Ocean Systems Engineering, *Vol. 9, No. 3 (2019) 219-240*
DOI: https:// doi.org/10.12989/ose.2019.9.3.219

A study on response analysis of submerged floating tunnel with linear and nonlinear cables

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(Received November 3, 2018, Revised January 10, 2019, Accepted January 14, 2019)

Abstract. This paper presents the comparison between SFT response with linear and nonlinear cables**.** The dynamic response analysis of submerged floating tunnel (SFT) is presented computationally with linear and nonlinear tension legs cables. The analysis is performed computationally for two wave directions one at 90 degrees (perpendicular) to tunnel and other at 45 degrees to the tunnel. The tension legs or cables are assumed as linear and non- linear and the analysis is also performed by assuming one tension leg or cable is failed. The Response Amplitude Operators (RAO's) are computed for first order waves, second order waves for both failure and non-failure case of cables. For first order waves- the SFT response is higher for sway and heave degree of freedom with nonlinear cables as compared with linear cables. For second order waves the SFT response in sway degree of freedom is bit higher response with linear cables as compared with nonlinear cables and the SFT in heave degree of freedom has higher response at low time periods with nonlinear cables as compared with linear cables. For irregular waves the power spectral densities (PSD's) has been computed for sway and heave degrees of freedom, at 45^0 wave direction PSD's are higher with linear cables as compared with nonlinear cables and at 90^0 wave direction the PSD's are higher with non-linear cables. The mooring force responses are also computed in y and z directions for linear and nonlinear cables.

Keywords: dynamic response analysis; submerged floating tunnel; linear cables; non-linear cables; tension legs

1. Introduction

The submerged floating tunnel (SFT) is a transportation tunnel under water which is built across a river, canal or a strait. SFT is a concept, which is followed in some countries, which is an alternate to long span bridges and tunneling below the seabed where the construction of long span bridges and tunnels becomes uneconomical. The SFTs are constructed below the mean water level

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http://www.techno-press.org/?journal=ose&subpage=7 ISSN: 2093-6702 (Print), 2093-677X (Online)

to avoid the wave action and they are supported with either with floating pontoons or tension legs or combination of both. The SFTs have more buoyancy force compared to its weight. The SFTs are normally laid close to the shore or where the water depth is shallow so they are subjected to environmental loads (waves, current, tides) which vary with seasons. The SFT is placed underwater avoid water traffic and weather, but not that deep. The depth variations should not be high so that they can be easily anchored to seabed or to pontoons at water surface prevent it from floating to surface or submerging respectively. Studying the dynamic response of the tunnel is important as it under goes responses due to waves and current. Remseth *et al.* (1999) studied the stochastic dynamic response and computational response of SFT using Navier stokes modeling of fluid and structure interaction. They discussed modeling of hydrodynamic and structural damping is very important when SFT is moored and they studied the effect of buoyancy in reduction of sway moment. Di Pilato *et al*. (2008) studied the nonlinear dynamic analysis of SFTs under seismic loading they performed time domain simulations to study the responses of SFTs in vertical, horizontal and transverse direction. Zhi-jie *et al*. (2009) studied the time domain responses of tunnel element and compared their experimental results with numerical results for different water depths and wave periods. The experimental results are approximately matching with numerical with varying error. They reported that the responses of tunnel, which have lower width have higher response when compared with tunnel which have lower response. Kunisu (2010) studied the wave action on the SFT using Morison equation. Tariverdilo *et al*. (2011) studied investigated the SFT under moving loads with 2D and 3D models and found the discrepancy between 2D and 3D models decreases as the tether stiffness increases. Man-Sheng et al. (2012) used computation fluid dynamics concepts to study the effect of escape device in SFT during major accidents. Li *et al*. (2012) studied the response of the tunnel due to the fatigue loads developed due to traffic loads, wave and current forces at anchor points, they developed a finite element model to study the response under fatigue loads. Chamelia *et al*. (2015) studied the dynamic response of SFT with mooring line configurations and mooring line angles for waves and current. The fluid structure interaction of SFT and flow around the SFT has been studied numerically using CFD tools by Mandara *et al*. (2016). The model responses and current excitation analysis of the SFT is important it gives an idea about the resonance of the SFT, Yan *et al.* (2016). Xiang *et al*. (2016) has studied the different layout plans for SFTs and also cost analysis.

Although research has been done on many aspects the SFT response for first order waves, second order waves is limited, the first order responses of cables and SFT responses for different currents are shown in Yan *et al.* (2016) and Jin and Kim (2018) has done numerical study on extreme seismic and wave excitation of SFT with irregular waves, in their work cables are modelled as rod elements. Wu *et al.* (2018) has done numerical study on the SFT cables considering the SFT as rigid tunnel using four different earth quakes, in their study the cable are modelled as beam and using combined action of hydrodynamic and seismic excitation the numerical study is carried out. In the present paper the dynamic responses of the SFT have been studied by considering a section of tunnel. Numerical simulation has been performed in Ansys-AQWA*TM and the cables are considered to be linear and also nonlinear. For both linear and non-linear cables the dynamic responses of the tunnel has been studied regular and irregular wave. The responses of SFT are also computed for one cable failure..

The section of paper is divided in to 1) Introduction 2) Numerical formulation and 3) Modeling and numerical simulation details and 4) Results and discussion.

2. Numerical formulation

The dynamic analysis of the SFT is computationally performed in Ansys-AQWA*TM for first order waves, second order waves and irregular waves by considering the cables anchored to seabed as linear and non-linear. One point of the cable is connected to tunnel and one point to the seabed. The numerical formulation of linear and non-linear cables is defined in Ansys-AQWA*TM (Technical manual Ansys (TMAA) (2011)).

Linear cable: The simplest numerical model for a mooring line is linear elastic cable which is a tension-only spring. For linear cable the tension is proportional to its extension, and the constant of proportionality is termed the stiffness. As the extension of spring or mooring or linear cable may vary during the analysis, the structure will experience a force with varying magnitude and direction. The magnitude of this force, which is equal to the cable tension.

The Cable is defined by means of initial unstretched length (L_o)- one point connected to tunnel and another point to the seabed, its stiffness (K) and it's a straight line between the connect points. $X_1(t)$ and $X_2(t)$ are the attachment point's one at structure and one at anchor point. The mooring line is assumed to have no mass and it is always a straight line and it bears only tension no compression.

The tension in mooring line is defined as

$$T = \begin{cases} K(L - L_0) & if\ L > L_0 \\ 0 & if\ L \le L_0 \end{cases} \tag{1}$$

Where stretched length of mooring line is $L = |X_1(t) - X_2(t)|$

Non Linear Steel wire: The steel wire can be modeled with nonlinear properties. As discussed in linear wire $X_1(t)$ and $X_2(t)$ are the attachment point's one at structure, and one at anchor point and initial unstretched length is (L_o)- The tension in the steel wire is

$$T = \begin{cases} K_a(L - L_t) & if\ L > L_t \\ 0 & if\ L \le L_0 \end{cases} \tag{2}$$

Where $L = |X_1(t) - X_2(t)|$ and $L_t = L_0 + d_a \tanh\left(\dfrac{L - L_0}{d_a}\right)$, K_a is the asymptotic stiffness, d_a is the asymptotic offset, The constants K_a and d_a occur from the reality that at great extension $\tanh\left(\dfrac{L - L_0}{d_a}\right)$ tends to unity and Equation tends to asymptotic form as

$$T = \begin{cases} K_a(L - L_0 - d_a) & if\ L > L_0 + d_a \\ 0 & if\ L \le L_0 + d_a \end{cases} \tag{3}$$

In the present paper as the extension is not high so the Eq. (2) applies for all the numerical simulations

2.1 Equation of motion

The equation of motion for submerged floating tunnel Muhammad *et al*. (2017) without considering earthquake excitation is given as given as

$$\left[M+M_a\right]\{\ddot{q}\}+\left[C\right]\{\dot{q}\}+\left[K_e+k_m\right]\{q\}=\{f\}+\{f(q,t)\} \tag{4}$$

Where "M" and "M_a" are mass and added mass matrix respectively, "C" is the damping matrix, "K_e" and "K_m" are stiffness of SFT and mooring lines respectively, "q" represents displacement which varies with time, "q" with one dot represents velocity and two dots represents acceleration of SFT which varies with time, "$f(q,t)$" represents hydrodynamic forces which varies with time and "f" represents hydrostatic load.

In the present work only two degrees of freedom is considered one is Z direction (heave) and in Y direction (sway).

3. SFT Modeling and numerical simulation details

SFT is modeled in ANSYS-Design Modeler. The Technical details of the SFT are taken from Yan *et al.* (2016). The technical details of SFT and tether details are listed in Table 1. 12 tethers are provided on both sides of tunnel with 60 degree angle between tunnel attachment point and seabed. The tunnel length considered for the modeling and numerical analysis is 100 m. The basic numerical modeling and simulation is implemented in the Ansys AQWA*TM software. The geometry is modeled in 'Ansys Design Modeler. The meshing is done in Ansys AQWA*TM and it has a limitation of 18,000 elements, where in diffraction analysis the meshing limitation is - ≤ 12,000.

