On-Bottom Stability Study of Non-Metallic Pipeline Due To Hydrodynamic Loadings

by

Hea Yih Torng
16251

Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

January 2016

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CERTIFICATION OF APPROVAL

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Approved by,

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(Assoc.Prof.Dr. Mokhtar Awang)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2016

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

HEA YIH TORNG

ABSTRACT

In order to prolong the service life, the integrity and stability of the submarine pipeline always been a concern of the oil and gas industry. However, conventional steel subsea are subjected to corrosion in sour service and even sweet service. Inspection of the subsea pipeline are frequently scheduled to ensure the integrity of the pipeline which is very costly. The non-metallic pipeline are introduced to be replacement of the steel pipeline. The non-metallic properties is known to have highly resistance to corrosion yet it also has lighter weight which lead to on-bottom stability problem. Hence, this project aim to determine the minimum weight of chain per unit length for the subsea non-metallic pipeline to be stabilized. The on-bottom stability study will based of DNV recommended practice with the use of finite element analysis package. This project also will include a finite element analysis of the submarine pipeline by using ABAQUS. The water velocity and acceleration are generated from the sea surface wave and current given the sea state in the South China Sea. The weight of chain is determine from the optimization of the simulation. The simulation's result by using one year return waves and currents show 32.32kg/m of chain can stabilize the non-metallic pipeline with 0.7654 m lateral displacement.

ACKNOWLEDGEMENTS

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Last but not least I would like to express my deepest gratitude to Mechanical Engineering Programme for giving me such a golden opportunity to accomplish the final year project which indirectly developed me to be an independent engineer. Throughout the duration of this project, I have faced many challenges, but with the degree knowledge, everything is solved and the project did achieve its own objectives.

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Nomenclatures

d	Water depth
C_1	Empirical parameter for wake correction
C_2	Empirical parameter for wake correction
C_{AW}	Added mass coefficient
C_D	Drag coefficient
C_L	Lift coefficient
C_M	Inertia coefficient
D	Outer Pipeline diameter
F_c	Vertical contact force between seabed and pipeline
F_D	Drag force
F_F	Pure Coulomb Friction
F_I	Inertia force
F_{rt}	Total lateral resistance
F_R	Passive Resistance
F_z	Lift force
g	Gravitational acceleration
H_s	Significant wave height
H_{max}	Maximum wave height during a sea state
k	Wave number
M_0	Spectral moments of order zero

n	Exponent parameter for wake correction
$r_{pen,y}$	Horizontal load reduction due to penetration
S	Site specific spreading parameter,
$S_{\eta\eta}(\omega)$	Spectral density function of sea surface elevation
S(ω)	Spectral density function of wave induced flow velocity
T_p	Peak Period
U	Free stream velocity
U_1	Oscillatory velocity
U_e	Effective velocity
U_m	Significant flow velocity
U_w	Velocity with wake velocity correction
$U_{w\theta}$	Velocity at that attack angle relative to pipeline
V_C	Current speed at pipe level
w_s	Submerged weight per unit length
z_o	Bottom roughness parameter
z_r	Reference elevation
z_p	Initial penetration depth
α	Generalised Phillips' constant.
λ	Wave length
κ_s	Constant for passive soil resistance
μ	Coefficient of friction.
θ_c	Angle between current direction and pipe.
ρ_w	Density of sea water 1 025 kg/m3.
γ_s'	Submerged unit soil weight
ω	Wave frequency
ω_p	Peak wave frequency

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Subsea pipelines also known as offshore pipelines is the pipelines that lay under the ocean which is commonly used to transport petroleum products and resources. The subsea pipelines are primarily for the transportation of the fluid from offshore platform to onshore facilities. Offshore pipelines can range in diameter from 76 mm to 1800 mm and the wall thickness of the steel pipelines range from 10 millimeters to 75 millimeters [1]. During the World War II, “Operation Pluto” the very first subsea pipelines under the English Channel to supply gasoline to the Allied armies. Operation PLUTO (Pipe Line under the Ocean) which consist of multiple pipelines stretched more than 110 km from the Isle of Wight in England to Cherbourg in France [2]. Since then offshore pipelines are constructed longer and deeper in the ocean. Hence, the integrity of the subsea pipelines is very essential in order to prevent pipeline failure.

