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Wave Effects on Varying Wave Motion Directions and Water Depth on the Hydrodynamic Force on Submerged Pipeline

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ABSTRACT: The study was conducted to analyse the effects of varying seawater depths and wave directions on the hydrodynamic force acting on submerged pipeline. Hydrodynamic force does act on the pipeline during its installation process, but, there is the need to determine the effect of wave motion direction and the depth of the seabed on the hydrodynamic force acting on the pipeline. The wave parameter was gotten from the coast of West Africa, Bonga Offshore located in Nigeria. The wave direction was from 0^o to 180^o while that of the seawater depth was from 500m to 2500m. MATLAB software with various wave and Morrison equations were used in the analysis. The results gotten from the analysis 500m (413.6170N) 1000m (402.1457N), 1500m (397.1199N), 2000m (394.1304N) and 2500m (392.1048N) at 0^o, it shows that the seawater depth and the wave directions does affects the hydrodynamic force on the submerged pipeline, it shows that as the seawater depth increases, the hydrodynamic force acting on the pipeline decreases and as the wave direction increases from 0^o (397.8114N, 500m) to 180^o (362.8285N, 500m), the hydrodynamic force on the pipeline reduces. The hydrodynamic force acting on the pipeline was more effective at 500m water depth at 0^o wave direction than at 2500m water depth at 180^o wave direction.

KEYWORDS: Hydrodynamic Force, Water Depth, Wave, Vessel, Seabed, Pipeline.

I. INTRODUCTION

Water waves are created by the gravitational pull of the sun, moon and planetary bodies, which travels with great speeds of wave circle that is half way across the earth. Thus, creating or generating the longest water waves known as tides. Wave act on anything that is along its path which can results to the erosion of the shoreline and damages to structures along its path. Waves can be of a height of 34m, due to this height, several ships which are exposed to this wave motion have sunk. Offshore platforms are built to a depth exceeding 300m to endure austere wave effects without failure of the structure, pipelines used for conveying crude oil and gas are submerged on the floor of the seabed. Hydrodynamic force does act on the pipeline during the installation process of these pipelines, but, how do the wave motion direction and the depth of the seabed affect the hydrodynamic force acting on the pipeline. Depending on the magnitude of the forces that are acting on the water, waves can occur in different forms and sizes which show that the pressure force that acts on the surface of the fluid are key and same as the displaced fluid magnitude. The minimum hydrodynamic force acting on the submerged pipeline needs to be determined at varying seabed depths and wave directions to prevent the collapse of the operation or possibly abandonment of the installation process [1].

Submerged Pipeline Construction

The construction of submerged pipelines on pipe laying vessels is done by the welding of the offshore sections which is placed on the deck of the vessel or the pipeline is prepared onshore before putting it on the reel or vessel. It is possible for up to 90 kilometre for 100 to 400 millimetre diameter pipes in winding the pipe onto the reel. In the laying process, when the pipe is being laid to a depth of 300 meter, the reel constantly rotates at a speed of 4 kilometres per hour. Stinger is used to support the pipeline from bending during the lowering of the pipeline on the deck, moving it away from the vessel. For moving of the pipeline, a conveyor specially designed and installed on the vessel also receive welded pipes which was tested for defects by an ultrasonic equipment and the welded parts of the pipes are covered with anti-corrosion coating to prevent it from corroding. In pipe laying operations, different ships are involved in the laying process, for the supply of pipes to the pipe laying vessels, vessels that are monitoring the seabed etc [2].

Pipe laying Procedure

The procedure for pipe-laying operations in offshore oil and gas industry is tasking when installing flow lines and pipe lines with their connections to platform, it requires the advancement in engineering technology, cost and size of the different types of pipe laying vessels. The control concert for the operation of pipe-laying on the seabed using pipe laying vessel is based on pipe fracture, the vessels motion which is controlled with the help of anchors or by the use of dynamic positioning vessel and the seabed touch-down point of the pipe. Pipe-laying industry has advanced its operation in the oil and gas industry for laying of pipe along the seabed to an international standard to meet up with the quest for energy in the world. Drilling has developed from shallow waters to deeper waters with harsh environmental conditions. The unsteady cost of the price of crude oil has made the pipe laying industry venerable having both boom period and recession periods for operators of the business [3, 4].