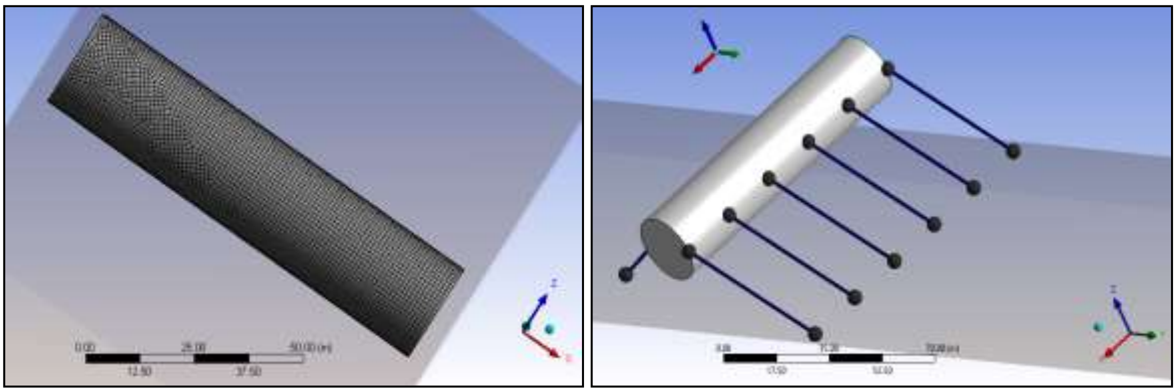

Fig. 1 Meshed model of SFT in Ansys-AQWA*TM indicating the axis.

Table 1 The Technical details of SFT and Tether adopted from Yan *et al*. (2016)

Outer Diameter	23 m
Inside Diameter	19 m
Density	2500 kg/m^3
Buoyancy	417.41 MN
Weight	292.19 MN
Weight to buoyancy ratio	0.7
Submerged depth (from centroid of the SFT to surface)	40 m
Length of the tether	55.361 m
Tether diameter	0.347 m
Tether mass/length	1474.23 kg/m
Tether Angle	60^0

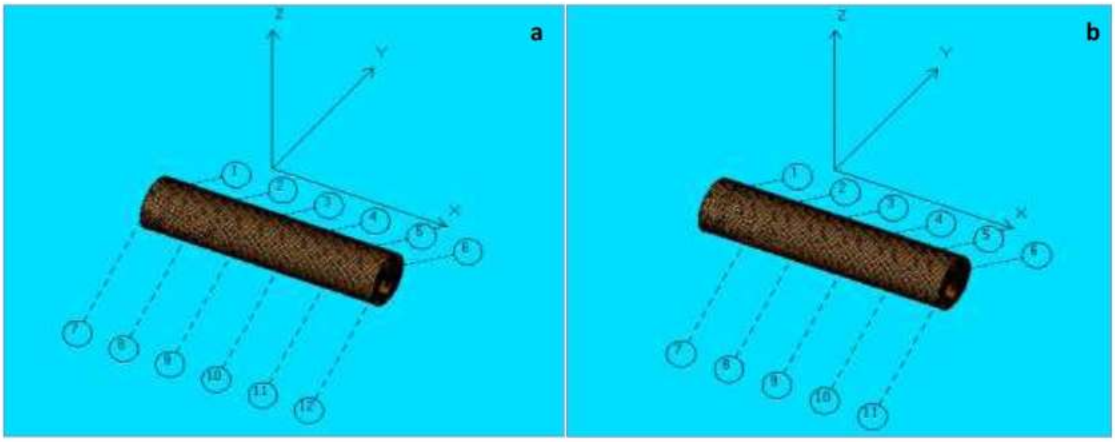

Fig. 2 (a) The SFT with all tension legs in place and (b) one tension leg removed

The SFT diameter to shortest wavelength ratio is greater than 0.2 the diffraction analysis is carried out in the first stage and time domain analysis is carried out in the second stage for first order waves, second order waves and irregular waves. The total simulation time is 3500 s and time step adopted is 0.05 s for all the analysis. The SFT meshed model and SFT with tethers are shown in Fig. 1. Wave direction is taken along the Y- axis which perpendicular to the tunnel that is at 90 degrees and 45 degrees from Y- axis and X- Axis. The axis is shown in Fig. 1and in Fig. 2.

4. Results and discussions

The time step used for the numerical simulation is 0.05 s, and total time for each simulation is 3500 s for all types of waves. Initially 0.1 s time step is used for the simulation but the solution did not converge, because of this we decreased the time step at 0.01 interval. At 0.07 time step results starts to converge and we used 0.05 s as the time step for all the simulations. If the time step is reduced beyond this, the prediction of responses to the accurate value may be achieved, but simulation time will be increased. For the present numerical simulation, we considered only 0.05 s, because the time taken for the one simulation is almost 3 hours. As the results, are satisfactory and our computing resources are limited and in order to save time we adopted 0.05 s for the numerical simulation. In order to capture the steady state response of the SFT the simulation is conducted for 1 hour. The unsteady state response time is different for different wave periods and for some wave periods extending till 1000 s, so in order to capture the steady state response and as a safety factor for the present work 1 hour simulation is carried out.

4.1 First Order Response Amplitude Operators (RAOs)

The RAO's are plotted for wave time periods versus the ratio of amplitude response of SFT and the wave amplitude. For the first order RAO's the wave is assumed linear i.e. the wave amplitude is constant for all the wave frequencies. The SFT tension legs (mooring lines or cables) are assumed to be linear and non-linear and the responses are also computed assuming a cable has failed. Although the tunnel is uniform throughout connected from land to land and floating part in the sea, but in present work only a section of it was considered and we assumed that last mooring line may be stressed and strained compared with the remaining, so the analysis is carried for one mooring line failure. The RAO's are plotted for all mooring lines in place and assuming one mooring line has failed. The RAO's are computed for two wave direct ions one at 45 degrees to the tunnel and one at 90 degrees to the tunnel. Fig. 2 shows one cable is not considered in the simulation of SFT responses.

4.1.1 For Linear Cables

The computed RAO's in sway and heave degrees of freedom are shown in Fig. 3. The wave time period is shown in x-axis and y-axis shows the ratio of SFT amplitude to wave amplitude. CF in the Fig. 3(a) to 3(d) indicates Cable Failure (CF). From Fig. 3 at 45^0 wave direction the RAO's of sway and heave are approximately same even when there is one cable failure. But at 90^0 wave direction there is increase in sway and heave RAO's of SFT, indicating when a cable fails SFT undergoes higher responses or the remaining tension legs undergo higher stress.

4.1.2 For non-linear cables

The numerical simulations are executed by assuming the tension legs or mooring lines or cables as non-linear. The RAO's for this case are shown in Figs. 4(a)-4(d). The wave time period is shown in x-axis and y-axis shows the ratio of SFT amplitude to wave amplitude. From the Fig. 4 the SFT has undergone higher responses when a tension leg fails. These responses are higher as compared with linear cables.

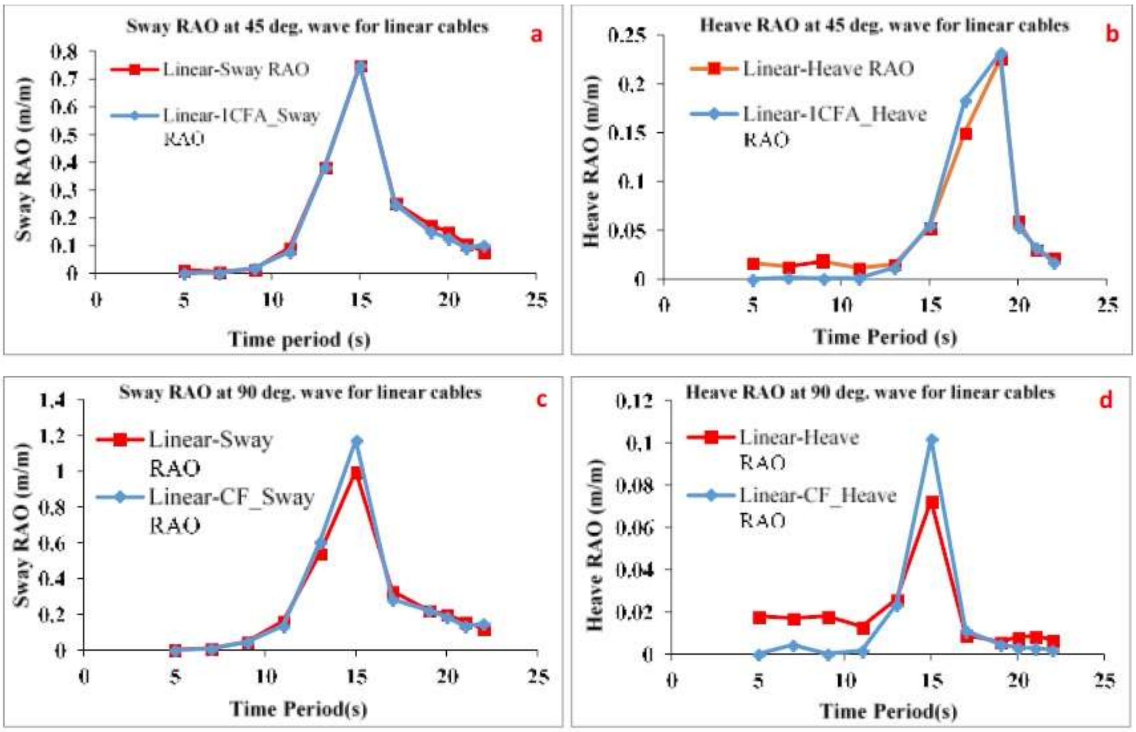

Fig. 3 Sway and heave RAO's for 1st order waves with linear cables

4.2 Comparison between linear and non-linear cables for first order RAO's

The comparison of RAO's of sway and heave are presented between linear and non-linear cables. The comparison is shown in Figs. 5(a)-5(h). As shown in Fig. 5 the SFT has higher response for non-linear cables as compared with linear cables. The sway RAO's are approximately 50% higher for non-linear cables as compared with linear cables and heave RAO's are approximately 90% higher and above for non-linear cables as compared with linear cables. In real world there will not be any linear cables and cable responses are always non-linear for any case. For example cables of suspension bridges always behave non-linear due to wind and vehicle loads and especially in ocean engineering industry where platforms are anchored to sea-bed with help of steel wires, the wires undergo very high dynamic action due to wave and current and their behavior will be always non-linear. But as the first order RAO’s corresponds to linear wave theory and the responses with linear cables are far less as compared with nonlinear cables, but in open ocean the linear waves hardly exists and there will be nonlinear waves. We also cannot take only linear wave in to account for the analysis of SFT, because irregular wave also should be taken in to account for analysis of SFT. As far as first order RAO’s are considered nonlinear cables have higher response and they can be used for simulating the responses of SFT.

