4 SFT and mooring line model

Table 3 Section modulus of SFT

Cross sectional area(m ²)		Shear area(m ²)
55.77		109.40
Moment of inertia(m ⁴)		Moment of polar inertia(m ⁴)
I _z	I _x	
745.18	599.47	1344.65

2.2 Dynamic relaxation analysis

SFT constant buoyancies of three cases are considered as the initial analysis condition in the dynamic relaxation analysis(Fig. 5); this analysis decreases an impact from constant loads, such as buoyancy under the underwater explosion environment(LS-DYNA Theory manual, 2006).

Dynamic relaxation is performed by the dynamic equilibrium Eq. (3), where the damping condition is added at time n .

$$Ma^n + Cv^n + Q^n(d) = 0 \quad (3)$$

$$Q^n(d) = F^n - P^n - H^n \quad (4)$$

Where, from the mass matrix M , damping matrix

(a) Dynamic relaxation

(b) Convergence

Fig. 5 Dynamic relaxation analysis

C , the n th time interval n , acceleration vector a^n , velocity vector v^n , and displacement vector d , Eq. (5) is obtained by the central difference scheme with a fixed time increment Δt .

$$v^{n+1/2} = \frac{d^{n+1} - d^n}{\Delta t}, \quad a^n = \frac{v^{n+1/2} - v^{n-1/2}}{\Delta t} \quad (5)$$

To maintain the explicit form of the central difference method, M and C have to be diagonal matrices. Where, C is expressed as Eq. (6) for the dynamic relaxation technique.

$$C = c \times M \quad (6)$$

Here, the damping parameter is calculated with Eq. (7) when the most recent convergence ratio checked against the optimum convergence ratio in the study by Papadrakakis(Papadrakakis, 1981) properly converges by automatic adjustment.

$$c = \frac{4\sqrt{\omega_{\min}^2 \times \omega_{\max}^2}}{\Delta t(\omega_{\min}^2 + \omega_{\max}^2)} \quad (7)$$

Where, $\omega_{\min}$ is the minimum eigenvalue of the structure and $\omega_{\max}$ is the maximum eigenvalue.

If the automatic adjustment approach is not used, damping is applied as in Eq. (8).

$$v^{n+1/2} = \eta v^{n-1/2} + a^n \Delta t \quad (8)$$

Where, η is the input damping coefficient. This relaxation process continues to the convergence criterion based on the total kinetic energy.

3. Underwater explosion analysis

3.1 Free field analysis

For verifying the validity of an applied finite element model for UE, the free field analysis of UE was executed to the condition of TNT 360kg(Cheonan ship Report, 2010) at depth of 50m. The finite element model for UE is modeled to two parts that are water and air models respectively. Height of

water model is 100m and air is 30m. These models are having same breadth of 100m each other.

Material properties of these models that are water and air are applied to proper values as follows. For water model, it is unit mass of 1.025kg/m^3 and coefficient of kinematic viscosity of 0.00113 and the unit mass of the air is 1.28kg/m^3 . For the explosive, there are considered to unit mass of 1630kg/m^3 and denotation velocity of 6930m/sec . Boundary conditions of the entire underwater explosion model are applied by the non-reflecting boundary condition that not to reflect the shock wave in fluid.

From results of the free field analysis for UE, the shock pressure is propagated to all directions during very short time and its characteristic is analyzed to be similar with theoretical value in 2m of the explosion radius as shown Fig. 6.

Here, The theoretical value that it is the pressure-time history, $P(t)$, with the peak pressure, $P_{\max}$, at a point is given by Eq. (8) and Eq. (9)(Webster, 2007).

$$P(t) = P_{\max} \times e^{\frac{-t-t_1}{\theta}} + P_D \quad (8)$$

$$P_{\max} = K_1 \left(\frac{W^{1/3}}{R} \right)^{A_1} \quad (9)$$

Where, P_D is the hydrostatic pressure at charge depth, t_1 is the time that it takes the shock wave to reach the point of interest, θ is the time constant, K_1 and A_1 are TNT constants, W is the charge weight and R is the radius to the point of interest from the center of the charge.