Pipe Laying Operation

Pipe laying operation started in the Gulf of Mexico in 1950s, where onshore companies decided to move from shore to near and bit by bit to deep water. The laying process was done with flat barges using sheer muscle power as shown in Figure 1. Inclined ramp was used to support the pipe laying down to the seabed to a depth of 15 meters, the development of the stingers was in the late 1960s to revolutionize the industry. The stinger is fixed at the end of the barge, the curved stinger support the laying of pipe under tension [5, 6].

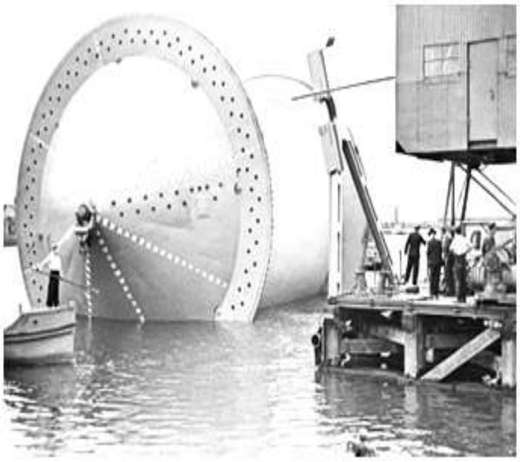

Figure 1: The Conundrum Pipe-Laying Process [7]

Different Soil Type and Stability Analysis

The environmental wave action on the hydrodynamic force on a pipeline when exposed to rough sea state was used to analyze the bottom stability of the pipeline on different types of soil (sandy, clay and gravel) and wave current conditions to determine its effect on the pipeline. Different modeled equations of the wave spectral were used with MATLAB source code to analyze the differences in the various spectral conditions which are Pierson & Morskowits, Brestschneider and the Jonswap spectral. In order to determine the submerged pipeline weight in the seabed, three different forces where used at various seabed heights, these forces are the drag, lift and the initial forces acting on the pipeline under the water due to wave current. The pipe self-weight usually increases when the seawater increases and also the pipeline self-weight varies in the different soil used in the analysis [8]. The stability of offshore pipelaying is a major part of the laying process of offshore pipeline, this is so due to the harsh environmental conditions and the roughness of the sea during laying operations. It is vital to maintain good pipeline stability and knowledge of the hydrodynamic forces acting on the pipeline to avoid the collapse of the pipelaying process which will put the safety of the workers at risks [9].

Pipelaying Methods

The result of the movement between the pipeline and the water around the pipeline causes an induced load on the pipeline and the forces that are acting on the submerged pipeline are the drag force, the initial force and the lift force. The use of

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Morrison equation on the underwater pipeline in the analysis will help in the understanding of the hydrodynamic loads acting on the submerged pipeline. There are three pipe laying installation methods that are widely in use for pipe laying operations in the world today. They are S-lay, J-lay and the Reeling methods, due to the specialized and advance equipment fitted in the pipe laying vessel and some of the companies that are having pipe laying vessels [10, 11, 12].

S-lay method is the most familiar methods of pipe laying used in the world as shown in Figures 2 and 3, in which several numbers of pipes are coated, joined onshore at about 12 meters long and taken to the pipe-laying vessel with the help of supply vessels to continue the pipe joining process onboard. The pipe is welded from the production facility horizontally known as the firing line to the end of the line. This method is used for shallow and intermediate deep water, the length of the pipe that can be laid per day is about 5 kilometres with departure angle of the stinger changing from horizontal to vertical in shallow and intermediate depth of the water respectively and also non-destructive testing was done on the welded joints [13].