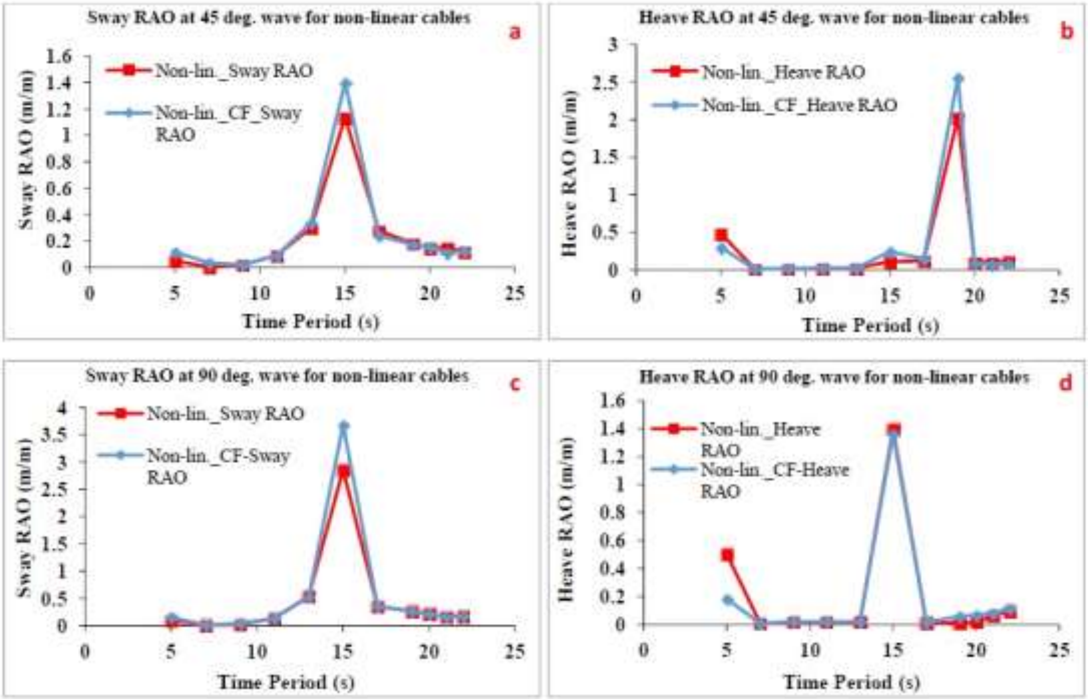

Fig. 4 Sway and heave RAO's for 1st order waves with non-linear cables

4.3 Second order RAO's

The Ansys- AQWA*TM has the capability to simulate the responses for Stokes second order wave. Same as in the case of first order RAO's, the second RAO's are plotted for wave time periods versus the ratio of amplitude response of SFT and the wave amplitude. For the second order RAO's the wave has a higher crest and longer tough and the wave amplitude is not constant for the entire wave time periods. As the wave periods increase the wave amplitude is increased. The wave amplitudes are computed using Fig. 6. As the depth is less and SFT center is at 40 m from water line in order to see the effect of second order waves on SFT the results are carried out. The 2nd order wave kinematics is included in Morision equation.

4.3.1 For linear cables

The RAO's of SFT for second order waves are shown in Fig. 7. The x-axis shows the wave time period and y- axis shows the ratio of SFT amplitude to wave amplitude. The comparison is shown between cable failure (CF) case and non-failure case of cable. The RAO's for CF case are approximately same or higher as compared with non-failure case. The sway RAO at 90^0 wave direction for CF case has higher response as compared to non-failure case

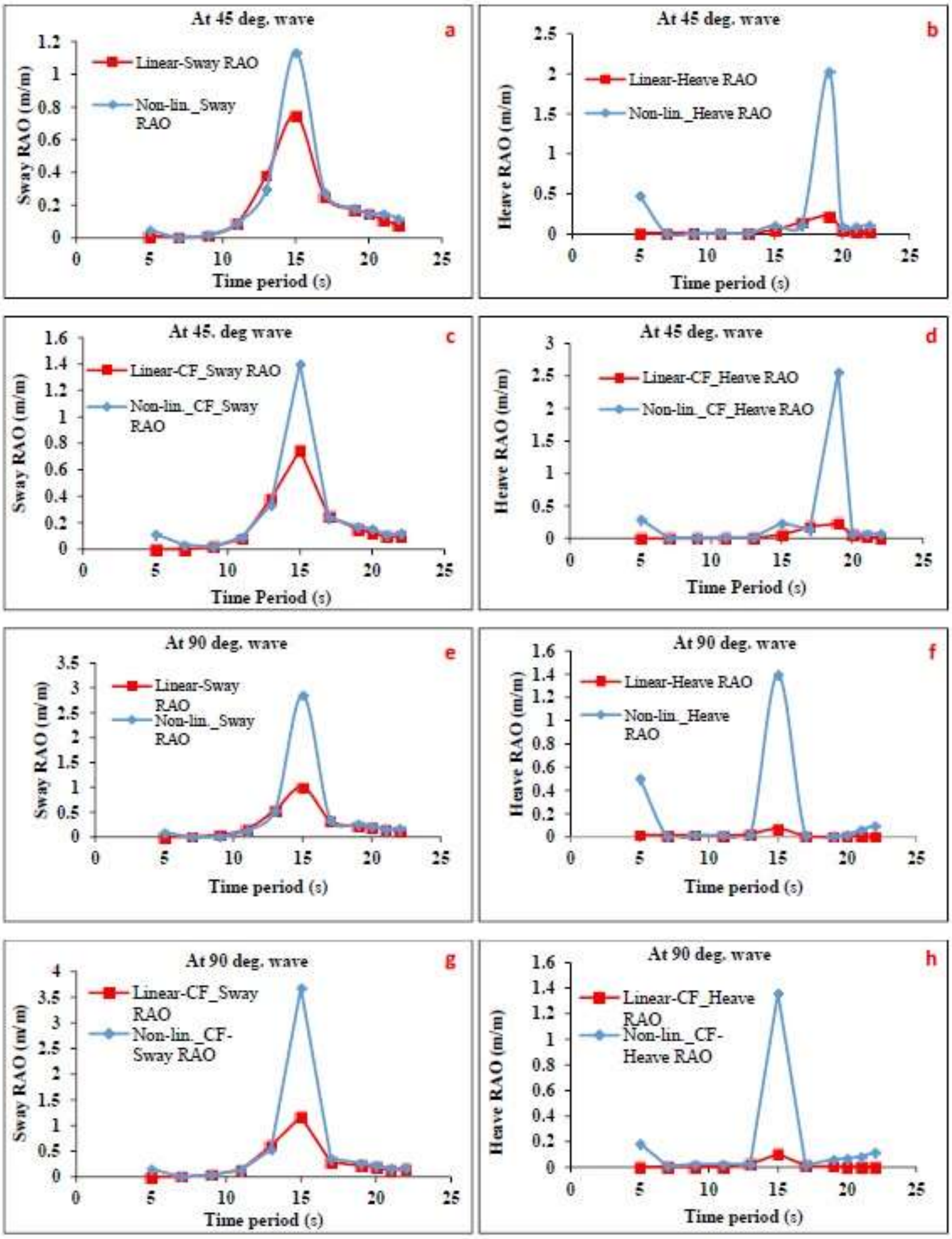

Fig. 5 Comparison of 1st order sway and heave RAO's at 45^0 and 90^0 wave direction between linear and non-linear cables

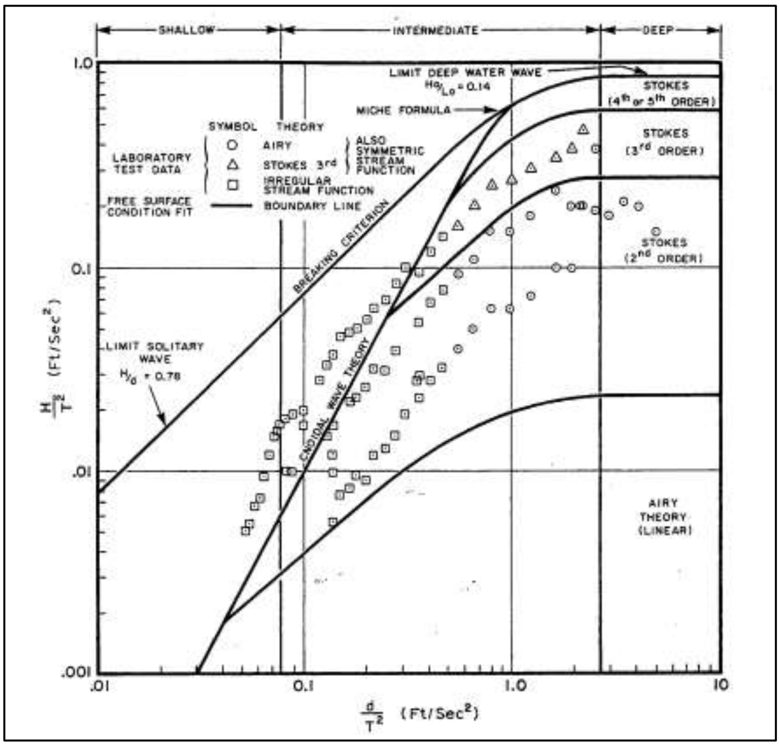

Fig. 6 Adopting wave theories depending on H, T and d (adapted from Chakrabarti (1987))

4.3.2 For non-linear cables

The RAO's of SFT for second order waves are shown in Fig. 8. The wave time period is shown in x-axis and y-axis shows the ratio of SFT amplitude to wave amplitude. The comparison is shown between cable failure (CF) case and non-failure case of cable. The RAO's for CF case are approximately same. Even one cable is not taken in to account for the simulation the SFT has the approximately same response for both cases. From this we can say that SFT is safe for one CF case for second order waves. The SFT response for 2 CF case has to be studied.

