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Submarine Dynamic Stability Analysis in Shallow Waters Utilizing MATLAB

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***Abstract* – A MATLAB program was developed in order to simulate the dynamic stability of un-trenched submarine cables and pipelines resting on the bottom of a 14m depth sea (shallow waters), utilizing the Fourier Decomposition method. The aim of this of the research is to develop a sophisticated understanding and an accurate estimation of the hydrodynamic forces acting on cables and pipelines due to combined effect of wave and current, and to preform dynamic stability analysis following the guidelines of DNV-RP-F109 for studying the dynamic response of the cable with presence of soil resistance. The main concern is to study the ability of the submarine pipeline/cable to be stable on the seabed using its own weight and if required, estimating extra weight to be added to achieve stability on the seabed as per DNV-RP-F109 recommendation. A validation of the developed hydrodynamic forces model with UWAHYDRO program developed at the Western Australia University by Youssef, B.S. is also included to confirm the ability of program to accurately estimate the hydrodynamic forces under given sea state.**

***Keywords* – MATLAB, Submarine, Dynamic Stability, Pipelines, Cables, DNV.**

I. INTRODUCTION

Modern codes go back to the 19th century where a huge expansion of infrastructure, particularly railway bridges and rapid industrial development took place, above all in boilers and ships. An intolerable number of failures occurred. For example, Gies's book on bridges claims that 40 bridges a year failed in the United State in the 1870s. Codes and standards are products of mistakes and errors made by human beings. In Europe, for example, there used to be many pipeline codes. In the United Kingdom, there was an institute of Petroleum PI6, which was very old-fashioned. About 30 years ago, there came a wave of new development, prompted by the offshore industry and led by the Norwegian organization, DNV, which was originally a ship classification society. Other countries have followed. The Dutch made the NEN3650, which is more famous in the Netherlands. The Germans produced the Germanischer Lloyd code. The British rewrote BS8010. The Americans wrote API 1111. There is also International Standards Organization (ISO) code, ISO13623, and Eruo-code, etc. The client and authorities in a country where a pipeline or cable is to be installed shall endorse the codes and standards used by the designer.

The widely used offshore pipeline design codes include

- Det Norske Veritas (DNV-RP-F109).
- American Bureau of Shipping (ABS).
- American Petroleum Institute (API-1111).
- American Gas Association (AGA Level 1-2-3).
- ISO-13623.
- British Standard (BS-PD-8010-2).

The AGA/PRCI Submarine Pipeline On-Bottom Stability Analysis Software and Sub-Sea Pipeline Design Standard (AGA/PRCI OBS) was developed by Halliburton Kellogg Brown and Root (KBR) under contract to the Pipeline Research Council International, Inc. (PRCI). The AGA/PRCI OBS is considered the world standard for the design and analysis of sub-sea pipelines. The new release consists of three levels with Level 1 being used for quick simplified analysis, Level 2 for comprehensive detailed design and modelling (most used) and Level 3 for advanced and very complex sub-sea pipeline design modelling.

In case of cables, no codes were developed from the point of view of stability design. Lately in 2014 DNV developed DNV-RP-J301 “Subsea Power Cables in Shallow Water Renewable Energy Applications”, which is concerned with the types, design, operation and application of submarine cables. But also following the stability design criteria of DNV-RP-F109 “On-Bottom Stability Design of Submarine Pipelines”. That’s is why DNV-RP-F109 design methodology and criteria is utilized in this research on cables as well as pipelines.

This research is concerned with the on-bottom cables and pipelines stability in shallow waters under the combined action of wave and current, hydrodynamic loading. It describes the development of an integrated MATLAB modelling code to numerically simulate an un-trenched different types of submarine cables and pipelines resting on a sandy seabed at shallow water in different locations having different wave characteristics. Simulation of hydrodynamic loads, pipe-soil interaction, force correction model and dynamic response of the submarine element are considered. The main goal is to achieve a reliable on-bottom stability design according to dynamic stability analysis approach presented by DNV-RP-F109 and to develop a sophisticated understanding of the importance of the key input parameters adopted.

This research main focus includes submarine cables due to their wide use and every day developed applications, yet the research done in this field is so limited. Therefore, investigating such field is mandatory due to its important role in today’s marine industries. Codes, equations and limitations of submarine pipelines were applied, as there was no specialized code regarding the on-bottom stability of submarine cables.

II. METHODOLOGY

This section discusses the approach methodology and the developed program operation flow chart presented in Figure 2. DNV-RP-F109 was used as design guild line as it’s a specialized code in the design of submarine pipeline stability. This research is interested in both pipelines and cables. The same design procedures and criteria was also implemented for submarine cables as there were no other code found, that investigates this field. As per DNV-RP-F109 Dynamic stability design procedures and criteria, the hydrodynamic loads need to be calculated depending on the input data such as element’s diameter and dry mass, meta ocean data such as area significant wave height, associated peak period, depth and current velocity, and the force model. Fourier Decomposition force model was utilized due to the significant advantage over Morisons force model in prediction of hydrodynamic forces. So as to study the combined effect of both wave and current, a shallow water depth case was used in all cases with depth of 14 m associated with current velocity of 0.55 m/sec.

The aim of this research is to study the effect of the hydrodynamic loads (lift, drag and inertia) on one-meter length of a submarine cable/pipeline, and simulate its dynamic response to check the stability within the stated criteria in DNV-RP-F109, being 10 diameter lateral displacement at most. After calculating the hydrodynamic loads, a force correction model is utilized in order to account for the relative motion difference between the water particle and the moving element, resulting in smaller or greater force which is more realistic depending on the element motion direction with respect to the applied force direction. The soil resistance model utilizing the equations presented in DNV-RP-F109 is embedded in the program so as to calculate the net forces acting on the cable/pipeline that will affect its motion horizontally or vertically according to forces direction as presented in Figure 1.

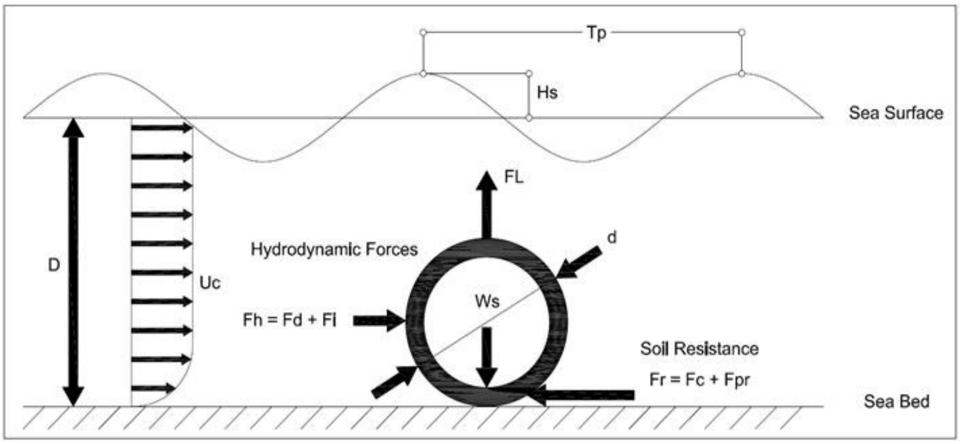

Fig. 1. Forces acting on cable /pipeline due to combined effect of wave and current.