Figure 2: S-Laying Vessel [14]

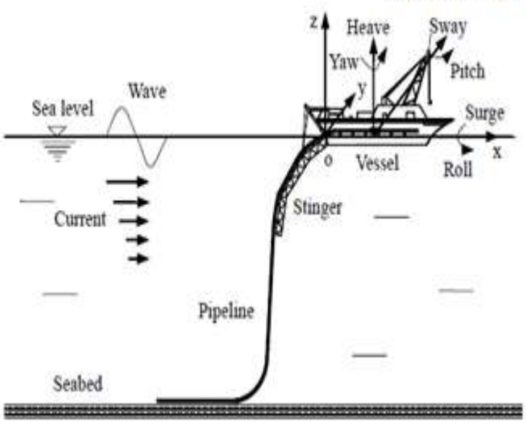

Figure 3: S- Lay Process and the Six Degree of Motion [15]

The operation of the S-lay method is economical and fast and its main advantage is the long firing line that is running from the forward to the aft part of the vessel. As the depth of the water increases, the departure angle is close to vertical and a very large stinger were needed to prevent the pipe from damage and also the rate of fuel consumption increases due to the increase in lay tension of the pipe**.** The lift angle in shallow water of a depth 100meters is about 30^0 from the horizontal also as the water depth increases, so as the lift angle from 30^0 to 90^0 as the tension is kept within the prescribed limits, this limit is called the steep S-lay, the steep S-lay arrangement reduces the pipes tension, when compared to the S-lay method. Pipe-laying vessel moves in a step as the same as the length of the pipe [13].

The J-lay method uses catenary arrangement of the pipeline from the bottom of the sea to the pipe laying vessel which is close to vertical at the end of the vessel and the depth is for intermediate and deep water conditions. The pipe will move in closely vertical position from the ramp of the vessel to the seabed during the laying operation. This method eliminated the problem of too much bending area as that of the S-lay due to this arrangement. The tensioner and a work station are attached to the J-lay tower as shown in Figure 4, the J-lay tower angle varies from 0^0 to 15^0 in the vertical direction (axis) [16]. The J-lay method has various advantages over the S-lay method as follows:

- It eliminates the use of a complex stinger
- It has a close touch down point as compared to the S-lay and easier touchdown point.
- The applied tension is low for controlling sag bend
- The length of the entire pipe line is shortened at the free end as the pipe leaves the vessel steeply down the seabed.

The major disadvantage of the J-lay method is that, it is slower when compared to the S-lay method [16].

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Figure 4: J-Laying Vessel [17]

The reeling method is mostly used for flexible pipes, umblicals and cables having smaller diameter of about 16inches. It is one of the most efficient methods of pipe installations in which the pipe construction is done onshore in an organised environment and wound on the large reel diameter that is attached to the reeling vessel. The capacity of the reel is about several miles of pipe laying per day depending on the diameter of the pipe. As the pipe laying vessel begins the installation process by unwinding the reel pipe and as the vessel moves continuously, the pipe is reeled out also. When using the reeling barges, the pipe is laid into the seabed horizontally with the help of a stinger as that of the S-lay method and also when using a ship-shaped vessel, the pipe is laid into the seabed vertically as that of the J-lay installation process as shown in Figure 5. Each processes of reeling are installed equivalent equipment for its laying operation [18].

Figure 5: Reeling Vessel [19]

Hydrodynamic Load Analysis

The in-line hydrodynamic forces of wave and current loads on offshore pipelines and risers are giving in equation 1. The fluid is in an accelerated environment in which the cylindrical pipes are vertical and stationary [20].

$$f_h = \frac{1}{2}\rho_\omega C_D d_o u|u| + \rho_\omega C_m A\dot{u} + \rho A\dot{u} \quad (1)$$

Where

f_h	=	Hydrodynamic force
ρ_ω	=	Density of water
C_d	=	Drag coefficient
d_o	=	Diameter of the cylinder
U	=	Velocity of flow
$\dot{U}$	=	Acceleration of flow
C_m	=	Hydrodynamic mass coefficient
A	=	Area of the cylinder

