STRUCTURAL BEHAVIOUR OF SUBMERGED FLOATING TUNNELS WITH DIFFERENT CABLE CONFIGURATIONS UNDER ENVIRONMENTAL LOADING

PERILAKU STRUKTURAL TEROWONGAN APUNG TERENDAM DENGAN KONFIGURASI KABEL YANG BERBEDA DIBAWAH BEBAN ALAM

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ABSTRACT

This paper presented the structural behaviour of a Submerged Floating Tunnel (SFT) for the Seribu Archipelago crossing under environmental loadings using the different cable configurations. The SFT is a tubular structure submerged in the water at a fixed depth, which features several advantages from the structural, economic and environmental impact points of view. In particular, it seems to be a suitable system for waterway crossings in seismicity zones, because the interaction with the water provides additional damping and inertia to the structural motion. In order to evaluate the SFT structural response to seismic events, response spectrum analyses were carried out considering for a ground multi-support excitation. The different cable system configuration was considered in this investigation. The static and dynamic analyses were carried out to find out the best configuration among them. Although they could not lead to definitive conclusions, the results gave useful indications about the seismic response of Submerged Floating Tunnels. Base on analyses, the SFT with two cable diagonals perpendicular with SFT's body (called Type C) showed the good results.
Keywords: submerged floating tunnel; stresses, displacement, modals, seismic loading

ABSTRAK

Makalah ini mempresentasikan perilaku struktural dari *Submerged Floating Tunnel (SFT)* untuk menyeberang Kepulauan Seribu yang dibebani beban lingkungan dengan menggunakan konfigurasi kabel yang berbeda. *SFT* adalah struktur tubular terendam di dalam air pada kedalaman tetap, yang mempunyai keunggulan ditinjau dari sudut pandang struktural, ekonomi dan dampak lingkungan. Secara khusus, tampaknya menjadi sistem yang cocok untuk penyeberangan jalur air di zona kegempaan, karena interaksi dengan air menyediakan redaman tambahan dan inersia dengan gerakan struktural. Untuk mengevaluasi respon struktural SFT pada peristiwa seismik, analisis respon spektrum dilakukan dengan mempertimbangkan pada eksitasi multi dukungan tanah. Konfigurasi sistem kabel yang berbeda dipertimbangkan dalam penelitian ini. Analisis statis dan dinamis dilakukan untuk mengetahui konfigurasi terbaik. Meskipun tidak dapat menyebabkan kesimpulan yang pasti, hasilnya memberikan indikasi tentang respon seismik yang berguna untuk *Submerged Floating Tunnel*. Berdasarkan analisis, SFT dengan dua kabel diagonal tegak lurus dengan badan SFT (disebut Tipe C) menunjukkan hasil yang baik.
Kata-kata Kunci: beban gempa, *modals*, perpindahan, *submerged floating tunnel*, tegangan;

INTRODUCTION

The Submerged Floating Tunnel (SFT) is a tubular structure placed underwater at an appropriate depth, fixed in position through anchorage groups linked to the seabed. Owing to a positive residual buoyancy (i.e. the buoyancy overcomes the weight of the tunnel) the anchorages, which can be made up of cables or tethers, are in tension, thus effectively restraining the tunnel when it is subjected to environmental actions, such as the hydrodynamic and seismic ones. An SFT basically consists of four parts: (i) the tunnel structure which is made up of tunnel segments and allows traffics and pedestrians to get through, (ii) the shore connection structures which connect SFT to shores, (iii) the cable systems which are anchored to the waterbed to balance the net buoyancy (the present paper concentrates on the SFT type of tunnel buoyancy larger than tunnel weight), and (iv) the foundation structures which are constructed at the waterbed to install cable systems (Long, 2009). As a water construction, the SFT should accept the water wave and current effect, earthquake effect and tsunami effect. The SFTs seem to be particularly suitable to cross waterways located in seismicity zones. This research investigated the SFTs with different cable system configurations subjected to earthquake loadings with a case study is a crossing in Seribu Archipelago.