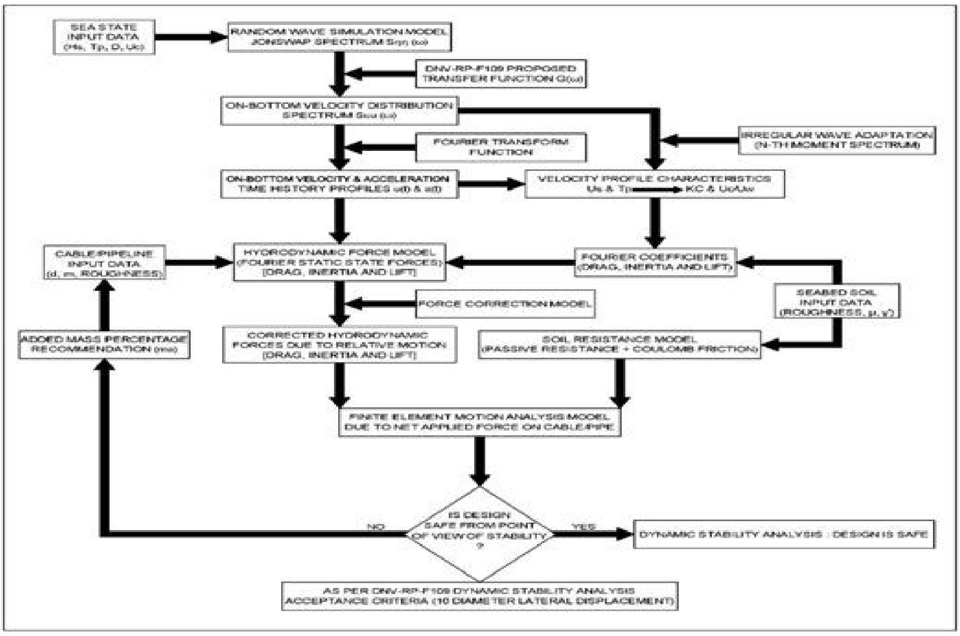

Fig. 2. Developed MATLAB program operation flow chart.

III. MATHEMATICAL MODEL

Following the equation model presented in the DNV-RP-F109. The JONSWAP spectrum formula based on the significant wave height and associated peak period takes the following form

$$S_{\eta\eta}(\omega) = \frac{\alpha . g^2}{\omega^5} . e^{\left[-1.25\left[\frac{\omega}{\omega_p}\right]^4\right]} . \gamma^a \tag{1}$$

$$a = e^{\left[-\frac{1}{2}\left(\frac{\omega-\omega_p}{\sigma.\omega_p}\right)^2\right]} \tag{2}$$

Where γ is the peak enhancement parameter, α is the Generalized Phillip's Constant and σ is the spectral width parameter. They take the following forms

$$\gamma = \begin{cases} 5 \; for \; \emptyset \leq 3.6 \\ e^{(5.75-1.1.\emptyset)} \; for \; 3.6 < \emptyset < 5 \\ 1 \; for \; \emptyset \geq 5 \end{cases}, \text{ where } \emptyset = \frac{T_p}{\sqrt{H_s}} \tag{3}$$

$$\sigma \begin{cases} 0.07 \text{ if } \omega \leq \omega_p \\ 0.09 \text{ if } \omega > \omega_p \end{cases}, \text{ where } \omega = 2.\pi.f \text{ and } \omega_p = \frac{2.\pi}{T_p} \tag{4}$$

$$\alpha = \frac{5}{16} . \frac{H_s{}^2.\omega p^4}{g^2} .(1 - 0.287.\ln \gamma) \tag{5}$$

The peak enhancement parameter value varies approximately from 1 to 5 and with a mean value of 3.3 and variance of 0.62. The JONSWAP spectrum reduces to Pierson-Moskowitz spectrum when the value of γ is 1. Then the transfer function suggested by DNV-RP-F109 to transfer the wave elevation spectrum from sea surface to cable level on sea bed as a velocity power spectrum is utilized having the following form

$$S_{UU}(\omega) = G^2(\omega).S_{\eta\eta}(\omega) \tag{6}$$

Where $G(\omega) = \frac{\omega}{\sinh(k.D)}$ (7)

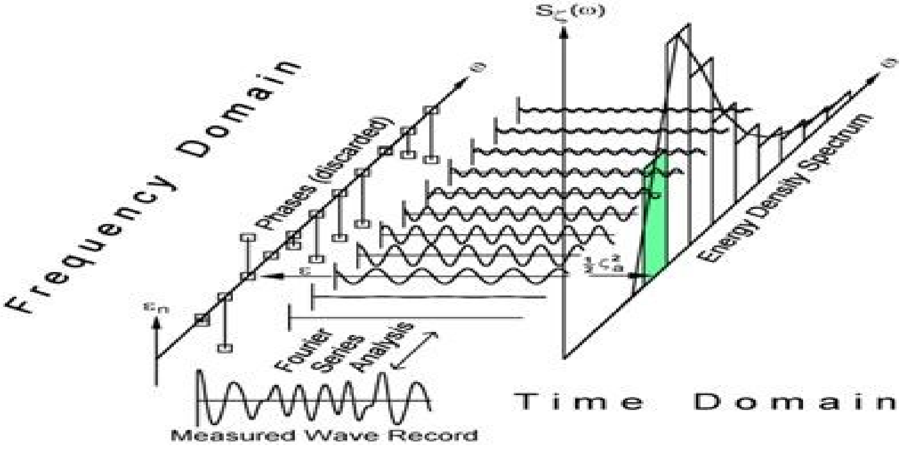

Fig. 3. Frequency Domain Spectrum to Time Domain Time History Profile
(Offshore Hydromechanics - First Edition - Journee and Massie, 2001).

In order to obtain the wave particle velocity time history profile in time domain from frequency domain velocity power spectrum, the Fourier series is used having the following formula

$$u(t) = \sum_{i=1}^{n} a_i.\cos(2\pi.f_i.t + \varphi_i) \tag{8}$$

$$a_i = \sqrt{2.S_{UU}(\omega)_i.\Delta f} \tag{9}$$

Where ai being the amplitude, φ_i is the phase angle which is random in nature and normally distributed between [-π to π], t is the storm/simulation duration. Determining the values of the amplitude and phase for each frequency gives the irregular shape for the velocity profile.

Regarding the Fourier Decomposition method adopted to analyze the hydrodynamic forces, the decomposition of the horizontal drag and lift forces have the following expressions

$$F_D = \frac{1}{2}.\rho.d.\mathrm{u(t)}^2(C_{H0} + \sum_{i=1}^{N} C_{Hi}.\cos(i\omega t - \emptyset_{Hi})) \quad (10)$$

$$F_L = \frac{1}{2}.\rho.d.\mathrm{u(t)}^2(C_{V0} + \sum_{i=1}^{N} C_{Vi}.\cos(i\omega t - \emptyset_{Vi})) \quad (11)$$

The inertia force is calculated separately according to the equation proposed by Sorenson et al. (1986) and AGA (1988) having the same formula for both models

$$F_I = C_M.\frac{\pi}{4}.\rho.d^2.a(t) \text{ \& } C_M = C_a + 1 \quad (12)$$

In order to adapt the Fourier method to an irregular wave profile, the nth-moment spectrum equation is used to obtain the significant wave velocity US of the velocity power spectrum and its associated velocity profile peak period TP. Then using these two properties, the Fourier coefficients can be selected from the experiments held by Sorenson, Bryndum and Jacobsen at the Danish Hydraulic Institute (1986) and was presented in the AGA PR-170-185 (1986) report based on the Keulegan-Carpenter KC and the current to wave particle velocity ratio M, with another two inputs being the cable and soil roughness.

$$m_n = \int_0^\infty \omega^n.S_{UU}(\omega)\ d\omega\text{, For n= 0, 1, 2, 3, 4… etc.} \quad (13)$$

$$U_s = 2\sqrt{m_0} \quad (14)$$

$$T_p = 2\pi\sqrt{\frac{m_2}{m_4}} \quad (15)$$

$$KC = \frac{U_s.T_p}{d} \quad (16)$$

$$M = \frac{U_c}{U_s} \quad (17)$$

At first, a set of nine harmonics [9 coefficients + 9 phase angles] were assumed to provide an acceptable accuracy in the representation of the forces, then it was found that only the first five harmonics can be used, as they give a sufficient description of the forces because there were no significant change after the fifth harmonic. The current effect is to be considered through the Fourier coefficients, as one of parameters of selecting these coefficients is the current to wave practical velocity ratio M.

The hydrodynamic loads acting on cable/pipeline are calculated as function of water particles velocity and acceleration with accordance to the cable lateral movements. For the case of horizontal movement, the relative cable to wave velocity and acceleration will be changed and will affect the hydrodynamic loads. Therefore, a force correction subroutine presented in [2] taking into consideration the relative vertical and horizontal velocities differences between the element and the water particle regarding the lift and drag forces respectively, as well as the horizontal acceleration differences between the element and the water particle regarding the inertia force so as to predict a more precise force time history that is acting on the element.

Verley & Sotberg (1992) has used three sources of pipe testing data, PIPESTAB (Brennodden et al. 1986), AGA (Brennodden et al. (1989) and DHI (Palmer et al. 1988), to develop and validate their pipe-soil resistance model. The model’s main governing equations and assumptions will be summarized in this section. However, for full details about the model, reference should be made to Verley & Sotberg (1992).