From the result of calculation, the maximum radius of bubble that is occur after propagation of the shock is calculated to be reached to 6.45m at 0.48826sec by the theoretical function. From results of the free field analysis, the maximum radius of bubble is reached to 8.82m at 0.48796sec that it is a time similar with the theoretical time. And the bubble is maintained up to 0.58297sec. From results compared with theoretical value, although the bubble by the explosion analysis is larger than theoretical value, the times reached to the maximum bubble is evaluated to be similar. After

Fig. 6 Shock wave by the free field analysis(Radius=2m)

the maximum bubble, its radius is decreased and gone up to surface of the water with formation of the water jet from bottom of bubble at 1.3109sec(Fig. 7).

(a) Bubble expansion by the underwater explosion(0.48796sec)

(b) Bubble contraction and water jet(1.3109sec)

(c) Jet impact on surface of the water(3.5449sec)

Fig. 7 Bubble and water jet by explosion analysis

3.2 Underwater explosion(UE) with SFT

The underwater explosion model that verified the validity by the free field analysis is assumed that the shock wave and the bubble strike on lateral wall of SFT. Where, a mass of the explosive that decide magnitude of the explosion is applied by 360kg. Boundary conditions of the underwater explosion model are considered to continuum domains by applying the non-reflecting boundary condition. For analyzing the

dynamic behavior of SFT, distances between SFT and an explosive point are considered by 2m, 5m, 10m and 15m, respectively(Fig. 8).

(a) 2m of distance between SFT and explosive

(b) 15m of distance between SFT and explosive

Fig. 8 Scenario for underwater explosion with SFT

Also, the buoyancies of SFT are applied by 1.2, 1.4 and 1.6 times for self-weight of SFT, respectively. The mooring angles in the diagonal mooring system are considered by 29.358°(90m) and 45°(160m) as Fig. 9.

By considering these analysis conditions, the characteristic of dynamic behaviors such as the penetration and horizontal displacements of SFT by the shock pressure are analyzed through the underwater explosion analysis. For the underwater explosion analysis with SFT, there are consisted of 9 cases of the environment conditions as Table 4.

Table 4 Conditions for underwater explosion analysis

Mooring angle	Buoyancy ratio	Radius from a explosive point(m)			
		2m	5m	10m	15m
29.358° (90m)	1.2	LC11	LC12	LC13	LC14
	1.4	LC21	—	—	—
	1.6	LC31	—	—	—
45° (160m)	1.2	LC41	—	—	—
	1.4	LC51	—	—	—
	1.6	LC61	—	—	—

Fig. 9 Mooring angles for diagonal mooring system

4. Analysis Results

4.1 Horizontal displacements of SFT system

From results of the underwater explosion analysis, horizontal displacements of SFT system are induced by the shock wave and the bubble expansion. Fig. 10 represent the effect by the bubble expansion when the mooring angle is 29.358°(90m) and the distance between the wall of SFT and an explosive point is 2m. This bubble expanding after propagation of the shock wave is prevented by SFT located on 2m

Fig. 10 Bubble expansion of underwater explosion with SFT(Buoy. ratio=1.2, SFT distance=2m, Mooring angle=29.358°)

position from an explosion point. The SFT that preventing an expansion of the bubble is generated to a severe internal damage with a horizontal displacement.

Also, the horizontal displacement of SFT system by the underwater explosion is rarely occurred in the entire SFT system but it is occurred only in a local part of SFT near to the explosion point(Fig. 11). It is assumed because the horizontal displacements of SFT are not propagated to the axis direction of SFT.

These horizontal displacements of SFT are rarely affected the ratio of the buoyancy to the weight of SFT(Fig. 12). Also there rarely have significant affects for the distance of the position of SFT and the explosion point(Fig. 13).

When the mooring angle of the diagonal mooring system is 45°(160m), the horizontal displacement of SFT is decreased more than its for 29.358°(90m) of the mooring angle with increasing the ratio of the buoyancy to the weight of SFT. However, the change of the mooring angle of the diagonal mooring system rarely affect the horizontal displacement of SFT(Fig. 12).