The first term in equation 1 is the drag force which is the resistance to the motion of the water, the second term is the hydrodynamic mass force which is the acceleration of the mass of fluid lose to the body due to the activities of pressure of the motion of the body while the last term is the Froude-Krylor force which is as a result of the fast movement of water outside the cylinder flow region. Some of the parameters that the drag and mass coefficient rely on are the ratio of the surface roughness of the sea, the current, Reynolds and Keulegan-Carpenter number which for a cylinder it is given as shown in equation 2 empirically and also equation 3 and 4 formulated from a new constant C_M and substituting it for c_m in equation 1 [21].

$$c_m = 1 \quad (2)$$

$$C_M = c_m + 1 \quad (3)$$

$$f_h = \frac{1}{2}\rho_\omega C_D d_o u|u| + \rho_\omega C_M A\dot{u} \quad (4)$$

Where

C_M = Inertia coefficient [22].

Pipeline Environmental Loads

The environmental loads that can affect the pipeline are waves and currents, the wave will causes stimulation of the loads on the small-volume pipe structure since it is $\lambda/d_o \rangle 5$. These loads were calculated with Morrison equation involving both the inertia forces and the viscous drag on the pipe structure. The calculation were done using $C_M = 2.0$ and $C_D = 1.0$ in the computation, the inertia forces was smaller compared to the viscous drag forces given H/do › 4π and H is the amplitude for peak to peak [23, 24].

II. METHODOLOGY

The wave parameter used for the analysis of the effects of the wave on pipe laying operation is obtained from Bonga offshore located in Nigeria, in the coast of West Africa. The wave is from the South Atlantic storm having peak period of 20 seconds, significant wave height of 2m and wave crossing periods of 14.29 seconds. The wave period of 5s was used in the course of this study, the wave position and direction varied from 0° to 180°. The wind speed and current speed of 30m/s and 1.2m/s respectively was used and Equations 5 to 9 was used for the wave parameter determination [25, 26, 27]

- Wave frequency calculation (ω)

$$\omega = \frac{2\pi}{T_p} \quad (5)$$

- Wave number calculation (k)

$$k = \frac{\omega^2}{g} \quad (6)$$

- Wave amplitude calculation (a)

$$a = \frac{H_s}{T_p} \quad (7)$$

- Wave length calculation (L)

$$L = 1.56{T_p}^2 \quad (8)$$

- Wave speed calculation (C)

$$C = \frac{\omega}{k} \quad (9)$$

Pipeline Seawater Parameter

Table 1 shows the material properties of the pipeline and the seawater that was used in the analysis of this research work.

Table 1: Pipe and Seawater Parameter [28, 29]

S/N	Parameters	Values
1	Carbon steel pipe	20 inch (0.508m)
2	Density	$7850 kg/m^3$
3	X 65 pipe	448MPA (MYS) & 530MPA (MTS)
4	Youngs Modulus	2.00×10^5MPa
5	Seawater density	$1.025 kg/m^3$
6	Pipe thickness	11mm (0.011m)
7	Seawater temperature	5.0°
8	Seabed friction (x & y direction)	0.3
9	Seawater depth	500m, 1000m, 1500m, 2000m, 2500m

Hydrodynamic analysis of the submerged pipe per unit length

The hydrodynamic analysis of the submerged pipe in wave and current is being calculated from equation 10.

$$f_h = \rho_\omega C_M A\dot{U} + {}^1\!/_2\, \rho_\omega C_D d_o U + U_c|U + U_c| \quad (10)$$

Where

U = Wave velocity

U_c = Wave induced current velocity

$\dot{U}$ = Wave particle acceleration

A = Area $\pi d_o^2/4$ of submerged pipe ($0.203 m^2$)

d_o = Outside diameter of pipe (0.508m)

ρ_ω = Sea water density ($1025 kg/m^3$)

C_D = Drag coefficient (1 for linear wave theory)

C_M = Hydrodynamic coefficient (0.95 for linear wave theory)

III. PRESENTATION OF RESULTS

The results gotten from the MATLAB Programme for the hydrodynamic force acting on the pipe are shown in figures 6 to 12 for varying water depth from 500m to 2500m at a given wave position in the positive x-direction from 0° to 180° respectively.