SFT'S MODEL

The Seribu Archipelago crossing is considered as a case study. However, since the aim of the study is to generally investigate the seismic behaviour of SFTs, 3 (three) cable system arrangements (Fig.1) were investigated. The considered case studies of the crossing length (L) is 150 m, is assumed to be flat along 90-m in the central part of the crossing and to be inclined along 30-m of both side end. The seabed depth is set equal to 21 m, i.e. the average water depth of the Archipelago crossing (Fig. 1). The tunnel is submerged 10 m under the water surface and the connections between SFT and shores are of pinned joints. The SFT cross-section is composed of the reinforced concrete, and the steel plates are used to connect the cable to the concrete. The concrete is given a waterproof coating on its outer and inner surfaces to prevent entry of water into the space in the SFT. The SFT module is consist of precast concrete with each module given fixed connections. Each module consists of a 3 (three) meter panel with each 10 panels joined together to form a module. Thus the SFT has the 3 horizontal modules and the 2 inclined modules as shown in Figure 1.

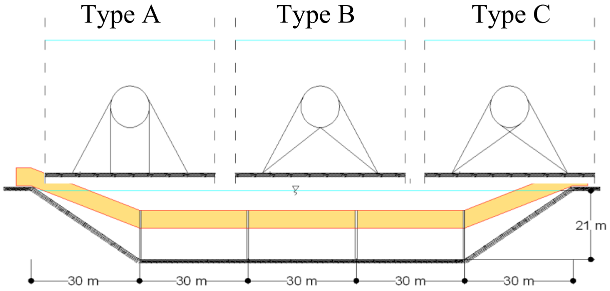


Figure 1. Geometrical configuration of the SFT

Before the SFT prototype will be built in the Seribu Archipelago cross, it needs to obtain the required data, especially the environmental data. The parameters of SFT structure and hydrodynamic environment of The Seribu Archipelago straits are listed in Table 1, which are used in the calculations.

A design criterion of the SFT (Long, 2009) is to provide buoyancy enclosed between an upper bound equal to the 130% of the permanent weight and a lower bound equal to 120% of the sum of permanent weight and traffic loads. However this criterion could lead to excessively large residual buoyancy in those cases where large internal dimensions are needed, so that lower bound values could be considered.

Table 1. Parameters of fluid dynamic environment and SFT structure

Fluid dynamic enviromental	**Symbol**	**Unit**	**Value**	**Structural Property**	**Symbol**	**Unit**	**Value**
Fluid density	ρ	kg/m^3	1,025	Tunnel equivalent density	ρT	kg/m^3	2,018
Water depth	h	m	20	Tunnel outer diameter	D	m	5.5
Wave height	H	m	1.2	Tunnel inner diameter	d	m	4.7
Wave period	T	m	3.58	Tunnel equivalent Young	ET	N/m^2	3.2×10^{10}
Surface current velocity	$U0$	m/s	1.2	Cable density	ρC	kg/m^3	7,850
Drag coefficient	CD	1	1	Cable diameter	dC	m	0.1
Mass/inertia coefficient	Cm	1	2	Cable Young modulus	EC	N/m^2	1.4×10^{11}
Added-mass coefficient	Ca	1	1	Kinetic viscosity Coefficient	υ	m^2/s	1.067×10^{-6}

For this study of the Seribu Crossing, the uplift force is 31563.5 KN and the total of structural weight is 25770 KN, thus the ratio of the uplift force and the weight is 1.22. This ratio will meet the required criteria, i.e. between 1.2 - 1.3. So that the size of a circular cross section of concrete outside the six-meter diameter by the 40 cm thick is used as a study of this SFT.

To analyses the structure, the Finite Element (FE) models of these structures are created using SAP2000 v.14 software. The geometric properties, material properties, support conditions and loading are then assigned. Finally, static analysis and modal analysis are conducted.

SFT'S LOADING

The loading is one of the important factors that must be considered in the modeling. There are three types of loadings namely: *the permanent loads* (including hydrostatic load), *the live load* due to traffic, and *the environmental loads* due to waves, currents and earthquakes. The combinations of loadings in these analyses are:

1. Dead + Live + Buoyancy + Hydrostatic + Current + wave
2. Dead + Buoyancy + Hydrostatic + Current + wave
3. Dead + Live + Buoyancy + Hydrostatic + Current + Wave + Earthquakes
4. Dead + Buoyancy + Hydrostatic + Current + Wave + Earthquakes

Earthquakes

Referred to Indonesia seismic code (SKSNI-1726-2002), the SFT is located in third seismic zone as shown in Figure 2. The value of the seismic loadings is referred to the code using the response spectrum with the PGA value about 0.15g and located in the moderate soil as presented in Figure 4.