(a) Positions for monitoring horizontal displacement of SFT

(b) at detailed model(Shell & Solid)

(c) at idealized model(beam)

Fig. 11 Horizontal displacements for SFT by underwater explosion(Buoy. ratio=1.2, SFT distance=2m, Mooring angle=29.358°)

Fig. 12 Horizontal displacements of SFT according to variation of ratio of buoyancy/weight for mooring angle (SFT distance=2m)

Fig. 13 Horizontal displacements of SFT according to variation of SFT distance (Buoy. ratio=1.2, Mooring angle=29.358°)

4.2 Local damage of SFT

The bubble expansions by the underwater explosion can not exactly form the spherical shape when the SFT is in a radius of the bubble expansion. And the wall of SFT that it is located as an obstacle in a radius of the bubble by the explosion is damaged by the bubble expansion(Fig. 14).

(a) SFT distance=2m

(b) SFT distance=5m

(c) SFT distance=10m

(d) SFT distance=15m

Fig. 14 Expansion of bubble and obstacle effects of SFT by explosion simulation (Buoy. ratio=1.2, Mooring angle=29.358°)

These penetration that it is induced by the damage of the wall are decreased when the SFT is far from a explosion point. However, the variation of ratio of buoyancy to weight of SFT don't affected the penetration of SFT(Fig. 15, 16).

Also, although the mooring angle of the diagonal mooring system is increased to 45°(160m) from 29.358°(90m), the variation of ratio of buoyancy to

Fig. 15 Penetration of SFT according to variation of SFT distance(Buoy. ratio=1.2, Mooring angle=29.358°)

Fig. 16 Penetration of SFT according to variation of buoyancy ratio for mooring angle(SFT distance=2m)

weight of SFT don't affected the penetration of SFT (Fig. 16).

4.3 Tension of diagonal mooring system

The initial tensions of the diagonal mooring system as shown Table 5 represent the maximum tension of mooring lines by the buoyancy of SFT. These maximum tension of the diagonal mooring system are mainly occurred on an outside of mooring lines named to B-line as shown Fig. 17.

Table 5 Initial tension of diagonal mooring system

Mooring angle	Buoyancy ratio	Initial tension(MN)			
		2m	5m	10m	15m
29.358° (90m)	1.2	6.4	6.4	6.4	6.4
	1.4	7.8	-	-	-
	1.6	9.4	-	-	-
45° (160m)	1.2	6.9	-	-	-
	1.4	9.0	-	-	-
	1.6	11.1	-	-	-

Fig. 17 Mooring line of diagonal mooring system

From results that analyzing the characteristic for the maximum tension of the diagonal mooring system, these maximum tensions are increased when a ratio of the buoyancy to weight of SFT is increased. Also, when the mooring angle of diagonal mooring system is 45° (160m), its maximum tension is increased to about 5.5~15.4% more than 29.358° (90m) of the mooring angle(Fig. 18).

Fig. 18 Maximum tension of mooring line with SFT according to variation of buoyancy ratio by each mooring angle(SFT distance=2m)

From results that analyzing the characteristic for the maximum tension of the diagonal mooring system according to a position of SFT from an explosion point, the maximum tension is rarely affected the variation of the distance between SFT and an explosion point(Fig. 19).

Fig. 19 Maximum tension of mooring line with SFT according to variation of SFT distance (Buoy. ratio=1.2, Mooring angle= 29.358°)

4.4 The horizontal shock pressure by the underwater explosion

The shock pressures acting on the wall of SFT by the underwater explosion are classified to the shock wave and the bubble expansion. The expansion of bubble by the underwater explosion is reached to the maximum radius at about 0.5 second and then it is gradually decreased. Therefore, it is analyzed about the characteristic of the shock pressure for 1 second.

The normal direction of shell elements that there are consisted to a steel material covering on the outer surface of SFT decides the sign of shock pressure acting on the shell element. In this paper, the direction about Z axis of local coordinate for shell element that it is a steel material covering on the wall of SFT is considered by a positive sign for the outer direction of the wall of SFT as shown Fig. 20.

Fig. 21 is represented as the time history curves of the shock pressure acting on the wall of SFT according to variations of distance between the SFT and the

Fig. 20 Normal direction of local coordinate for shell elements of SFT

Fig. 21 Time history curve of shock pressure acting on SFT according to variation of SFT distance (Buoy. ratio=1.2, Mooring angle= 29.358°)

explosive point with 1.2 of ratio of buoyancy to weight of SFT and 29.358° (90m) of the mooring angle.