4.4 Comparison between linear and non-linear cables for second order RAO's

The comparison of RAO's are shown in Figs. 9(a)-9(h). From the figures the sway response is higher for linear cables as compared to non-linear cables for both CF and non-failure cases except at 90^0 wave direction for sway non-failure case. If we observe the heave RAO's the non-linear cables show higher SFT responses at low time periods as compared with linear cables. If we observe the Figs. 9 (b), 9 (d), 9 (f) and 9 (h) the heave RAO's are higher for non-linear cables as compared with linear cables, but the linear cables did not show this response at all. Even though with linear cable RAO's are higher for sway degree of freedom, they cannot predict the same for heave. But with non-linear cables the RAO's for sway response are not very low as compared with linear cables. If we consider the non-linear cables for the design of SFT, safety of the SFT will be increased as there is high response for SFT at low time periods. So considering non-linear cables for second order RAO’s is a good choice.

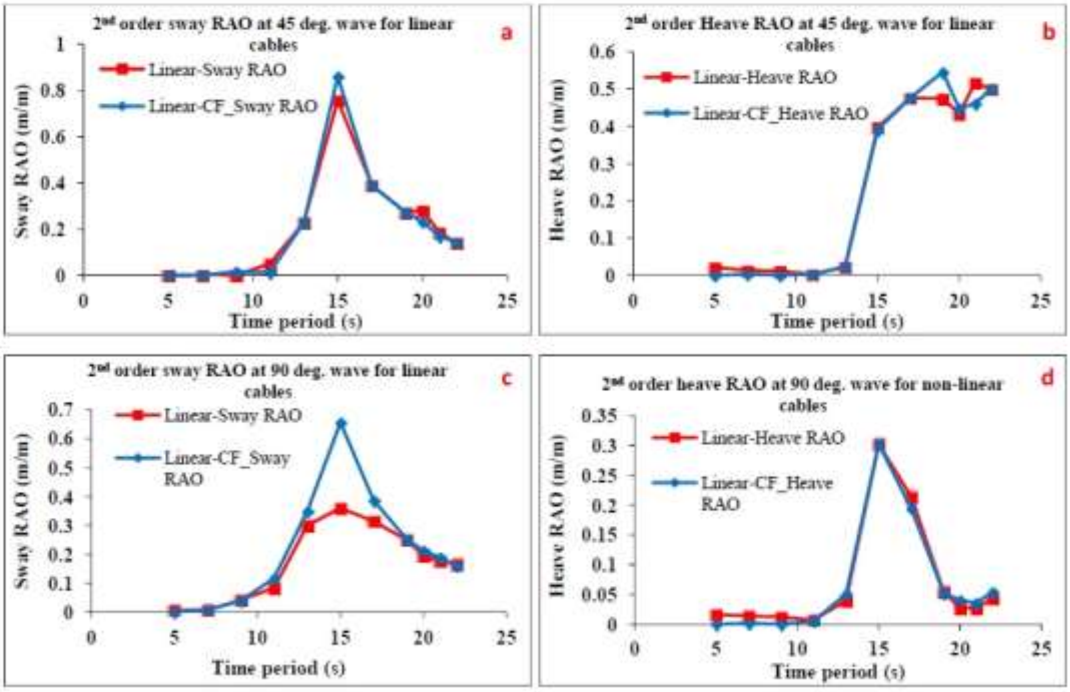

Fig. 7 Sway and heave RAO's for 2nd order waves with linear cables

4.4.1 Comparison between 1st and 2nd order RAO's for linear and non-linear cables

The comparison of 1st order and 2nd order RAO's for linear and non-linear cables are shown in Figs. 10(a)-10(d). From the comparison the sway response RAO's for 1st order waves or linear waves are higher when compared with 2nd order waves for both linear and non-linear cables, this is because of the second order waves attenuation with depth. But this is not observed for heave response RAO's for linear cables where the 2nd order RAO's has higher response as compared with 1st order RAO's, this might be because linear cables for heave response cannot capture the attenuation of the 2nd order waves. For non-linear cables 1st order heave RAO's has the higher response as compared with linear cables, here the 2nd order waves attenuation is observed for non-linear cables. Since the mooring lines are modeled as linear and non-linear springs. The increase in heave RAO's at low time periods are not much significant for linear cables but for non-linear cables the increase is significant. There are important points to be noted out, 1) the modeled SFT end to end is fixed between land or under the sea and remaining portion is submerged in the sea water. In present model as we considered only a part of the SFT and its whole portion is in sea water and it is similar to Tension leg platform which is submerged. The natural time periods of the tunnel will be below 5 s for heave and it may excite the tunnel at low time periods and 2) It may happen due to the non-linear spring model adopted for mooring lines.

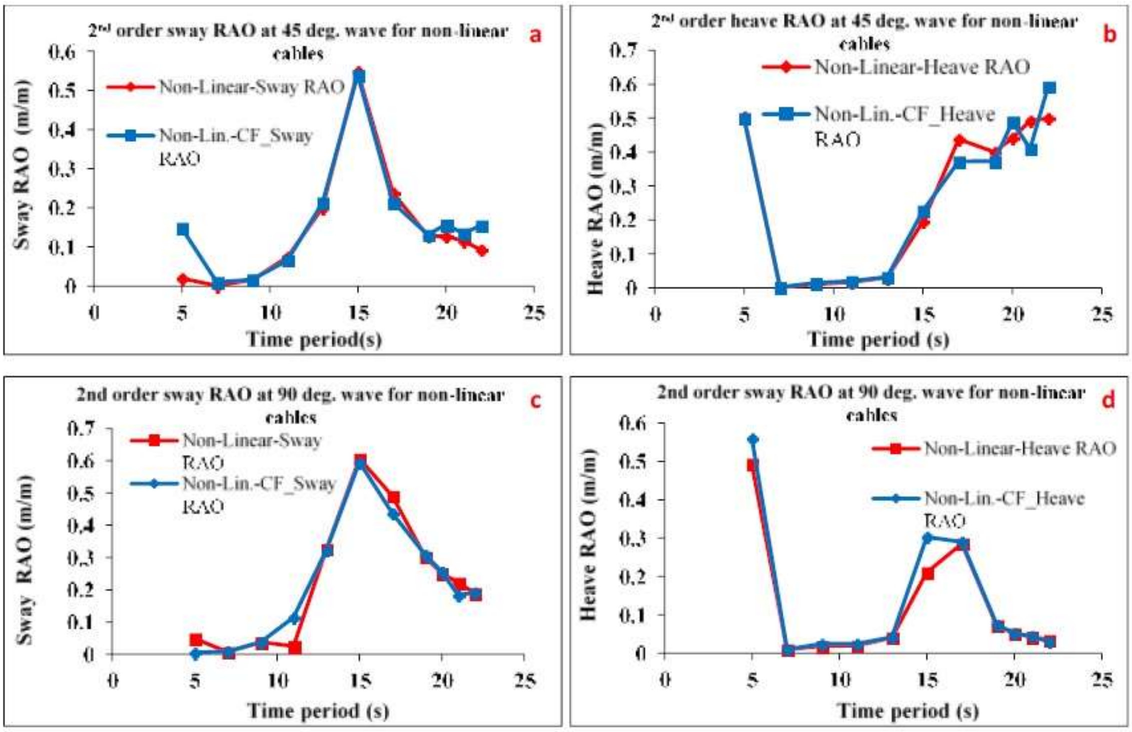

Fig. 8 Sway and heave RAO's for 2^{nd} order waves with non-linear cables

4.5 Irregular wave response

The time response analysis is carried out for irregular wave using both linear and non-linear cable for CF and non-failure case, the irregular wave details are listed in Table 2. The Stokes 2^{nd} order wave is not included in irregular waves. The irregular waves are generated for almost for 1 hr and almost 50 frequencies between 1 Hz and 0.0333 Hz are included in the simulation and all the values of Table 2 are inputted to the program AQWA.