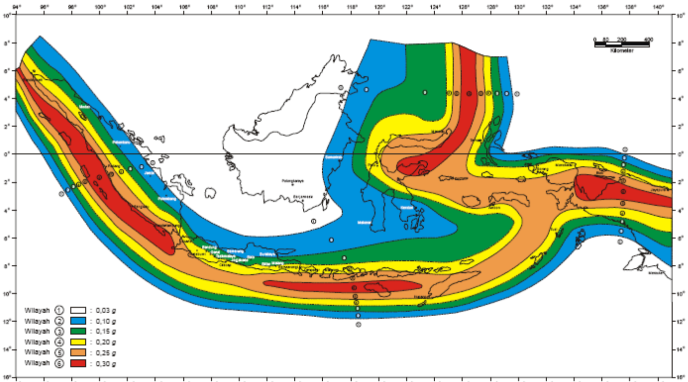


Figure 2. Indonesia seismic zone (SNI-1726-2002)

Hydrodynamics

The forces F_h per unit length arising from the water-SFT interaction, due to their relative motion, during a seismic event can be evaluated through the Morison's equation (Martirea, 2010):

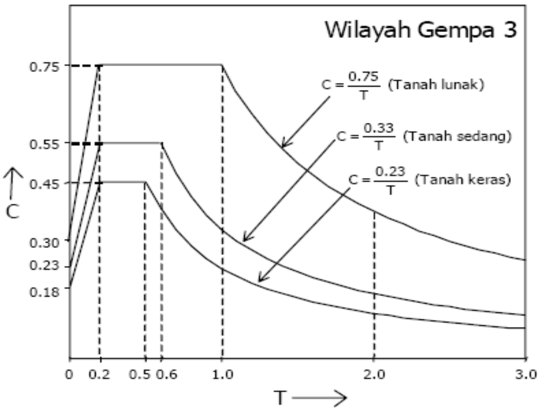


Figure 3. The seismic zone 3 (SNI-1726-2002)

$$F_h = \rho_w \frac{\pi D^4}{4}\left[\left(C_t - 1\right)\left(a_w(t) - a_s(t)\right)\right] + \frac{1}{2} C_D . D . \left(v_w(t) - v_s(t)\right) . \left|v_w(t) - v_s(t)\right| \quad (1)$$

where ρ_w is the water density, *D* is the external diameter of the structural element (i.e. tunnel or cable), *CI* is the inertial coefficient, *CD* is the drag coefficient, aw and as are the water particle and structure acceleration, respectively, *vw* and *vs* are the water and structure velocity, respectively.

Hydrostatic actions

Any surface immersed in a fluid will have a force exerted on it by the hydrostatic pressure, and the force acts in the direction of the normal, or the perpendicular to the surface; that is, the direction of the force depends on the orientation of the face considered. The pressure increases linearly with increasing depth into the fluid (Dean, 1991) as shown in the equation (2).

$$p = -\rho g z \quad (2)$$

Where ρ is mass density, g is gravity acceleration and z is depth.

Buoyancy

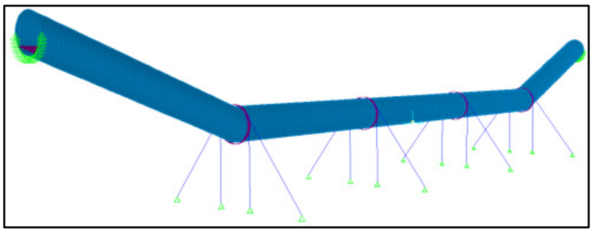
The buoyancy force is equal to the weight of the fluid displaced by the object, and is in the positive *z*(vertical) direction (and it acts through the center of gravity of the displaced fluid) (Dean,1991)

$$F_{buoyancy} = \rho\ g\ V \qquad (3)$$

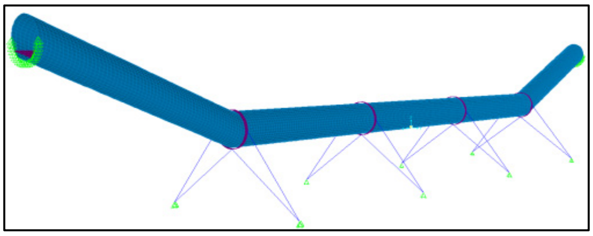
Where: ρ is mass density ;g is gravity acceleration ;V is volume of the fluid displaced by the object.