The failure of the subsea pipelines will lead to catastrophic economic and environment damages. Recently, oil and gas company shown growing interesting on non- metallic pipeline subsea application as the alternative solution for steel pipeline replacement once the non-metallic pipeline is proven reliable.

Non-metallic pipelines have some advantage over the conventional steel pipelines which it has lighter weight, better resistance to corrosion and more flexible. Hence, non-metallic pipelines is considered to replace the common steel subsea pipeline with further research due to different in material properties. However, non-metallic pipelines has few demerits which include light weight, low collapse resistance to external pressure, and additional on-bottom stability analysis [3]. In order to benefit from the highly corrosion resistant or chemically inert thermoplastic materials in the application of pipeline, and to remedy the disadvantages of low tensile strength and low softening point, laminating glass-containing materials or glass filaments has been proposed to reinforce plastic materials, as well as thermoplastics. [4]

The reinforced thermoplastic pipeline is a non-metallic pipeline coated or laminated with reinforced layer or high strength synthetic fiber and also with an outer layer to protected the reinforcement layer. The multilayer pipeline have overall mechanical properties as strong as medium-pressure service steel pipes. The advantage of RTP is having very high impact strength compare to rigid steel pipeline. The maximum allowable temperature of RTP materials ranging from 65°C to 130°C [5]. The figure 1 shows a typical non-metallic pipeline with three layers which the inner layers for the transportation of fluid, the reinforcement layer to increase the tensile strength of the whole pipeline and also the outer layer as the protective layer of abrasion with a smooth surface.

All submarine pipelines resting on seabed are subject to the forces in both the horizontal and vertical directions due to waves and currents hydrodynamic loads. [6].Submarine pipelines are susceptible to some damages that cause by seabed mobility, waves, currents, corrosion and geography of the seabed structure too. Issues face when the subsea operation switch to non-metallic pipeline will discuss further in the following chapter.

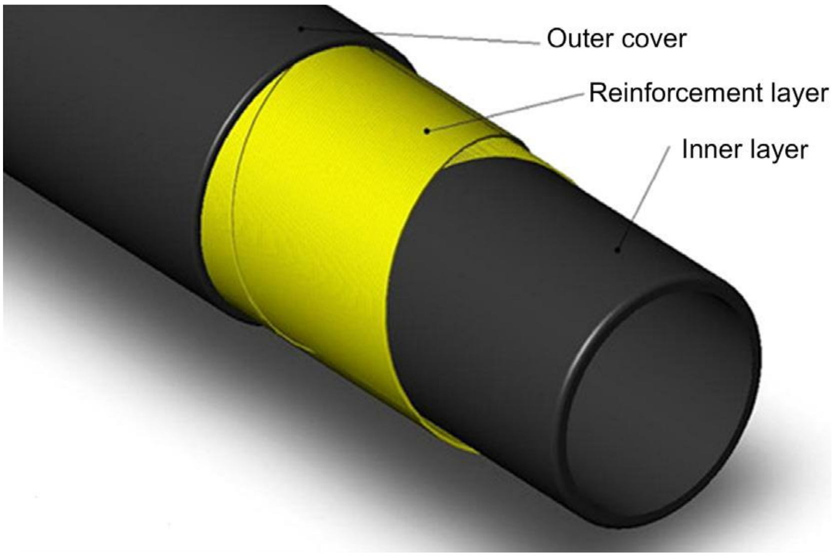

FIGURE 1. Reinforced Thermoplastic Pipe [3]