IV. DEVELOPED HYDRODYNAMIC MODEL VALIDATION

In order to validate the ability of the developed model to accurately estimate hydrodynamic forces acting on both submarine pipelines and cables with different diameters, UWAHYDRO program developed at the University of Western Australia by Bassem S.Youssef was chosen to be a reference of check.

Table 1. Input parameters for validation with UWAHYDRO program

PARAMETER	VALUE
SIGNIFICANT WAVE HEIGHT, H_S	12 m
PEAK WAVE PERIOD, T_P	10 Sec.
SPECTRUM USED	JONSWAP
SPREADING FUNCTION	NOT USED
CURRENT VELOCITY, U_C	0 m/Sec.
WATER DEPTH, D	50 m
PIPE DIAMETER, d	1 m
PIPE ROUGHNESS	FINE
SOIL ROUGHNESS	FINE
STORM SIMULATON DURATION	60 Sec.
PIPE LENGTH	UWAHYDRO: 250m
	MATLAB code: 1m
TIME INCREMENT, Δt	UWAHYDRO: 1 Sec.
	MATLAB code: 0.1 Sec.
FORCE MODEL USED	UWAHYDRO: FOURIER MODIFED
	MATLAB code: FOURIER

In the UWAHYDRO data input, a pipe of 250m in length is to be simulated, while in the MATLAB program a 1m pipe length was studied. The reason being that the spreading function was not activated. Therefore, the full forces load is assumed to be perpendicularly hitting the pipe, and the effect on one-node with length of 1m is the same as for the full 250m length except for the fixation points (start and end of pipe).

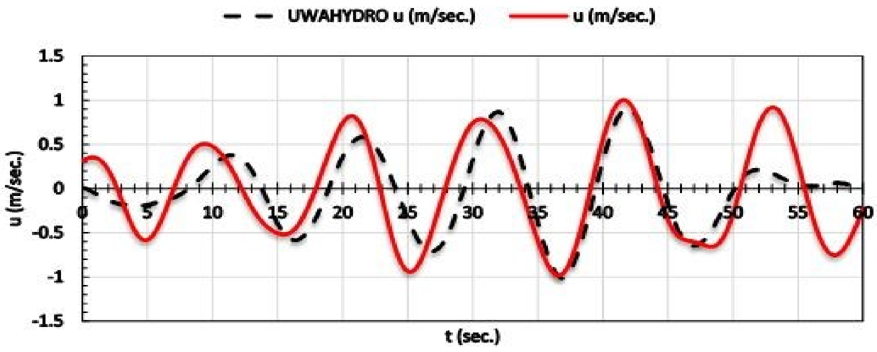

Fig. 4. Wave particle velocity at pipe level, profile estimations of MATLAB program Vs UWAHYDRO.

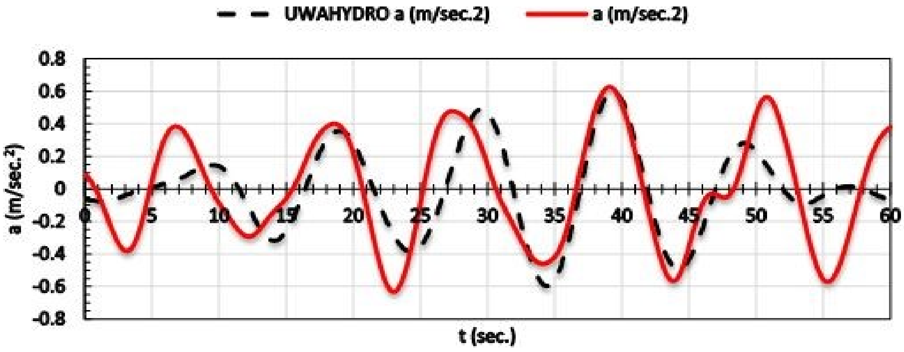

Fig. 5. Wave particle acceleration at pipe level, profile estimations of MATLAB program Vs UWAHYDRO.

The wave particle velocity and acceleration profile, shows near perfect match in both profiles shape and magnitudes except for a small shift in phase, this is due to the random phase angle used to simulate an irregular sea state, which makes it hard to achieve a hundred percent match.

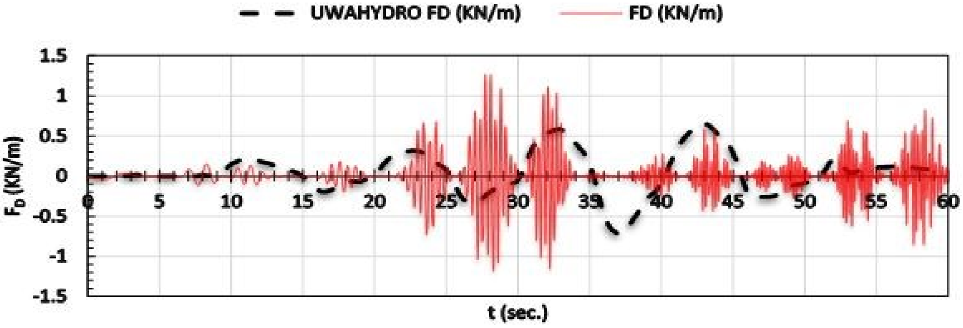

Fig. 6. Drag forces profile estimations of MATLAB program vs UWAHYDRO.

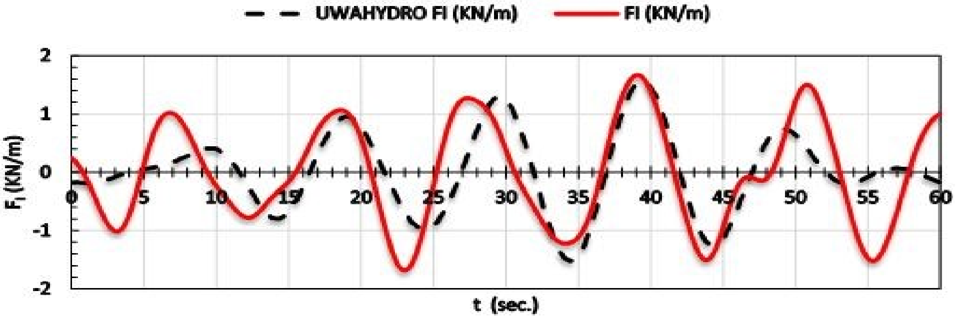

Fig. 7. Inertia forces profile estimations of MATLAB program vs UWAHYDRO.

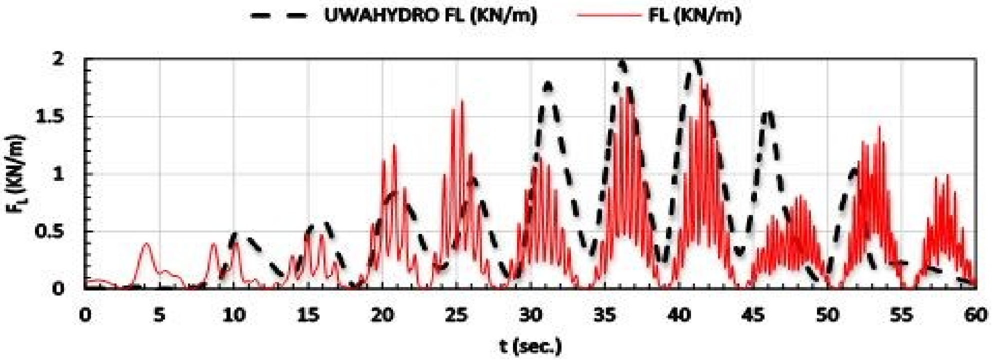

Fig. 8. Lift forces profile estimations of MATLAB program vs UWAHYDRO.

As for the hydrodynamic forces profiles, the drag, lift and inertia forces presented in Figures 6, 7 and 8, shows a great agreement with the results from UWAHYDRO in terms of profile shape and magnitudes. The smaller time increment 0.1-second chosen showed more regressions, even higher peaks than the 1-second time increment used in UWAHYDRO program, which helps in increasing the accuracy of the estimated forces and anticipating even higher loads than bigger time increments utilized in most programs specially regarding up lift force.