RESULTS OF THE ANALYSES

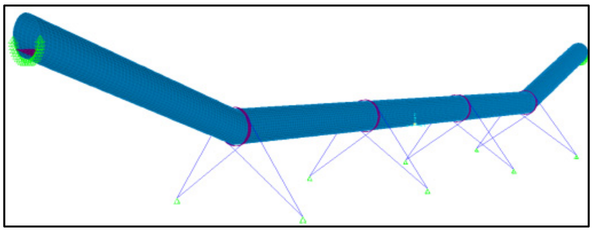
From the three types of the model, which are the models with different cable configuration as shown in Figure 5, the static and dynamic analyses were conducted.



a. Type A Model



b. Type B Model



c. Type C Model

Figure 5. Configuration cable in three type models

Static analysis

The stresses and displacements of the SFT, where can be called as the straight side and inclined side, were occurred due to the applied loadings as mention in the previous section. Tables 2 and 3 showed the longitudinal (s11), transversal (s22) and shear (s12) stresses, the maximum displacements and the maximal axial forces on cables at straight side and inclined side of the SFT respectively. These values were divided based on the results of the four loading combinations and the earthquake loadings from the three models.

As shown in the Tables 2 and 3, the type A has smallest values were compared to the others, whether in the straight side or in the inclined side. The stresses subjected to the earthquake loadings are about 9% to 28% of the stresses of the load combinations. Due to the earthquake loadings, the displacements of the SFT is about 30% of the 4th load combination, it means that the earth loading influences displacement value significantly.

Dynamic analysis

The dynamic behaviour of structures was analysed in order to know the most hazardous conditions due to the structure exposed by the dynamic loads, such as waves, earthquakes, currents (Wahyuni, 2010). Also it is necessary to discover the natural period of the structure and to compare with the period of the structure when the dynamic loads applied. For this case the fluid mechanics influence the structure. The fluid mechanical loads must be counted using Vincent Strouhal known Strouhal number given by formula (Wahyuni, 2010):

$$St = \frac{f\ L}{V} \qquad (4)$$

where: f is the natural frequency of structure ; L is the length; V is the current velocity;

Table 2. Stresses of three models of SFT

Loading combination	Type A Stresses			Type B Stresses			Type C Stresses		
	s11 N/mm^2	s22 N/mm^2	s12 N/mm^2	s11 N/mm^2	s22 N/mm^2	s12 N/mm^2	s11 N/mm^2	s22 N/mm^2	s12 N/mm^2
Comb-1	4.4	4.996	8.785	7.63	7.164	7.335	7.82	7.288	7.423
Comb-2	4.64	5.248	9.164	8.11	7.564	7.801	8.32	7.693	7.893
Comb-3	4.95	5.247	11.318	8.06	7.599	8.591	8.28	7.73	8.697
Comb-4	5.19	5.499	11.697	8.54	7.999	9.058	8.77	8.135	9.167
Seismic	0.55	0.251	2.533	0.43	0.435	1.256	0.45	0.442	1.274

Table 3. Displacements of three models of SFT

Loading combination	Type A			Type B			Type C		
	Max (U1) mm	Max (U2) mm	Max (U3) mm	Max (U1) mm	Max (U2) mm	Max (U3) mm	Max (U1) mm	Max (U2) mm	Max (U3) mm
Comb-1	110.28	116.13	108.09	53.40	53.40	171.92	55.44	55.37	175.65
Comb-2	110.33	116.13	115.19	53.45	53.40	184.18	55.50	55.38	187.79
Comb-3	179.66	189.64	111.76	99.94	100.57	173.40	103.69	104.15	176.72
Comb-4	179.72	189.64	118.85	99.99	100.57	185.29	103.74	104.16	188.85
Seismic	70.48	73.51	4.26	46.70	47.18	1.11	48.37	48.80	3.77

Table 4. Stresses of SFT cable

Loading combination	Max stress of cable		
	Type A	Type B	Type C
	MPa	MPa	MPa
Comb-1	601.59	649.58	393.38
Comb-2	637.38	686.70	414.03
Comb-3	711.03	747.37	473.91
Comb-4	727.19	784.50	494.56
Seismic	78.91	126.30	100.58