4.5.1 Linear cables

The displacement time history in sway and heave degrees of freedom are shown in Figs. 11 and 12. The displacement time history is shown for 500 s for both sway and heave degrees of freedom. The power Spectral densities (PSD's) are shown in Figs. 13(a)-13(d). The x- axis represents frequency in radians/second (rad/s) and y- axis represents corresponding degree of freedom response (sway and heave). The CF case the PSD is on lower side or approximately equal for both non-failure and failure case. From Fig. 13(b) for heave degree of freedom the non-failure case has higher PSD as compared with CF case and from Fig. 13(d) CF case has higher PSD for heave degree of freedom, but this occurred at low frequency. The same has been observed for sway degree of freedom for 45^0 and 90^0 wave directions from Figs. 13(a) and 13(c). The high peak heave RAOs at the low frequency or higher wave periods may be due to slowly varying motion induced by mooring lines and it may be due to water depth. In shallow water this response will be significant as compared with deeper water for the given mooring line. As the water depth decreases the wave height increases and the energy increases. Depending on the water depth the mooring lines behaves differently and non-linear spring model of mooring lines may have captured this effect.

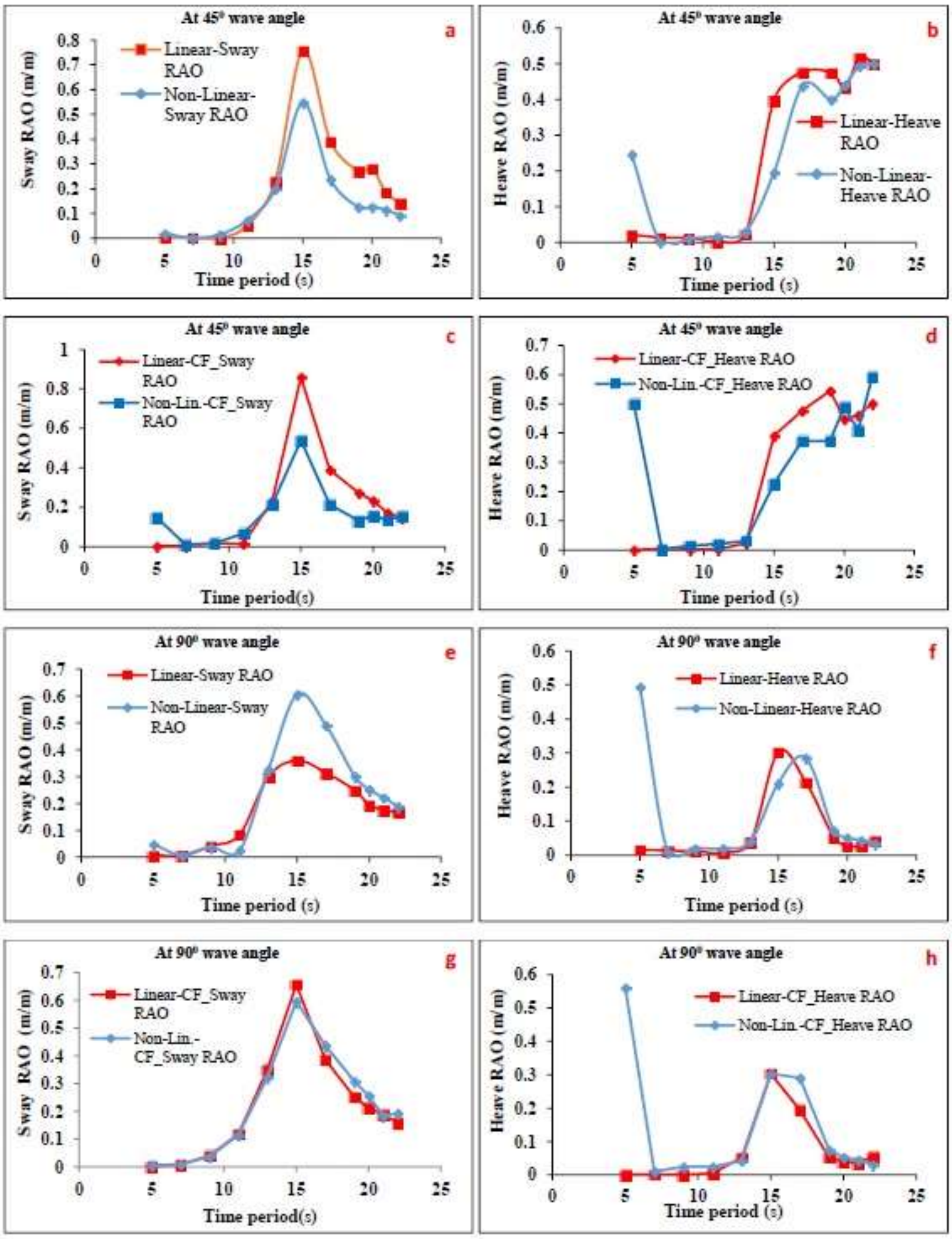

Fig. 9 Comparison of 2nd order sway and heave RAO's at 45^0 and 90^0 wave direction between linear and non-linear cables

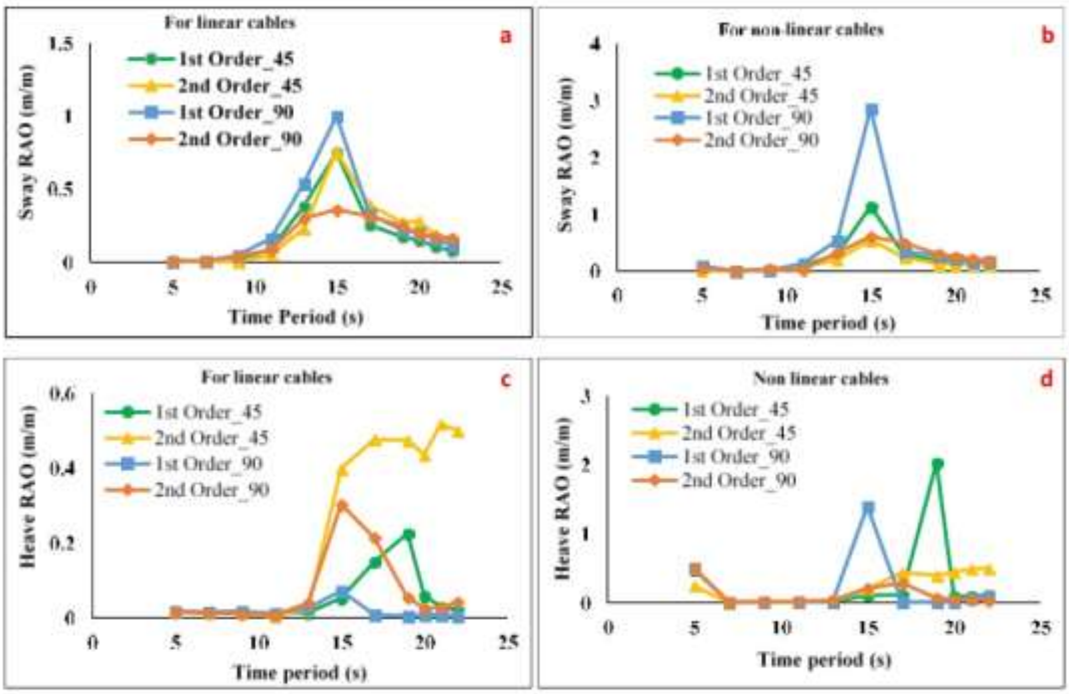

Fig. 10 Comparison of 1st and 2nd order sway and heave RAO's at 45^0 and 90^0 wave direction between linear and non-linear cables

4.5.2 Nonlinear cables

The Displacement time histories for sway and heave degrees of freedom are shown in Figs. 14 and 15. The PSD's are shown in Figs. 16(a)-16(d). From the Figs. 16(a)-16(d) the CF case has higher response as compared to non-failure case except for heave degree of freedom at 45^0 wave direction and at 90^0 wave direction the sway response is approximately same for both CF and non-failure case of cable.

Table 2 Irregular wave and current details

Irregular wave details	
Significant wave height (m)	12.2
Zero crossing period (s)	14
Maximum Frequency (Hz)	1
Minimum Frequency (Hz)	3.33E-02
Current details	
Depth (m)	m/s
-67.7	0.25
-30	0.6
0	0.7

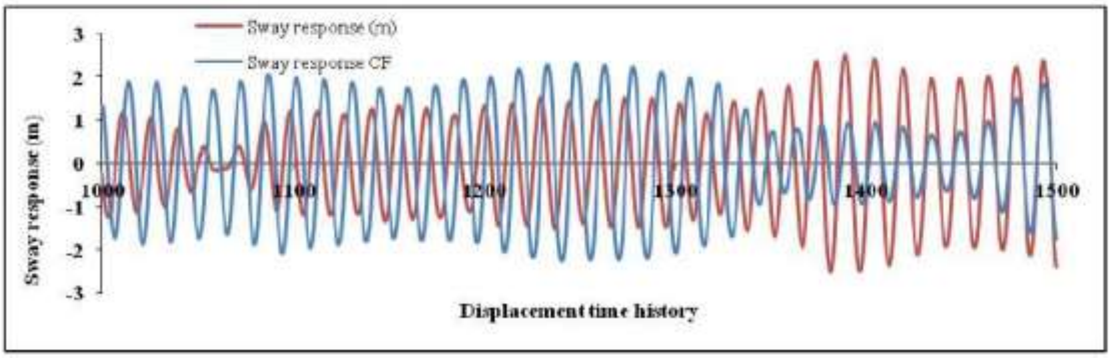

Fig. 11 The displacement time history in sway degree of freedom at 45-degree wave direction with linear cables