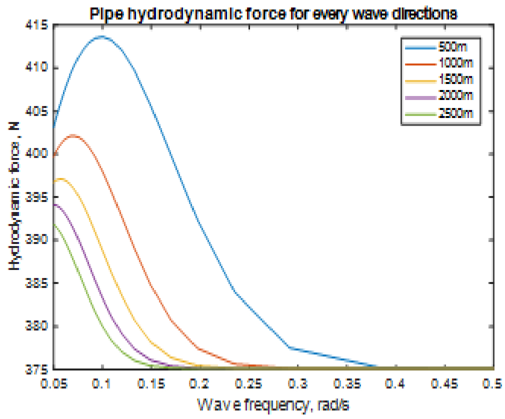

Figure 6: Hydrodynamic force against wave frequency for 0° wave direction

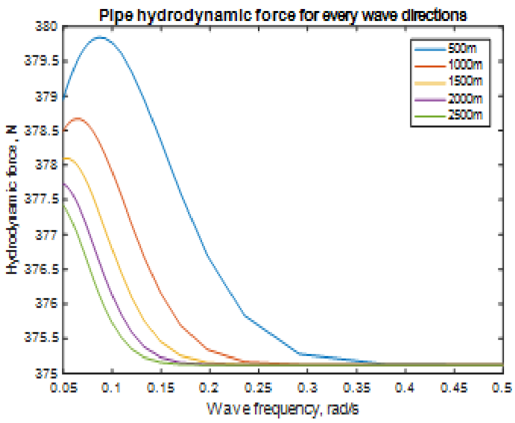

Figure 7: Hydrodynamic force against wave Frequency for 300 wave direction

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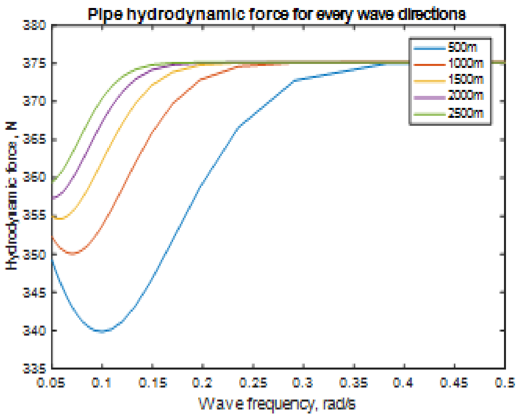