V. CASE STUDY, RESULTS AND DISCUSSION

This section in concerned with the analysis of submarine pipelines and cables held using the developed MATLAB program to investigate their stability following the guide lines of DNV-RP-F109 dynamic stability analysis, setting a maximum lateral displacement up to 10 times the element diameter as an allowable margin throw a storm of three hours in duration, so that the design is considered safe. The worst-case scenarios were taken into consideration, for pipelines, the pipe is supposed to be empty depending only on the pipe self-weight including all coatings. Also, the distribution function was not utilized, meaning that the forces of waves and current are supposed to be at an angle of attack equals to 90 degrees. A finite element motion analysis model was utilized in the program to simulate the motion both laterally and vertically due to the forces applied on the element. Several types of cables were considered with different diameters and masses, as well as a 24-inch pipeline, in order to investigate their stability in more than one region across the world having different wave characteristics. Both cable/pipeline and region wave, characteristics are shown in tables 2 and 3.

Table 2. Cables and pipeline physical characteristics

Cable Type	Outer Diameter (mm)	Dry Mass (Kg/m)
URC-1-RC	64	14.5
POWER - 24 kV	88	14.4
POWER - 145 kV	194	77
Umbilical	161	44.4
24" Pipeline	814	1192.7

Table 3. Regions wave characteristics

Area	D (m)	H_S (m)	T_P (sec.)	U_C (m/sec.)
North Sea	14	16	18.5	0.55
Brazil	14	7.16	14.8	0.55
Gulf of Mexico	14	14.2	14.9	0.55
Arabian Gulf	14	9.65	4.54	0.55

Figures 9 to 12 show the lateral movement time history of all five elements in each region.

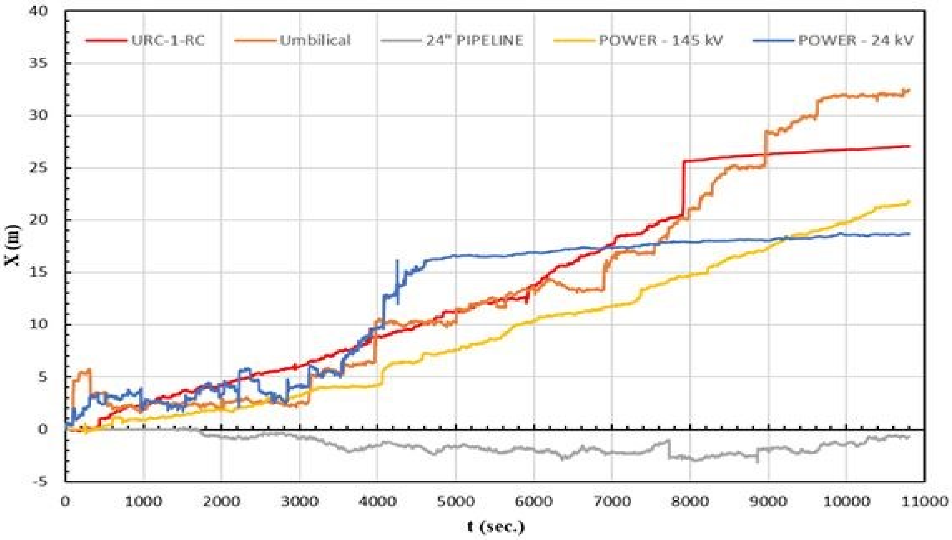

Fig. 9. Arabian gulf lateral motion analysis.

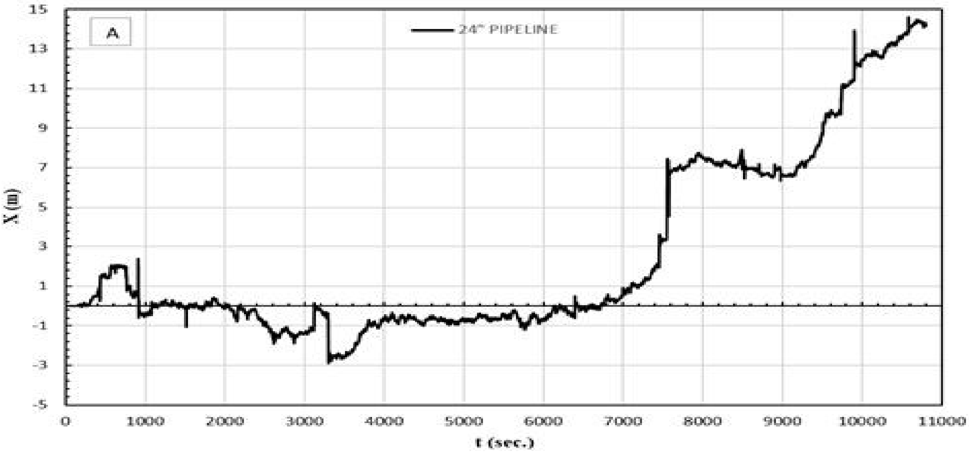

Fig. 11-A. Lateral displacement time history for 24" pipeline.

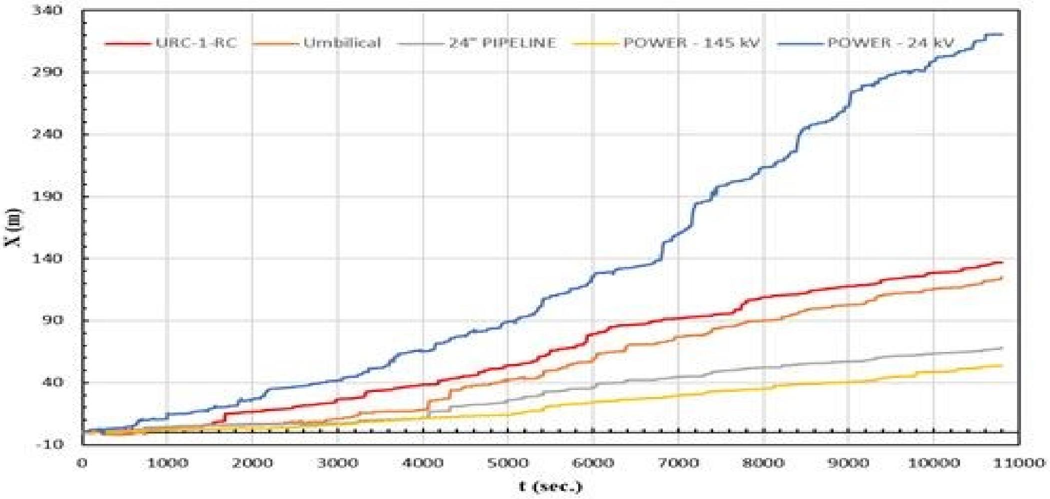

Fig 10. Brazil lateral motion analysis.

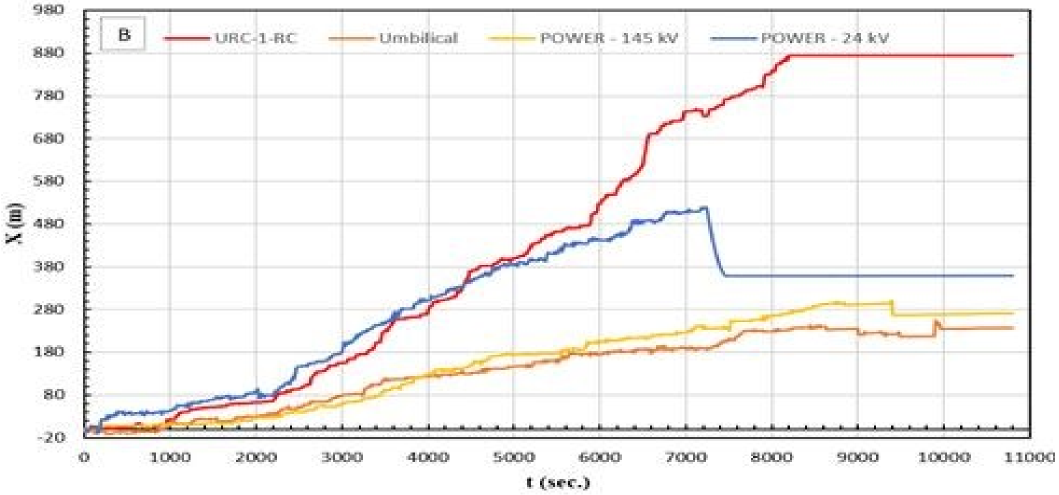

Fig. 11-B. Lateral displacement time history for URC-1-RC, Umbilical, Power 145kV and Power 24kV cables.