1.2 PROBLEM STATEMENT

Non-metallic pipeline is proposed to replace steel pipelines due to their resistance to corrosion. While additional cathode protection, sacrificial anode and protection coatings are required to prolong the life span of the subsea steel pipelines, thus increase the cost of the subsea pipelines. The conventional steel pipeline required high maintenance cost due to the corrosion. The non-metallic pipeline is introduce into subsea pipeline application. However, non-metallic pipeline will face stability issues during the installation and operation phase. The low density of properties of the non-metallic pipelines makes it have lighter weight than steel pipeline. When the pipeline weight per unit length is too small, the subsea pipeline could easily destabilize by the ocean waves and currents. The instability of the pipeline will then lead to large lateral displacement and eventually causing large buckling at the subsea non-metallic pipeline. Furthermore, floating may occur during the installation phase of the non-metallic pipeline due to its low density. Hence, additional anchoring or weight need to be added to reach the minimum submerged weight for the non-metallic pipelines.

1.3 OBJECTIVES

This project is aimed to reach the following objectives:

a. To develop finite element model of the non-metallic pipeline under hydrodynamic loadings.
b. To determine the minimum weight of the chain to stabilize the subsea non-metallic pipeline.

1.4 SCOPE OF STUDY

The scope of study of this project is to study the response of the subsea non-metallic pipeline due to hydrodynamic loadings will be modeled by using finite elements analysis software package ABAQUS. The minimum weight of the chain to stabilize the submarine non-metallic pipeline is determine through finite elements analysis. In this paper, DNV standards will be used to determine the minimum submerged weight for the non-metallic pipeline with chains.

The hydrodynamic loading will be assessed during the non-metallic pipeline installation phase. The dynamic lateral stability analysis of the non-metallic pipelines will be assessed during the pipelines operation and pipelines filled with seawater with combination of one year return currents with one year return waves loading. The given sea state in South China Sea will be used in this project.

CHAPTER 2

LITERATURE REVIEW

This chapter presents the literature review of non-metallic pipeline, on-bottom stability analysis methods, hydrodynamics loadings and submarine pipeline stabilization methods.

2.1 SUBMARINE NON-METALLIC PIPELINE

Non- metallic materials such as polyvinyl chloride, polypropylene, high density polyethylene, fiberglass and other materials are allowed in some of the facilities piping at onshore facilities in very restricted service condition as stated in the industrial practices [7]. Reinforced thermoplastics pipelines (RTP) applications in offshore still in its infancy in oil and gas industries. The PIPELIFE Nederland B.V. provide SOLUFORCE offshore RTP up to service temperature of 65°C and diameter of 6 inch. The SOLUFORCE offshore RTP is reinforced with steel warping to achieve higher pressure reaching 150 barg of service pressure [8]. The Figure 2 showing example of submarine pipeline on the seabed.

There are very few researches conducted experiments on of non-metallic pipeline in the oil and gas industries available in the published technical paper. The research of on-bottom stability study on conventional steel pipe start from 1960s, while the research of submarine non-metallic pipeline can only be found in recent years. One of the research is Reliability-based design of subsea light weight pipeline against lateral stability done by Yong Bai in year 2015 [9].

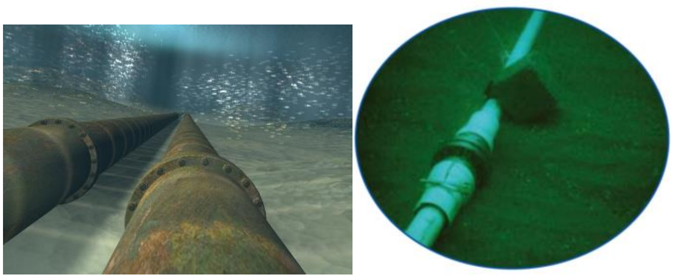

FIGURE 2. Submarine RTP on the seabed [8]

2.2 ON-BOTTOM STABILITY AND ON-BOTTOM STABILITY STUDY OF NON-METALLIC PIPELINE

Factors included in this subsea pipeline on-bottom stability are the hydrodynamics loadings due to waves and currents. The vertical stability design will assess possible pipeline sinking, resting or floatation on the seabed. The liquefaction of the soil on the seabed will directly affect the stability of the pipeline.