Figure 8: Hydrodynamic force against wave frequency for 60° wave direction

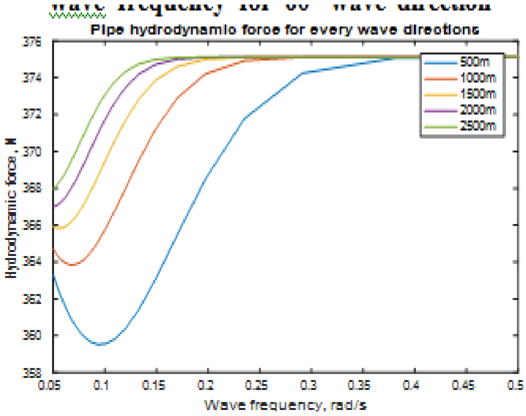

Figure 9: Hydrodynamic force against wave Frequency for 90o wave direction

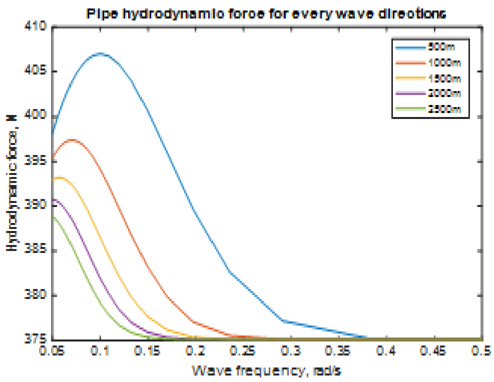

Figure 10: Hydrodynamic force against wave Frequency for 120° wave direction

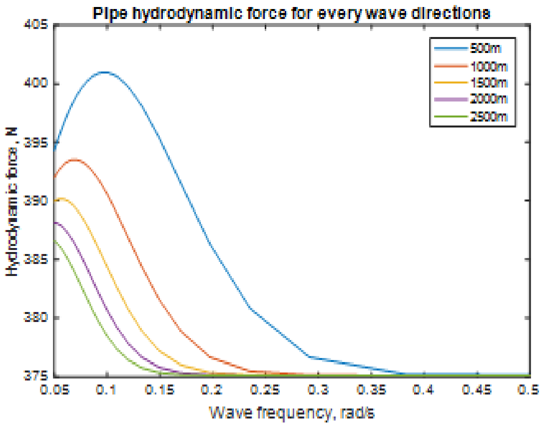

Figure 11: Hydrodynamic force againstwave Frequency for 150° wave direction

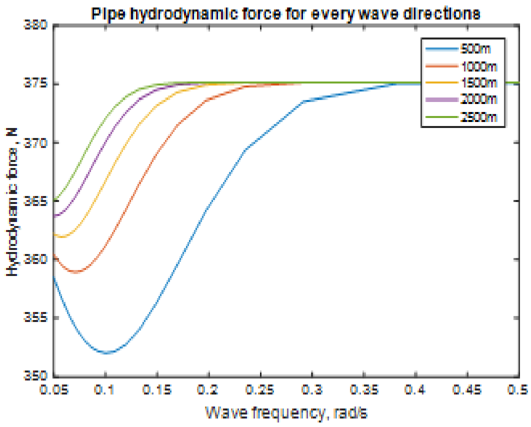

Figure 12: Hydrodynamic force against wave Frequency for 180° wave direction

IV. DISCUSSIONS OF RESULTS

0° Wave Direction

The hydrodynamic force acting on the pipeline at 0° wave direction and water depths of 500m to 2500m is shown in figure 6. From the figure, the hydrodynamic force increases from 395.8114N to 398.1100N up to a peak of about 413.6170N at a water depth of 500m before reducing its effects to 375.1235N. Similarly cases was experience for the other depths of 1000m (394.5635N), 1500m (393.3917N), 2000m (392.2912N) and 2500m (391.2578N) are achieving its peak forces at 1000m (402.1457N), 1500m (397.1199N), 2000m (394.1304N) and 2500m (392.1048N). The hydrodynamic forces acting on the pipe reduces as the depth of the seabed increases, the least recorded force on the submerged pipe at the various depths are 375.1235N at 500m to 2500m respectively which remains constant at this force.

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30^o Wave Direction

The hydrodynamic force acting on the submerged pipe at a wave direction of 30^o for water depths of 500m to 2500m is shown in figure 7. The figure shows that at the various water depths, the hydrodynamic force were at 378.0569N, 377.8818N, 377.7172N, 377.5624N and 377.4168N for depths of 500m to 2500m respectively, which increases to 379.8428N, 378.6722N, 378.0996N, 377.7429N and 377.4918N for water depths of 500m to 2500m respectively. The force then decreases from these peak values to 375.1235N for 500m to 2500m water depths respectively. The hydrodynamic force acting on the pipe at 30^o wave direction decreases as the seabed depths increases.