Fig. 11. Gulf of Mexico lateral motion analysis.

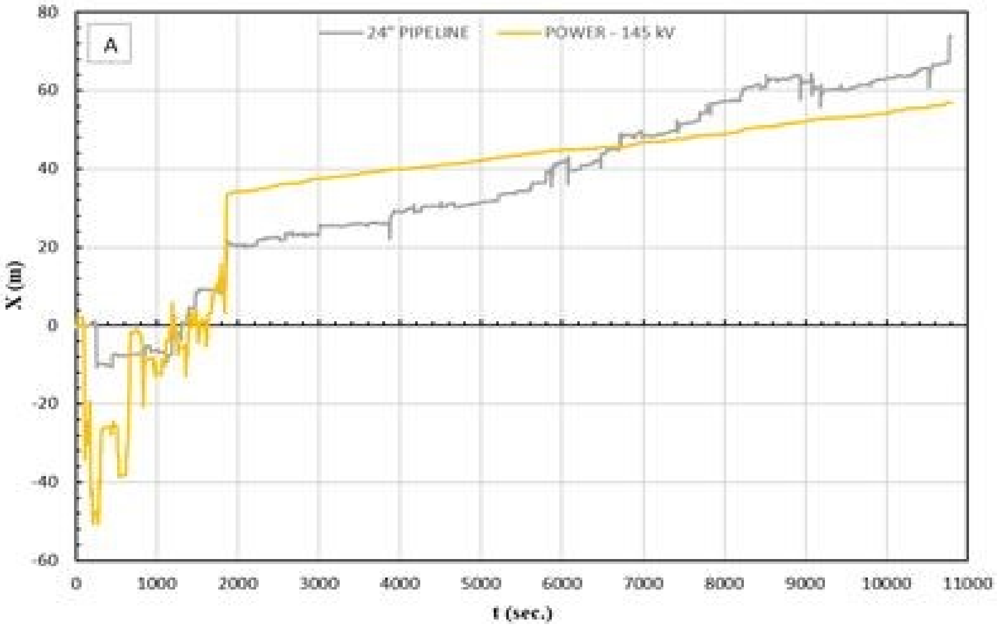

Fig. 12-A. Lateral displacement time for 24" pipeline and power 145kv cable.

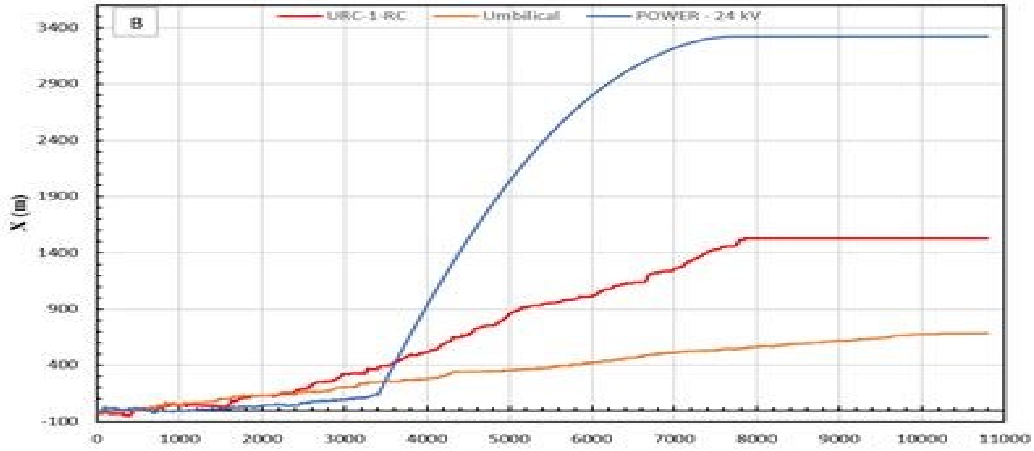

Fig. 12-B. Lateral displacement time history for URC-1-RC, Umbilical and power 24kv cable.

Table 4 summarizes the status of each run from the point of view of stability. As shown in the figures above, all elements in four regions comes short satisfying the recommended limits as per dynamic stability analysis, except for 24-inch pipeline in the Arabian gulf region. Therefore, the added mass required to stabilize each element was as well calculated and presented in Table 4.

Table 4. Stability recommendations for studied cables under various conditions

Type	Arabian Gulf	Brazil	Gulf of Mexico	North Sea
URC-1-RC	130% ≈ 19 Kg/m	180% ≈ 26 Kg/m	800% ≈ 116 Kg/m	110% ≈ 16 Kg/m
POWER - 24 kV	210% ≈ 31 Kg/m	275% ≈ 40 Kg/m	1150% ≈ 166 Kg/m	210% ≈ 30 Kg/m
POWER - 145 kV	**90% ≈ 70 Kg/m**	105% ≈ 81 Kg/m	553% ≈ 426 Kg/m	670% ≈ 516 Kg/m
Umbilical	120% ≈ 54 Kg/m	190% ≈ 85 Kg/m	**920% ≈ 409 Kg/m**	1350% ≈ 600 Kg/m
24" PIPELINE	Safe	130% ≈ 1550 Kg/m	120% ≈ 1432 Kg/m	150% ≈ 1790 Kg/m

Two examples will be presented with full analysis details and discussion, for 24-inch pipeline in the Arabian Gulf representing safe analysis, and the other being umbilical cable in the Gulf of Mexico representing an unsafe analysis, trying to find the sufficient added mass in order to reach the limits of safety.

VI. ARABIAN GULF – 24 INCH PIPELINE ANALYSIS

The JONSAWAP wave spectrum based on wave characteristics is shown in Figure 13 along with the velocity spectrum, and the 14m depth associated transfer function in Figure 14. It's clear that the energy distribution on sea surface is much bigger than that on seabed at pipe level, this is due to the fading of the wave effect as the depth increases.

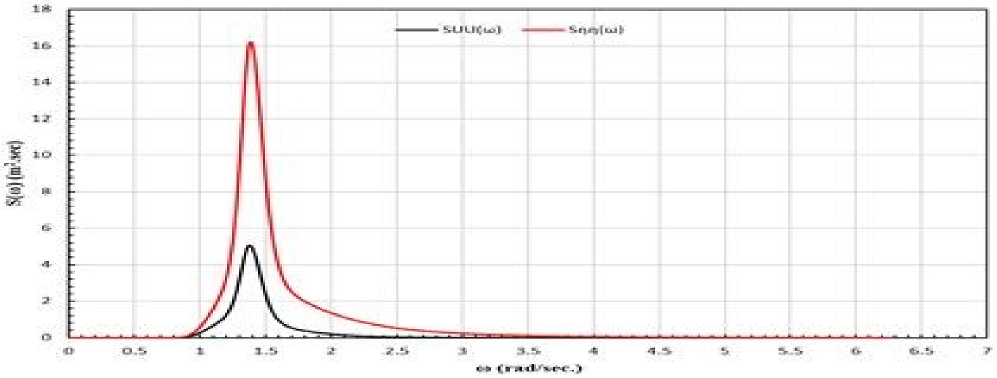

Fig. 13. Arabian Gulf spectrum analysis (Hs = 9.65m, Tp = 4.54 sec, D = 14m).

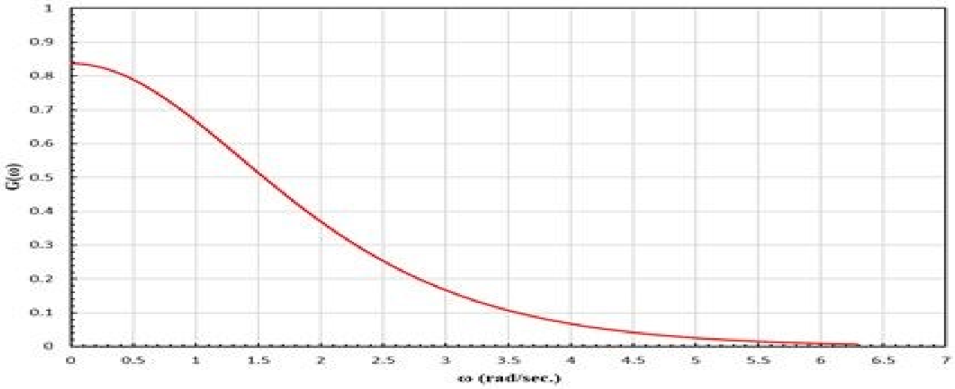

Fig. 14. Associated transfer function for 14m depth.