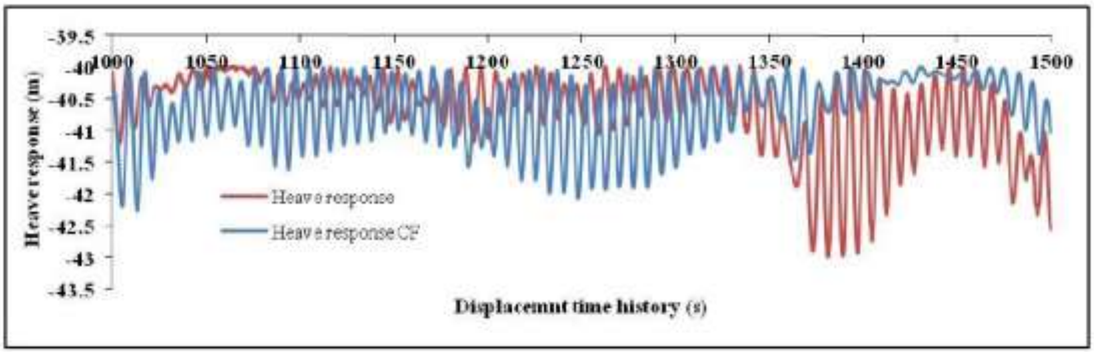

Fig. 12 The displacement time history in heave degree of freedom at 45^0 wave direction with linear cables

If we observed the heave RAO's in Fig.s 3, 4 and 5 for linear waves, there is only one peak response as compared to Figs. 13 and 16, for irregular waves the sway causes set down in heave degree of freedom and it was captured in irregular wave case but not in regular wave or linear wave case. For irregular wave minimum wave period is 1 s and maximum is 30 s and also there is difference wave height with zero crossing period of 14 s as compared with regular wave which has fixed wave length and wave height. The following differences may have decreased the heave set down for regular wave case.

4.5.3 Comparison between linear and non-linear cables for irregular wave.

The comparison PSD's in sway and heave degrees of freedom for linear and nonlinear cables are shown in Figs. 17(a)-17(h). For 45^0 wave direction the SFT with linear cables has higher PSD's as compared with nonlinear cables. When the wave direction is 90^0 the SFT has higher PSD's for nonlinear cables as compared with linear cables. The situation has been completely reversed when the wave direction is changed.

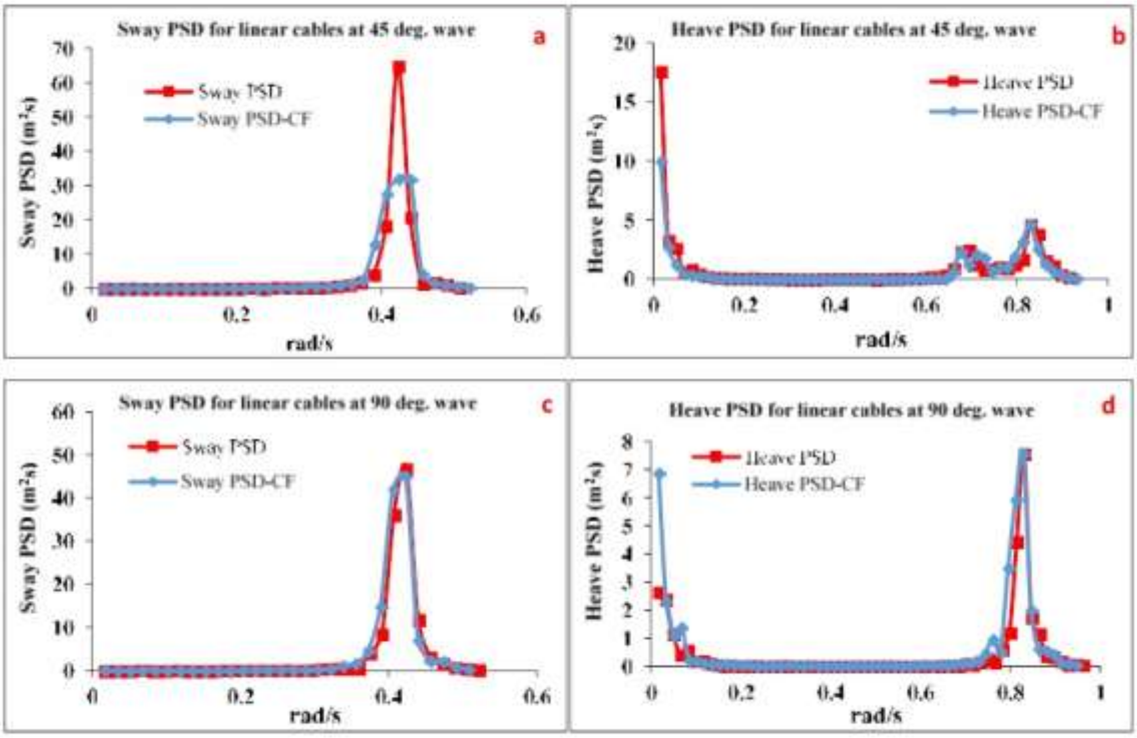

Fig. 13 Power spectral densities for heave and sway at 45^0 and 90^0 wave direction

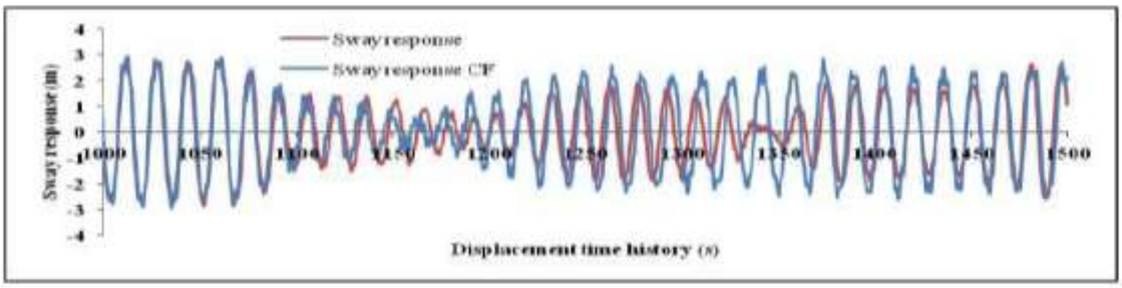

Fig. 14 The displacement time history in sway degree of freedom at 45^0 wave direction with non-linear cables

4.5.4 Heave and sway simulation of Jin and Kim (2018) with present numerical approach

The irregular wave responses for sway and heave from Jin and Kim (2018) are simulated with present numerical approach with nonlinear cables and compared with Jin and Kim (2018) results. Jin and Kim (2018) has performed time domain responses of the SFT with seismic and wave excitations. In their work the SFT length is 700 m and the middle 350 m length portion of SFT is moored along the length of the tunnel with 25 m frequency, and the total number of cables are 60. The cables are modeled as rod elements and the buoyancy to weight ratio of tunnel is 1.3. For the present work we adopted the all the details (total number of cables, cable properties and wave spectrum) as given in Jin and Kim (2018), but the cables are modelled as nonlinear cables. The wave direction is 90^o to the tunnel, the time step adopted for simulation is 0.05 s and the total mesh elements are 9538. The modelled SFT is shown in Figs. 18(a) and 18(b) and the PSDs comparison is shown in Figs. 18(c) and 18(d). From the results the sway and heave peak responses occurred at same frequency as in Jin and Kim (2018) but the peak response is lower in both cases (sway and heave) as compared with Jin and Kim (2018), this may be due to the cables are modeled as spring elements.

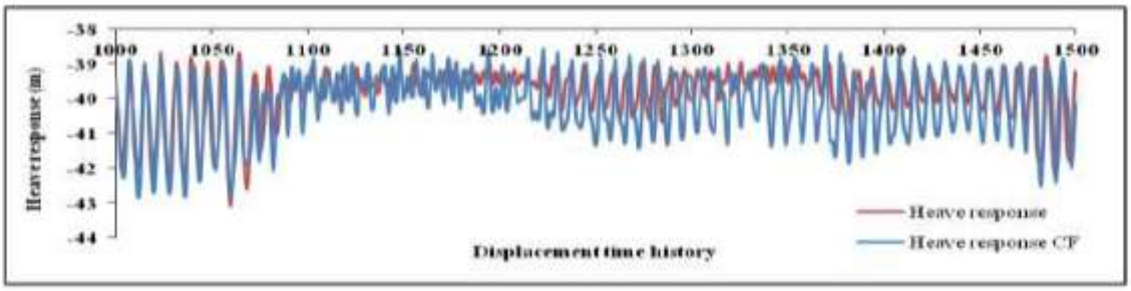

Fig. 15 The displacement time history in heave degree of freedom at 90^0 wave direction with non-linear cables