The maximum shock pressure and the mean shock pressure acting on the shell element of SFT by the underwater explosion simulation are calculated to the absolute value only for shock pressures having the negative value. Where, the mean shock pressure is defined by averaging with the curve of negative inclination.

From results that analyzing the characteristic for these shock pressures acting on the wall of SFT, the maximum and the mean shock pressures that there are results from the underwater explosion analysis with SFT are a little declined that increasing ratio of the buoyancy to the weight of SFT as shown Fig. 22. And Value of the mean shock pressure that it is a value from a result of the free field analysis is similar with the theoretical value(Fig. 23).

Fig. 22 Maximum and mean pressures acting on SFT according to variation of buoyancy ratio by each mooring angle(SFT distance=2m)

Fig. 23 Maximum and mean pressures acting on SFT according to variation of SFT distance (Buoy. ratio=1.2, Mooring angle= 29.358°)

When the distance between the SFT and an explosion point is increased, the shock pressure acting on the wall of SFT is decreased. And the maximum shock pressure acting on it is occurred that being larger about 3.5~4.9 times than the mean shock pressure. Also, when 29.358° (90m) of the mooring angle is increased to 45° (160m), the variation of these mooring angles rarely affect the shock pressure acting on SFT(Fig. 22).

5. Conclusion

In this paper, there is analyzed for the dynamic characteristic of SFT under the underwater explosion.

From results of the explosion simulation, when the distance between SFT and an explosion point is increased, the penetration and the shock pressure on SFT are decreased. But there don't have significant affects for the horizontal displacement of SFT and the mooring tension of the diagonal mooring system.

When the ratio of the buoyancy to the weight of SFT is increased, the mooring tension of the diagonal mooring system is increased with it. But it does not have significant affects for the relation with the horizontal displacement of SFT and the penetration and the shock pressure on the wall of SFT.

Also, when the mooring angle of the diagonal mooring system is increased, the mooring tension of the diagonal mooring system is increased with it. But it does not have significant affects for the horizontal displacement of SFT and the penetration and the shock pressure on the wall of SFT.

Because the dynamic behavior of SFT by the underwater explosion showed an unique characteristic, studies for this field will need further. Also, studies for a design load and a design methodology with the evaluation for dynamic behavior according to shape of cross-section of SFT will need too.

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요 지

본 논문에서는 수중폭발(UE: underwater explosion)에 의한 해중터널(SFT: submerged floating tunnel)의 동적거동을 양해법(explicit)을 이용하는 LS-DYNA에 의한 유한요소해석을 통하여 분석하였다. SFT의 유한요소모델은 원형단면의 강재 라이너에 콘크리트가 채워진 복합재 원형단면으로 고려되었다. 해중터널 시스템의 중앙부 100m 구간은 탄소성재료를 고려한 솔리드(solid)요소로 상세하게 모델링하였으며, 양측 방향으로 각각 1km 구간에 대해서는 탄성재료를 고려하여 빔(beam)요소로 이상화하여 모델링하였다. 사선계류시스템은 케이블(cable)요소를 적용하였으며, 수중폭발에 의한 동적거동시 수리동적질량의 영향을 고려하기 위하여 원형단면에 대한 추가질량을 고려하였다. 또한 부력과 같은 상시하중을 초기조건으로 고려하기 위하여 동적완화해석(dynamic relaxation analysis)을 수행하였다. UE는 부력비(B/W)와 폭발지점으로부터 거리의 변화에 대해서 고려하였으며, 폭발의 규모는 천안함 합동조사보고서(2010)를 참조하여 TNT 360kg로 결정하였다. 수중폭발 해석결과, 폭발지점으로부터 SFT까지 거리는 관입량, 충격압력의 크기와 반비례 관계에 있고, 부력비(B/W)가 커질수록 계류장력도 커짐을 확인하였다. 그러나 사선계류라인의 계류각 변화는 SFT의 수평거동, 관입량, 계류력, 충격압력과의 연관성을 찾을 수가 없었다.

핵심용어 : 수중폭발, 해중터널, 동적거동, 복합재 원형단면, 사선계류시스템, 동적완화해석, 부력비(B/W)