Figure 15 shows the horizontal displacement time history of the 24-inch pipeline in the Arabian Gulf region after a 10800 second simulation duration (three hours storm). Although there is a lot of movement, the pipe didn't exceed the allowable limit of dynamic stability analysis which is 8.14 meters (10 times the pipe diameter), therefor the pipe is considered stable under the action of its own weight and requires no additional mass.

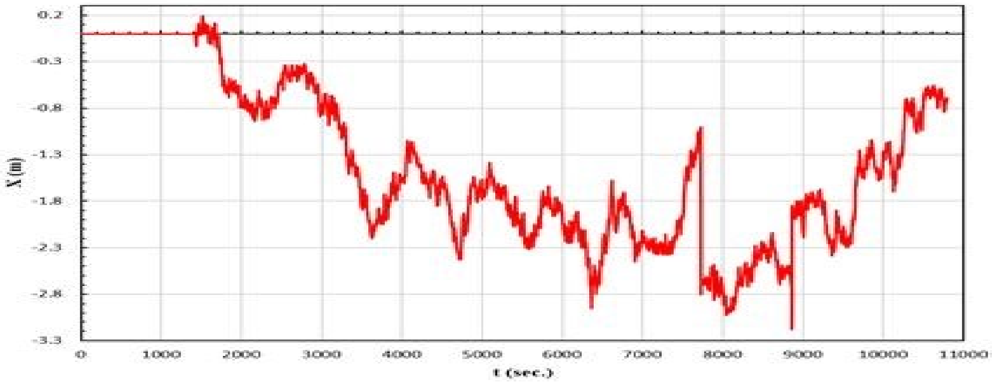

Fig. 15. 24-inch pipeline horizontal displacement time history.

The lateral motion is due to the horizontal net force between the corrected horizontal force presented in Figure 16, consisting of both drag and inertia components relative to velocity variation due to element movement, and the friction force (passive resistance force and Coulomb friction force), resulting of the element bottom touching the seabed soil and its penetration due to movement. Causing the pipe to move laterally according to the velocity direction, as well as the finite element analysis model correct the motion with respect to time variation.

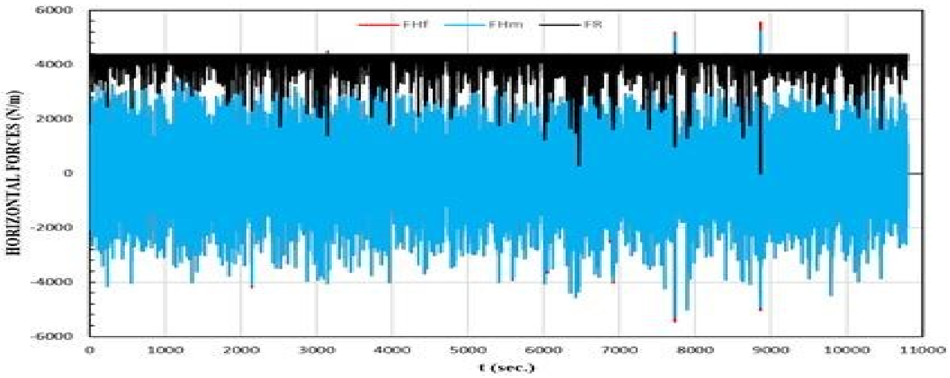

Fig. 16. Hydrodynamic horizontal forces vs soil resistance force.

The pipe submerged weight was sufficient to overcome the hydrodynamic lift forces most of the simulation time except for one single spike above the submerged weight which lead to vertical motion and the pipe being lifted above the seabed as shown in Figure 17, resulting in cancelation of resistance force as the pipe no longer touches the seabed and subjecting the pipeline to be fully under control of the hydrodynamic horizontal forces (drag and lift) momentarily before it returns back to its zero vertical position on seabed but after affecting the horizontal displacement aggressively.

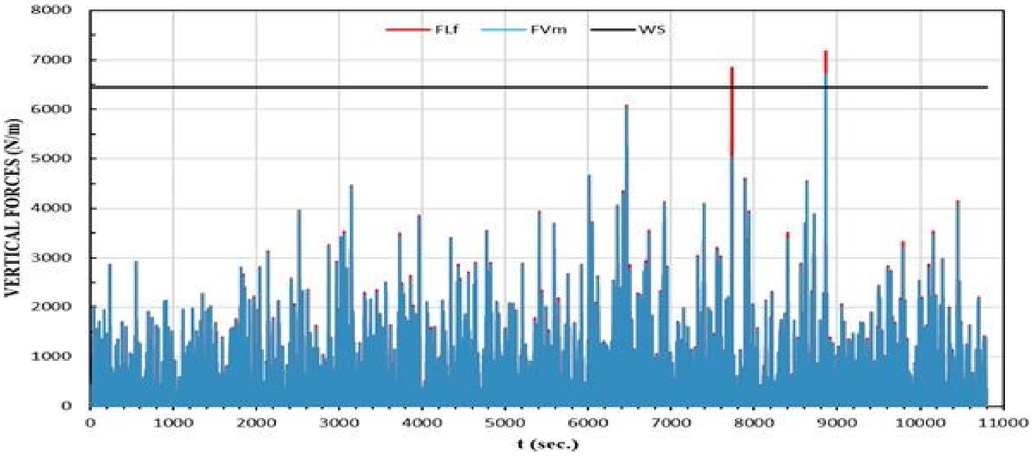

Fig. 17. Hydrodynamic lift forces vs submerged weight.

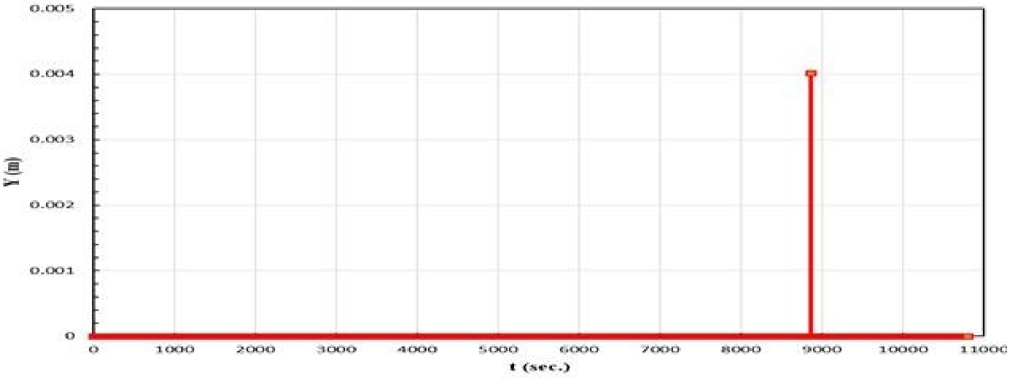

Fig. 18. 24-inch pipeline vertical displacement time history.

VII. UMBILICAL CABLE - GULF OF MEXICO ANALYSIS

Both wave elevation spectrum and velocity distribution spectrum at cable level are presented in Figure 19, and as all elements were simulated at the same depth in four regions, therefore the transfer function presented in Figure 14 applies also for this case, as it depends mainly on the depth.

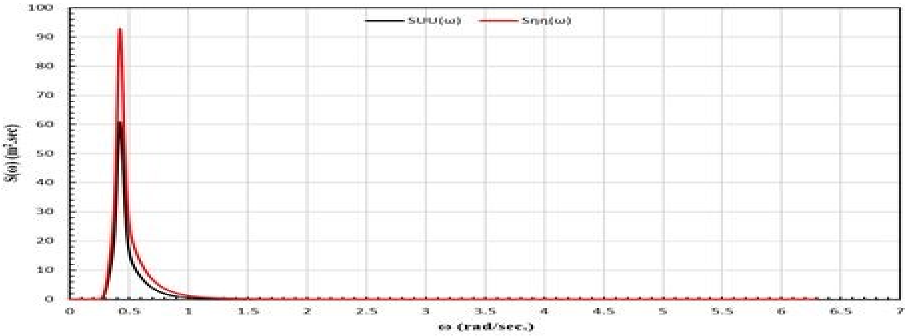

Fig. 19. Gulf of Mexico spectrum analysis (Hs = 14.2m, Tp = 14.9 sec, D = 14m).