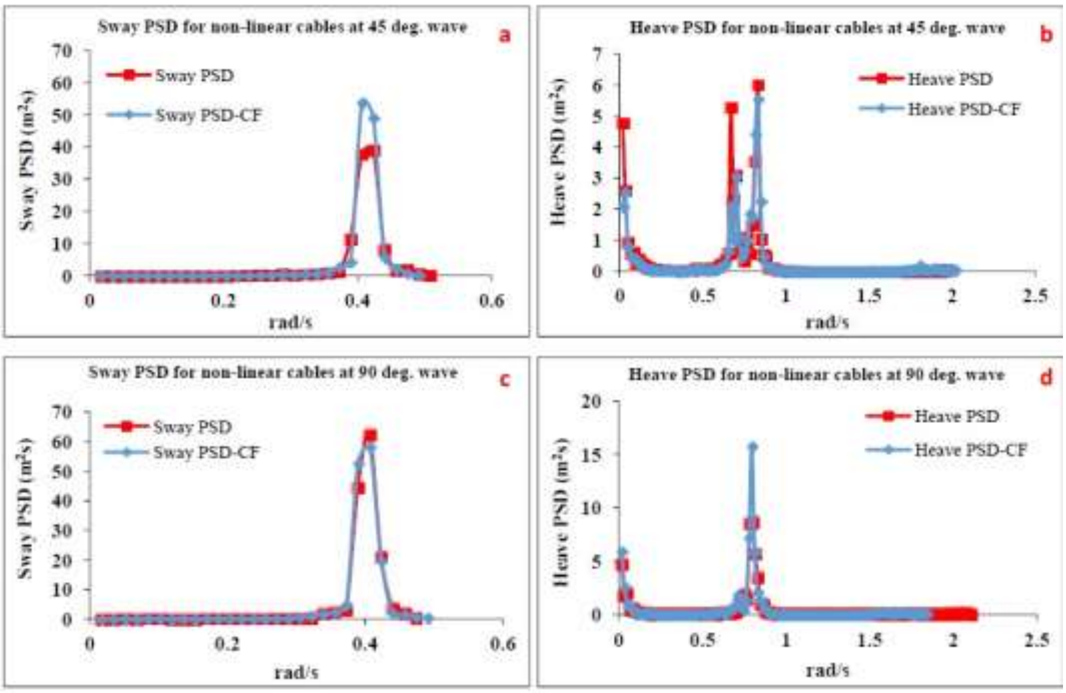

Fig. 16 Power spectral densities for heave and sway at 45^0 and 90^0 wave direction for non-linear cables

4.6 Tension legs or mooring lines responses for irregular waves

The Tension legs or mooring lines force responses are studied assuming mooring lines as linear and non-linear same as in previous cases. The time history of non-linear mooring force in Y (sway) and Z (heave) directions are shown in Fig. 19 for failure and non-failure (CF) case. From Fig. 19 the force on mooring lines have increased as compared with the non-failure case. When a cable is failed the remaining cables have started to distribute the force. This indicates that the SFT under goes higher responses as compared with non-failure case.

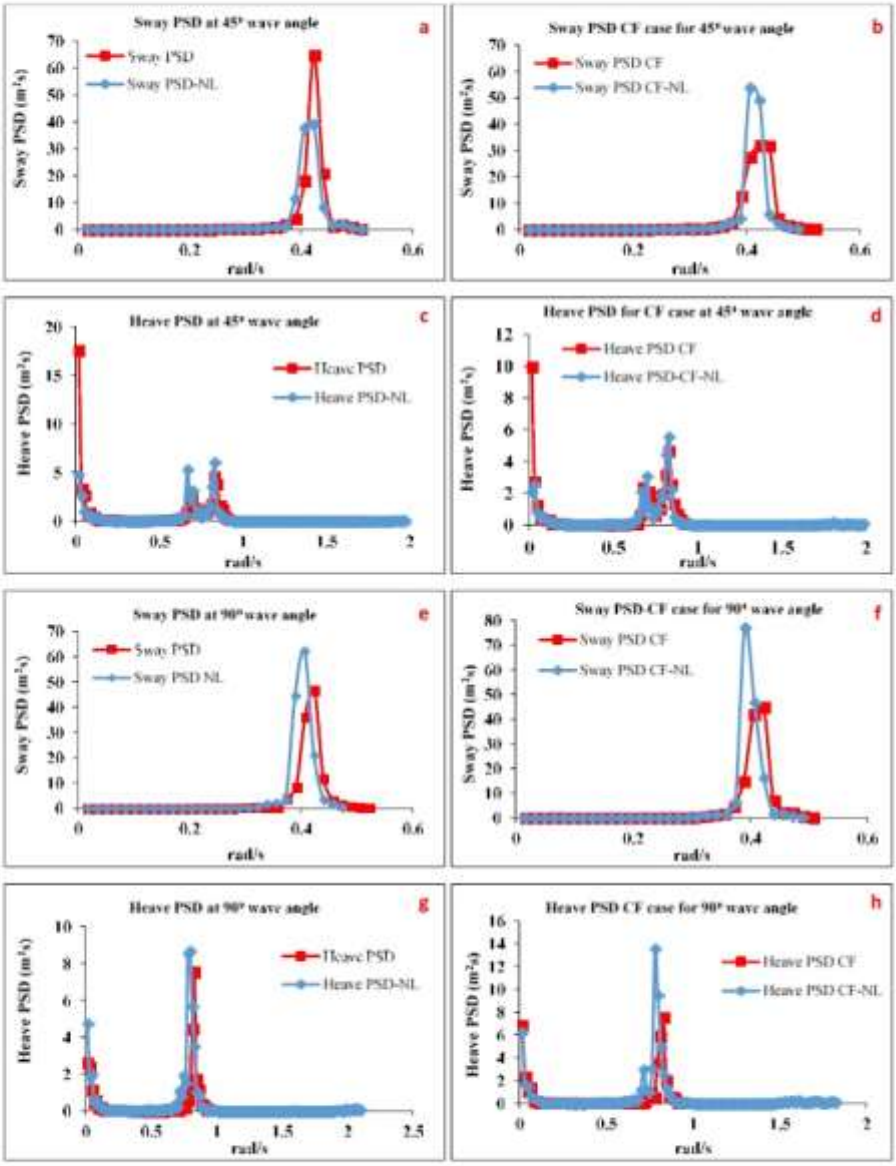

Fig. 17 Comparison between PSD's of linear and non-linear cases

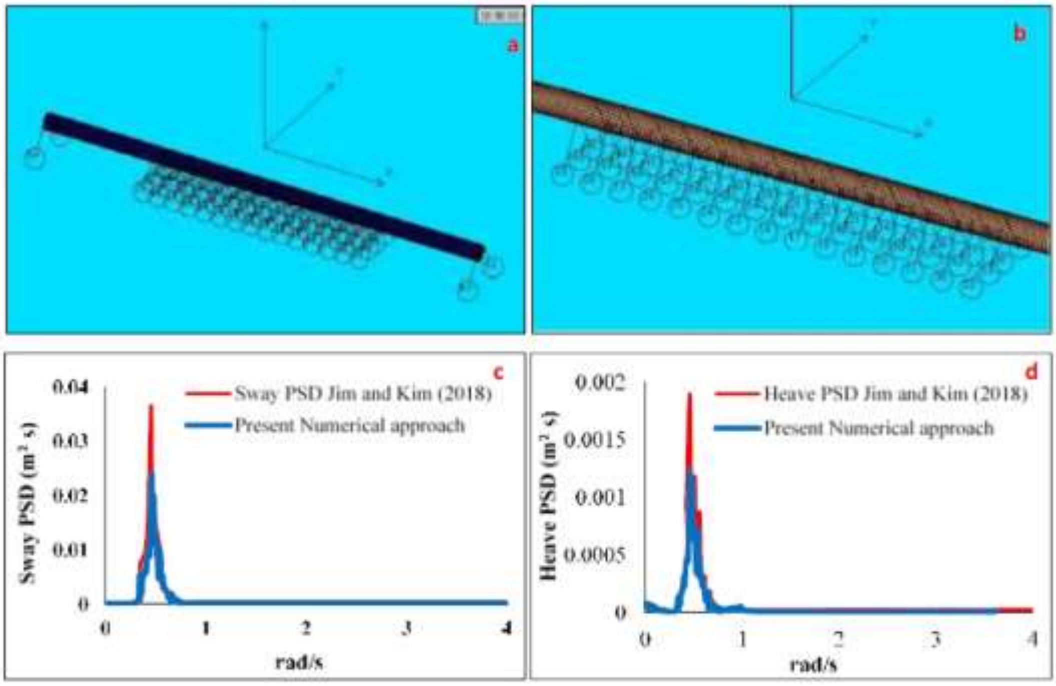

Fig. 18 (a) and (b) Meshed SFT tunnel with cables, (c) and (d) Comparison between present numerical simulation and Jin and Kim (2018)