60^o Wave Direction

The hydrodynamic force on the pipeline at a wave direction of 60^o and various water depths is shown in figure 8, the figure shows that the initial hydrodynamic force on the pipeline at the various water depths are 349.8215N, 352.6355N, 355.1410N, 357.3708N and 359.3546N for 500m to 2500m respectively. The forces later reduce to about 339.8466N, 350.0789N, 354.6359N, 357.3663N and 359.2270N for 500m to 2500m respectively. The hydrodynamic force then started increasing from 339.8466N to the peak force of about 375.1235N (500m) and for 1000m to 2500m water depths, which also increases to their various peaks forces to about 375.1235N respectively maintaining stability at this hydrodynamic force.

90^o Wave Direction

The hydrodynamic force at various seabed depths at 90^o wave direction is shown in figure 9, the forces was at 363.2003N, 364.6424N, 365.9112N, 367.0274N and 368.6090N for 500m to 2500m water depths respectively. These values later reduces to about 359.6337N, 363.8416N, 365.8208N, 367.0172N and 367.8443N for the various water depths which increases steadily from theses values to 359.5337N, 363.8416N, 365.8208N, 367.0172N and 367.8443N to about 368.5009N, 374.2069N, 374.9972N, 375.1061N and 375.1211N for 500m to 2500m water depths respectively. The entire forces at the different water depths increases to a peak hydrodynamic forces of about 375.1235N as the wave frequency increases from 0.005rad/s to 0.5rad/s of which the hydrodynamic force maintain this value (375.1235N) as the frequency increases.

120^o Wave Direction

The hydrodynamic force acting on the submerged pipe against the wave frequency is shown in figure 10 for various water depths at 120^o wave direction. The forces increases steadily from its initial forces of about 392.0553N, 391.0364N, 390.0793N, 389.1803N and 388.3358N for the seabed depths of 500m to 2500m respectively to a peak hydrodynamic forces of 407.0131N, 397.3999N, 393.2147N, 390.7372N and 389.0595N for water depths of 500m to 2500m respectively as the wave frequency increases from 0.05rad/s to 0.5rad/s. the hydrodynamic forces at these water depths falls steadily from these peak forces till they reaches a stable force of about 375.1235N for each of the water depths.

150^o Wave Direction

The pipe hydrodynamic force against the wave frequency for various water depths and 150^o wave direction is shown in figure 11. The figure shows an increase of the hydrodynamic forces from 389.3709N, 388.5146N, 387.7101N, 386.9544N and 386.2443N for water depths of 500m to 2500m respectively to the peak values of 400.9916N, 393.4933N, 390.1559N, 388.1582N and 386.7903N for 500m to 2500m water depths respectively. These forces at the various water depths then decreases from these peak values steadily as the wave frequency increases to a stable force of 375.1235N for each of the water depths without further increase on the hydrodynamic forces.

180^o Wave Direction

The hydrodynamic force against the wave frequency is shown in figure 12, the figure shows the hydrodynamic forces affecting the submerged pipe at various water depths from 500m to 2500m at 180^o wave direction. The forces decreases from 362.8285N, 363.5554N, 364.2396N, 364.8836N and 364.9494N for 500m to 2500m water depths respectively as the wave frequency increases from 0.05rad/s to 0.5rad/s. The hydrodynamic forces from these points started increasing to about 369.3710N, 374.7794N, 375.1029N, 375.1222N and 375.1234N at 500m to 2500m water depths respectively before maintaining a stable force of about 375.1235N without increasing as the wave frequency increases for each of the seabed depths.

V. CONCLUSION

The analysis was conducted on the hydrodynamic force acting on submerged offshore pipeline at varying seabed depths (500m to 2500m) and wave directions (0^o to 180^o). The hydrodynamic force effects on the submerged pipeline shows that as the water depth from the seabed is increasing from 500m to 2500m, the wave effects on the hydrodynamic force was dropping and also as the wave motion direction is increasing from 0^o to 180^o, the hydrodynamic force was falling. This study now shows that the wave motion directions and the seabed depth do affects the hydrodynamic force acting on the submerged pipeline. Further increase of the seabed depth and the wave motion direction beyond 2500m and 180^o respectively will not yield much decrease in the hydrodynamic force acting on the submerged pipeline.

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