It’s clear when compared to the previous case that the energy distribution is much higher than the case in Arabian Gulf, which indicates the probability of higher forces magnitude, due to higher energy spectrum values.

Figure 20 presents the lateral displacement of the cable under the action of both drag and inertia forces combined into one horizontal force, and after the relative motion between wave particles and the cable was accounted for, still the cable managed to move way beyond the permissible limits due to several reasons. The main reason being the insufficient self-weight leading to poor soil resistance as the lift forces over comes the cable’s submerged weight resulting in lifting the cable of seabed as shown in Figure 21.

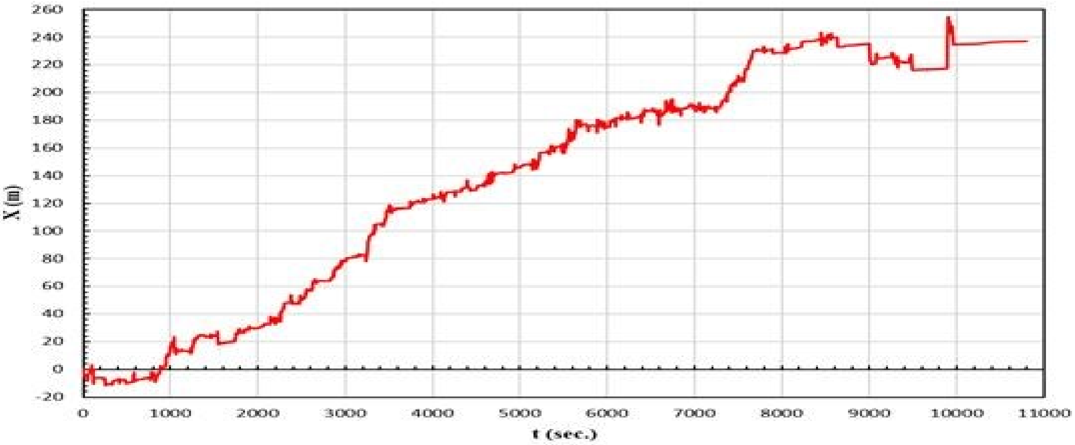

Fig. 20. Umbilical cable horizontal time history.

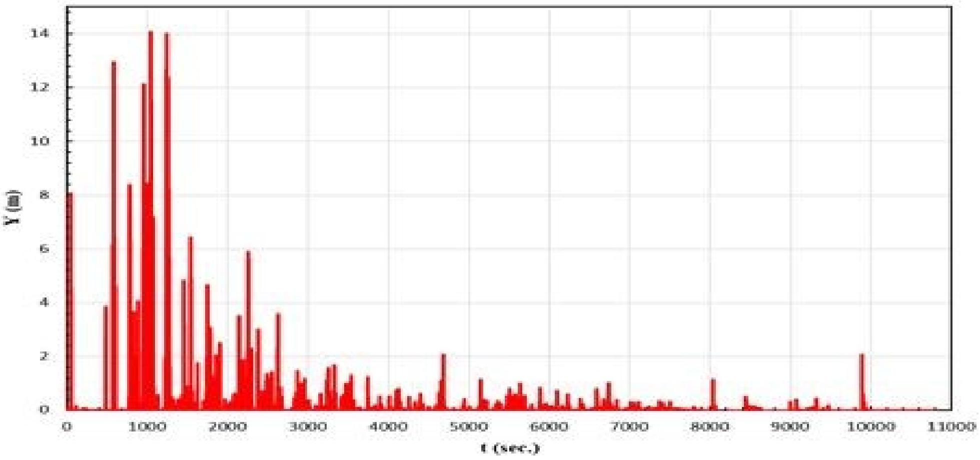

Fig. 21. Umbilical cable vertical displacement time history.

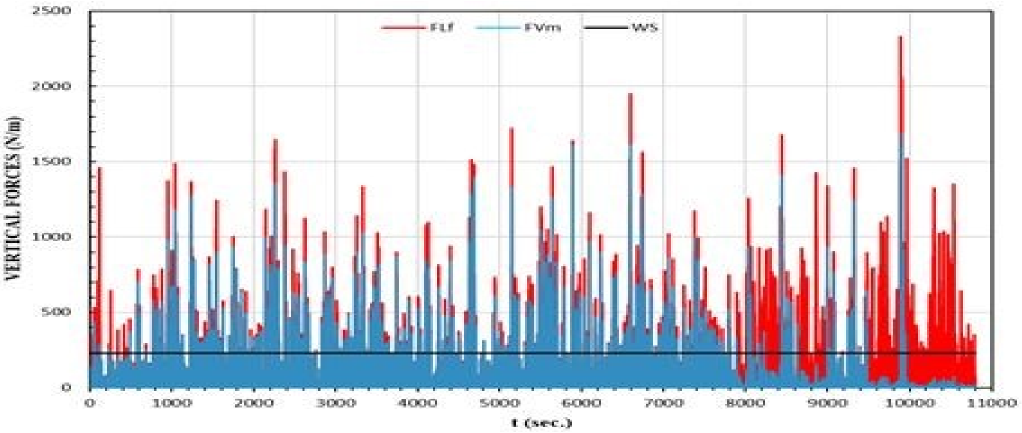

Fig. 22. Hydrodynamic lift force vs submerged weight.

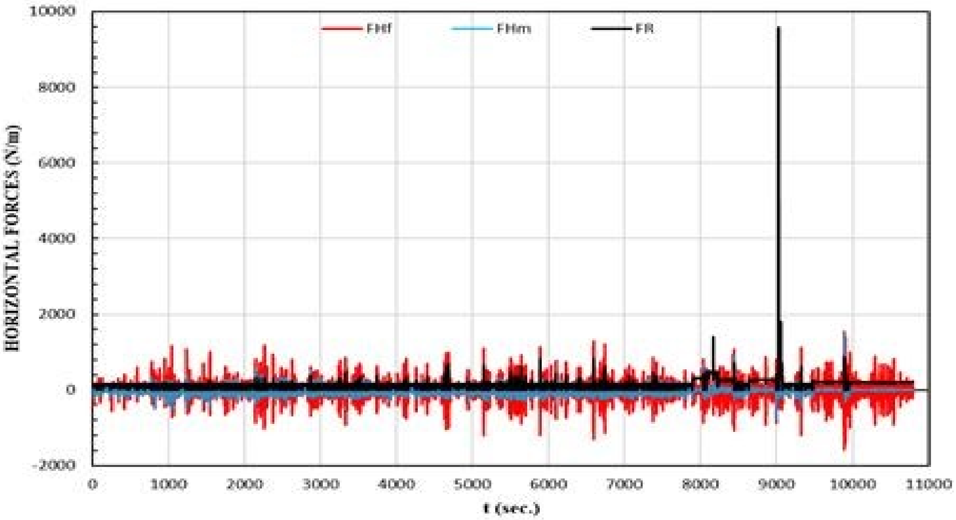

Fig. 23. Hydrodynamic horizontal force vs soil resistance.

As shown in both Figures 22 and 23, the vertical forces overcome the submerged weight causing the cable to be lifted from the seabed resulting in poor soil resistance which forces the cable to move laterally under the action of horizontal hydrodynamic forces applied by both waves and current.

Figure 23 shows the hydrodynamic horizontal hydrodynamic forces acting on the cable before and after accounting for cable movement and considering the relative motion, resulting in significant reduction in horizontal forces. Though in most of the simulation, the horizontal corrected force overcomes the soil resistance in magnitude forcing the cable to move laterally. This poor soil resistance is a direct result of the un- sufficiency of the cable submerged weight which was much less than the hydrodynamic lift forces even after accounting for the cable motion.

Another analysis was performed aiming to find the suitable added mass to satisfy the dynamic analysis limits being maximum lateral movement not more than 10 element diameter equals to 1.6 meters. The added mass was found to be 920 % of the original cable dry mass (408.5 Kg/m), this caused the cable to be stable having lateral motion within the permissible limits by dynamic stability analysis stated by DNV-RP-F109. Full analysis results are presented in Figure 24 through 27.