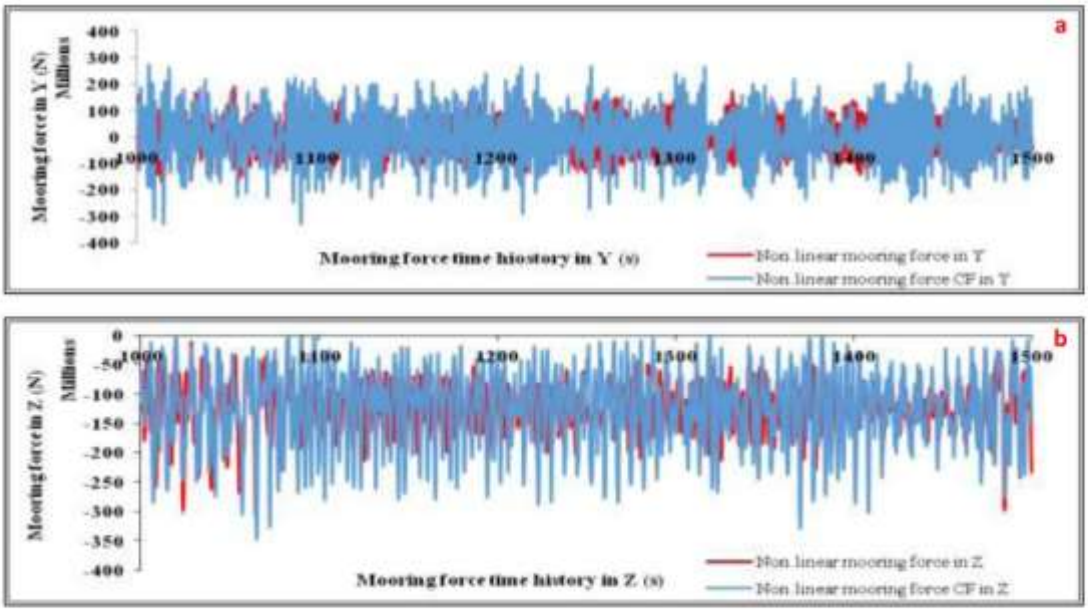

Fig. 19 Time history of mooring force in Y (sway) and Z (heave) direction

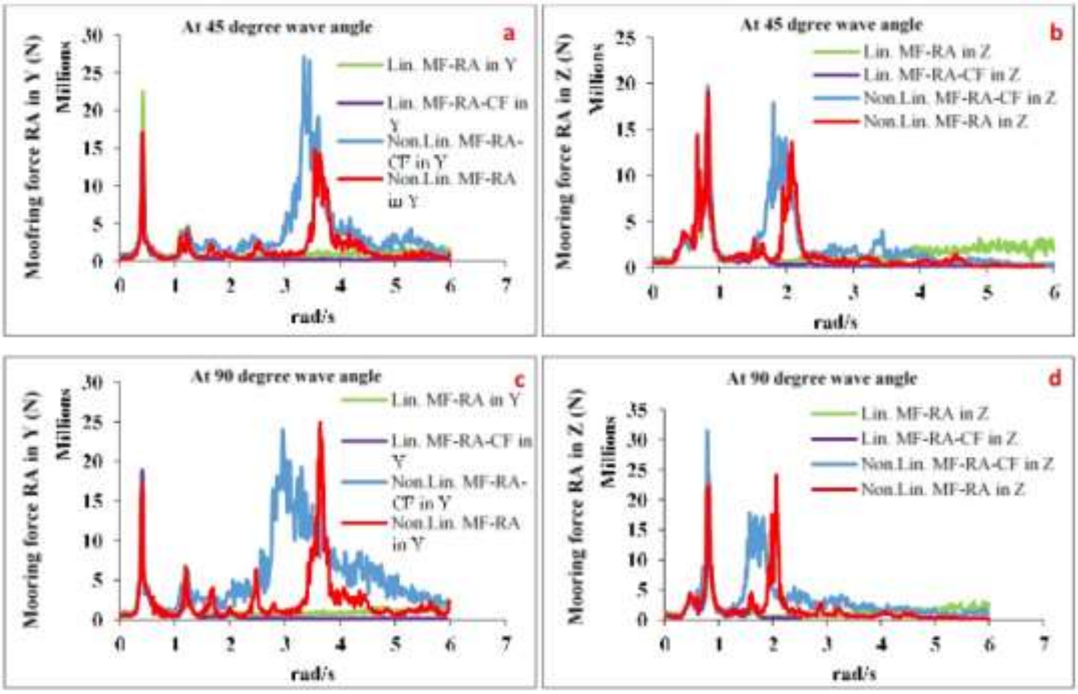

Fig. 20 Mooring force response amplitude at 45^0 and 90^0 wave directions

4.6.1 Mooring force response amplitude with linear and nonlinear cables case

Mooring Force Response Amplitude (MFRA) are shown in Figs. 20(a)-20(d). The x- axis represents frequency in radians/second (rad/s) and y- axis represents MFRA which is shown in Millions. The MFRA is shown for non-failure and cable failure (CF) at 45^0 and 90^0 wave direction for Y (sway) and Z (heave) degrees of freedom. From Figs. 20(a)-20(d) the force responses are approximately same for failure and non failure case, except for 45^0 wave direction for sway degree of freedom for linear cables. From Figs. 20(a)-20(d) the force responses for CF case have happened at lower frequency or higher wave period as compared with the non-failure case with non-linear cables. Increase in MFRA has been seen for CF as compared with non failure case except at 90^0 wave direction for sway degree of freedom, where they are almost equal but as explained response happened at lower frequency, this is not seen in linear cables. When the force response is compared between linear and nonlinear cables the higher response occurred at low frequency for linear cables, but for non-linear cables there are two peak responses one at low frequency and one at low frequency.

5. Conclusions

This paper presents the dynamic response comparison of Submerged Floating Tunnel (SFT) for linear and nonlinear cables. Time domain simulations are performed for studying the responses of SFT for first order wave, second order waves and irregular waves. The tension legs, cables, or mooring force responses are carried out for irregular waves. The comparison of SFT responses is done for both non-failure case of cable and with a single Cable Failure (CF) case.

For first order waves: the SFT has significant high response with nonlinear cables as compared with linear cables. For most of the times, the CF case has higher response as compared with non-cable failure case, but the SFT response is not significant higher for CF case.

For second order waves: the SFT has approximately equal response for CF case and non-cable failure case. When SFT response is compared between linear and nonlinear cables, the heave response is higher at low time periods for nonlinear cables. This is not shown when linear cables are used and the heave response is very minimum for linear cables. As energy decrease with depth is high for 2^{nd} order waves sway RAO's with 1^{st} order has higher response and this is vice versa for heave RAO's for linear cables where decrease in energy for 2^{nd} order waves is not captured by linear cables. But the decrease in energy is observed with non-linear cables for Heave RAO's.

For irregular waves: The power spectral densities of SFT is higher for linear cables at 45^0 wave direction as compared with nonlinear cables for both sway and heave degrees of freedom, except for CF case. The non-linear cables have captured the two peaks of heave for irregular waves this is not observed for regular waves. At 90^0 wave direction the SFT PSD's are higher with nonlinear cables as compared with linear cables. When MFRA is compared between linear and nonlinear cables, the linear cables have higher peaks at low frequency and less than the values of nonlinear cables. The nonlinear cables have two peak responses one at low frequency and one at high frequency. For CF case with nonlinear cables the peak response shifted towards lower frequencies as compared with non-cable failure case.

The linear cables have shown approximately predicted SFT response when compared with nonlinear cables. But when we are doing the analysis it depends which type of wave analysis are we doing. Since the results are yet to be verified with the laboratory experimental data, where the cables always behave nonlinearly due to dynamic action of waves and current. The tension response of tension legs are also to be studied for linear as well as nonlinear. This is our future scope of work.

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References

Chakrabarti, S.K. (1987), "Hydrodynamics of Offshore Structures", Springer Verlag.

Chamelia, D.M., Wardhana, W., Prastianto, R.W. and Sivianita (2015), "Dynamic response analysis on submerged floating tunnel due to hydrodynamic loads", *Procedia Earth and Planetary Science*, **14**, 220-227.

Chen, Z., Wang, Y., Wang, G. and Hou, Y. (2019), "Time-domain responses of immersing tunnel element under wave actions", *J. hydrodynamics*, **21**(6), 739-749.

Di Pilato, M., Perotti, F. and Fogazzi, P. (2008), "3D dynamic response of submerged floating tunnels under seismic and hydrodynamic excitation", *Eng. Struct.*, **30**, 268-281.

Dong, M., Miao, G., Yong, L., Niu, Z., Peng, H. and Hou, C. (2012), "Effect of escape device for submerged floating tunnel (sft) on hydrodynamic loads applied to set", *J. Hydrodynamics*, **24**(4), 609-616.

Jin, C. and Kim, M.H. (2018), "Time –domain hydro-elastic analysis of a SFT (Submerged Floating Tunnel) with mooring lines under extreme wave and seismic excitations", *Appl. Sciences*, **8**, 2386, DOI:10.3390/app8122386.

Kunisu, H. (2010), "Evaluation of wave force acting on submerged floating tunnels", *Procedia Eng.*, **4**, 99-105.

Li, J., Lv, X. and Tan, J. (2012), "Research on the response of submerged floating tunnel under fatigue loads", *Procedia Eng.*, **31**, 447-452.

Mandara, A., Russo, E., Beatrice, F. and Mazzolani, F.M. (2016), "Analysis of fluid-structure interaction for a submerged floating tunnel", *Procedia Eng.*, **166**, 397-404.

Muhammad, N., Ullah, Z. and Choi. D.H. (2017), "Performance evaluation of submerged floating tunnel subjected to hydrodynamic and seismic excitations", *Appl. Sciences*, **7**, 1122, DOI:10.3390/app7111122.

Remseth, S., Bernt, J., Leira, K.M., Okstad, K.M. and Mathisen, T.H. (1999), "Dynamic response and fluid/structure interaction of submerged floating tunnels", *Comput. Struct.*, **72**, 659-685.

Tariverdilo, S., Mirzapour, J., Shahmardani, M., Shabani, R. and Gheyretmand, C. (2011), "Vibration of submerged floating tunnels due to moving loads", *Appl. Math. Model.*, **35**, 5413-5425.

TMAA (2011), Technical Manual Ansys - AQWA v 14.0, website:www.ansys.com.

Wu, Z., Ni, P. and Mei, G. (2018), "Vibration response of cable for submerged floating tunnel under simultaneous hydrodynamic force and earthquake excitations", *Adv. Struct. Eng.*, DOI:10.1177/1369433218754545.

Xiang, J., Pi, X., Feng, S. and Bian, C. (2016), "Research on the layout plan of tether-typed submerged floating tunnel", *Procedia Eng.*, **166**, 69-75.

Yan, H., Luo, Y. and Yu, J. (2016), "Dynamic response of submerged floating tunnel in the flow field", *Procedia Eng.*, **166**, 107-117.

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