Using equation (4) with the data as follows:

$St = 0.2$ (current is about $800 < Re < 200{,}000$)

$V = 1.2$ m/s (current velocity)

$L = 5.5$ meter (diameter of SFT)

Thus the natural frequency of the vortex shedding is

$$f = \frac{St\ .\ V}{L} = \frac{0.2\,x\,1.2}{5.5} = 0.043636\ Hz$$

Thus the period is

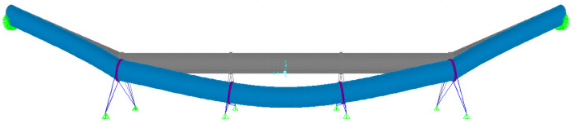
$$T = \frac{1}{f} = \frac{1}{0.043636} = 22.91\,\text{second}$$

The natural frequencies and period from the numerical analysis of the three models can be seen in Table 4 together with the vibration shapes of the SFT's models. The four first modes of the type B model are depicted in Figure 6.

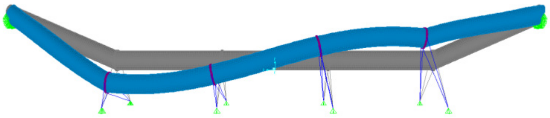
Table 5 shows that the natural periods of the structure are far away from the period subjected to fluid mechanics, thus it can be said that the structure is safe and that a resonance could not occur. The natural period from the model in the first vertical wave is in 2nd mode with the value of 0.896 second in type A, 0.606 in type B and 0.629 in type C which is far away from 22.91 second.

Mode-1 (horizontal vibration)

Mode-2 (vertical vibration)



Mode-3 (vertical vibration)



Mode-4 (horizontal vibration)

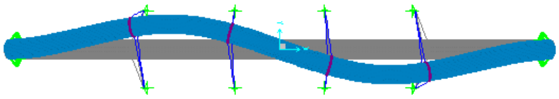


Figure 6: SFT vibration four-first modes

CONCLUSIONS

The conclusions of this work can be drawn as follows:

1. The earthquake loading influences the structure; however the values are smaller compared to the other loadings.
2. The 4th loading combination (comb-4) gives the highest stress value among other loading combination in all type of SFT structures. It means that the most hazardous conditions due to seismic loadings occur when structure is in the empty condition or without any live loads.
3. The cable configuration of the type C give better structure behavior, although stresses and displacement of SFT body give similar value with type B but stress of SFT's cable type C give smaller value than type B. There are inclined cables in both type B and C which can give a better horizontal restraint than type A.
4. The natural period from the three models gives the value quite far from the theoretical value based on Strouhal number. It can be concluded that the structure will have no resonance due to the fluid load.

ACKNOWLEDGEMENTS

We would like to acknowledge the financial support provided by the Agency for the Assessment and Application of Technology and ITS research grants to conduct this research.

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Table 5. Natural frequencies and periods of the SFT

Mode	TYPE-A		TYPE-B		TYPE-C		vibration shapes
	Period	Frequency	Period	Frequency	Period	Frequency	
1	0.896109	1.1159	0.605572	1.6513	0.629596	1.5883	1 curve in horizontal wave (y axis)
2	0.421448	2.3728	0.486683	2.0547	0.49682	2.0128	1 curve in vertical wave (z axis)
3	0.41039	2.4367	0.449845	2.223	0.456464	2.1908	2 curve in vertical wave (z axis)
4	0.396291	2.5234	0.372863	2.6819	0.378212	2.644	2 curves in horizontal wave (y axis)
5	0.243111	4.1133	0.232649	4.2983	0.233083	4.2903	3 curves in horizontal wave (y axis)
6	0.191999	5.2083	0.197187	5.0713	0.197734	5.0573	3 curves in vertical wave (y axis)
7	0.15734	6.3557	0.160291	6.2386	0.160603	6.2265	4 curve in vertical wave (z axis)
8	0.151102	6.618	0.154521	6.4716	0.1526	6.5531	Horizontal curve in the body tunnel
9	0.141669	7.0587	0.139284	7.1796	0.139595	7.1636	4 curves in horizontal wave (y axis)
10	0.107152	9.3325	0.107163	9.3316	0.107164	9.3315	5 curve in vertical wave (z axis)