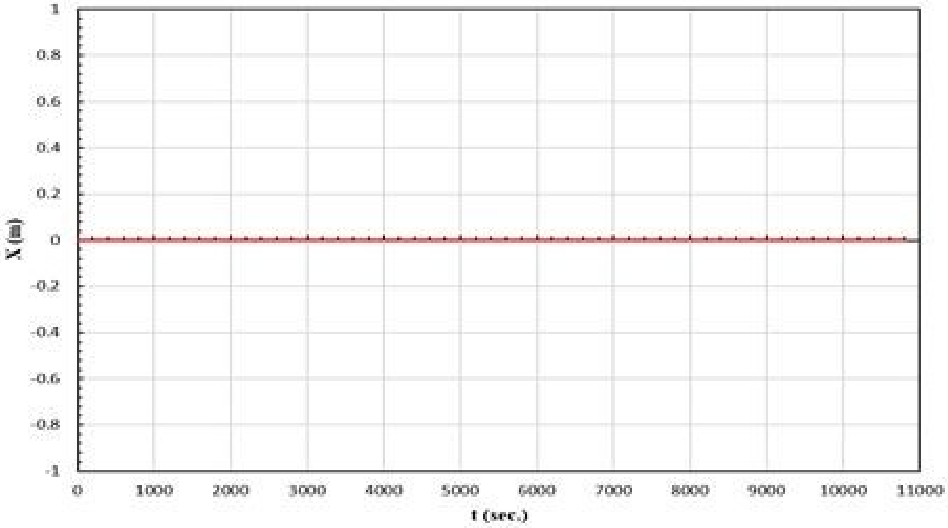

Fig. 24. Umbilical cable horizontal displacement time history, after added mass (920% of cable original dry mass).

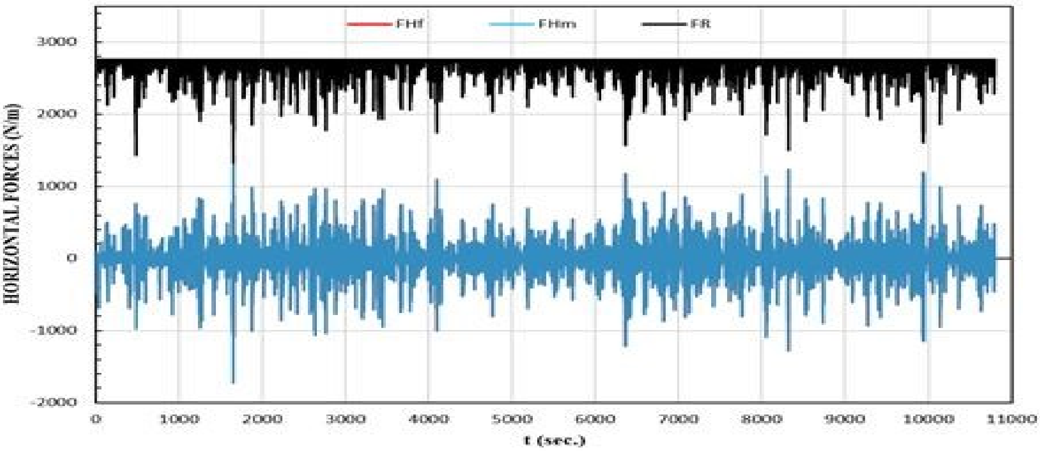

Fig. 25. Hydrodynamic horizontal force vs soil resistance, after added mass (920% of cable original dry mass).

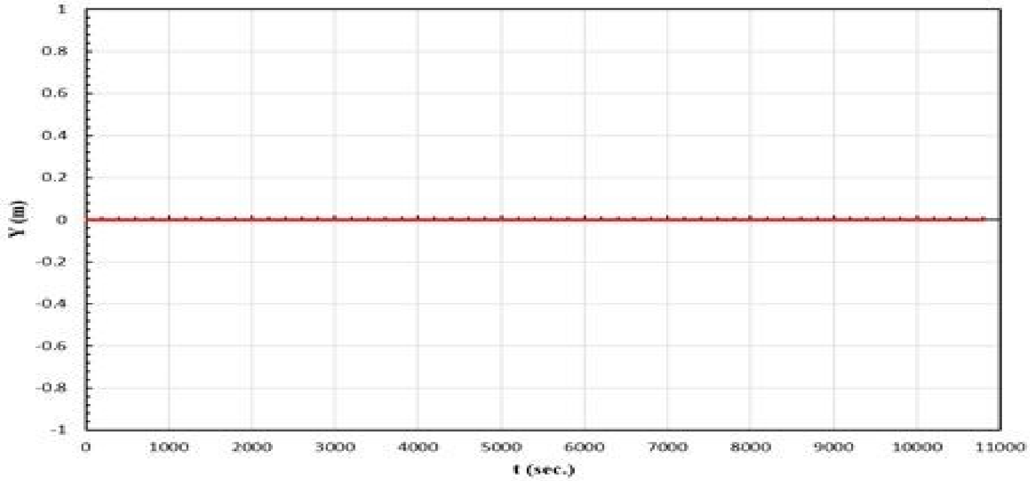

Fig. 26. Umbilical cable vertical displacement time history, after added mass (920% of cable original dry mass).

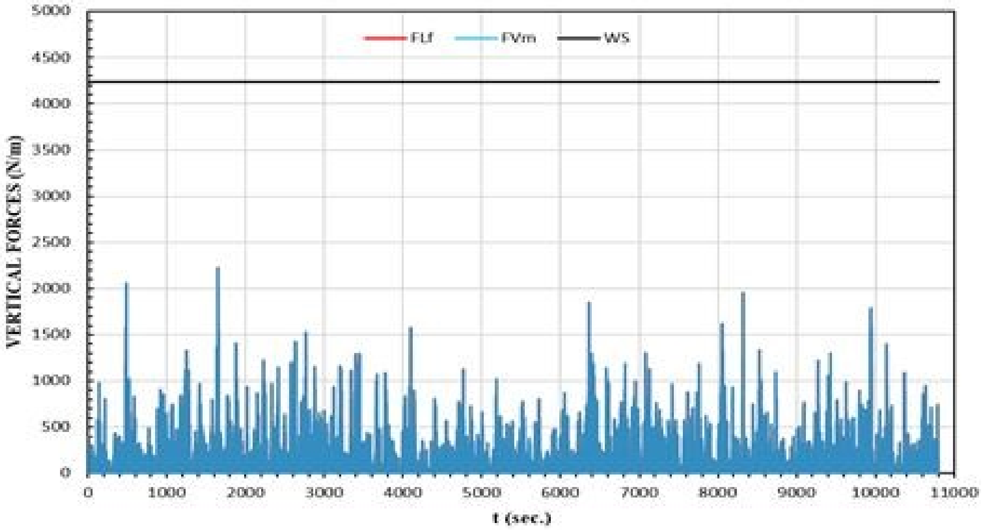

Fig. 27. Hydrodynamic lift force vs submerged weight, after added mass (920% of cable original dry mass).

As presented in the results shown above, the cable become both vertically and horizontally stable after adding extra weight, increasing both the submerged weight as well as the soil resistance. As the soil resistance is in a directly proportional relation with the submerged weight. The required added mass was found out to be 920% of the cable original dry mass (≈ 408.5 Kg/m), increasing the dry mass of the cable from 44.4 Kg/m to 452.9 Kg/m.

VIII. CONCLUSIONS

An integrated MATLAB program combining the hydrodynamic force model and the soil interaction model presented in DNV-RP-F109 developed by Verley & Sotberg, was developed also accounting for the element motion and relative velocities, as well as a finite element motion analysis model to simulate the element response with respect to time variation and creating a displacement time history, both vertically and horizontally, throw a three hours storm simulation duration as per dynamic stability analysis recommendations.

Results showed that some submarine elements can hold its own under the worst considered storms in some areas, for example, the 24 inch pipeline case in the Arabian gulf region, while others can reach the desired stability with adding reasonable amount and cost effective added mass per meter length to insure satisfying the dynamic stability criteria, while in other cases the use of alternative stabilization method showed be considered as the added mass required is both financially and industrially hard to achieve.

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