A study by Dunlap et al. [10] reported that extreme weather able to induce pore pressures in soft clayey sediments in the Mississippi Delta where the measuring instruments sink up to 6–14 ft. into the soil was noted during the storm, due to the reduction of soil strength caused by the hydrodynamic loading to the soil. Another study conducted by Christian et al. [11] reported that a 10-ft diameter steel pipeline in Lake Ontario has failed few times due to the section pipe floated to the surface of the soil even with a backfill of 7 ft. deep of soil over the pipeline. The failure of the pipeline is largely due to liquefaction of soil during storms. Both studies shown that even with steel pipeline which has a very high density compare to water , it’s stability still could affected by hydrodynamic loadings. The non-metallic subsea pipeline which has lower density than steel will even severely affected by waves and currents.

Currently there are no industrial standard and code for the on-bottom stability study for subsea non-metallic pipeline application in oil and gas industries. The recommended practice DNV-RP-F109, on-bottom stability design of submarine pipelines [12] by Det Norske Veritas company which was updated in 2010, provide three design methods for lateral on-bottom stability which are absolute lateral static stability method (ALSS) , generalized lateral method (GLS) and dynamic lateral stability analysis (DLS).

The generalized lateral stability method based on a sets of design curves and tables which the design will allow lateral displacement up to 10 diameters in the design sea wave’s consideration. The lateral displacement of pipe is governed by seven non-dimensional parameters. This design method allows up to a significant displacement of 10D of pipeline outer diameter, D for a virtually stable pipeline [12]. This method basically generalized from the dynamic lateral stability method.

The absolute lateral static stability method gives a static equilibrium of loadings which the resistance exerted by the pipeline is sufficient to withstand the given hydrodynamic loadings. The pipeline on the seabed will be assumed no horizontal displacement under the design wave's condition. The on-bottom stability of reinforced thermoplastic pipe done by Qiang Bai and Yong Bai [3] using absolute lateral static stability with ABAQUS to conduct the analysis. This analysis also shown that the result done by absolute method for minimum required weights are far higher than the actual experimental tests. This is because the ALSS method only allow assumption of absolute static pipeline with zero displacement.

The DLS method give out a time domain simulation model of pipe response. Dynamic lateral stability is considered to be the most extensive analysis because a comprehensive three-dimensional pipeline simulation can be modeled given random combination of waves and currents in time domain analysis[13]. The wave theories in this method is described by using JONSWAP spectrum. The JONSWAP spectrum is established back in 1973 during a joint research project [14]. An Analysis of subsea pipeline based on reliability is conducted by Hezhen Yang [15] in 2013 by using dynamic stability analysis in finite element software ABAQUS.

2.3 HYDRODYNAMIC LOADINGS

The irregular waves gave the significant wave height required in the on-bottom stability analysis was defined by using wave spectrum JONSWAP [12] as recommended in DNV-RP-F109. The current flow at the subsea pipeline may composite currents from different sources which may include tidal current, storm surge induced current, wave induced current at shallow sea, wind induced current and density driven current. The current velocity itself will be affected by type of seabed, trenching of pipeline and embedded pipeline. The sea state can be described by using the following spectral density equation with the user defined function in the finite element analysis software.

From the given sea state, the velocity at subsea pipeline level can be calculated through linear wave theory, wave directionality and wave spreading equations. The forces exerted on the pipeline can be obtain from the waves and currents velocity by using three methods of analysis the method suggested by least square-fit method, Fourier analysis and Wake II model. The Least Square-fit (LSF) method, for both horizontal and lift force is based on Morison type force equation by including inertia, drag and lift coefficients.

The LSF method was used in the model testing in Hydrodynamic Forces from Wave and Current Loads on Marine Pipelines done by M.B. Bryndum [16]. The test result from the study shown that the Morison type of lift force equation unable to predict the force precisely except at low Keulegan–Carpenter (KC) number. The KC number is a dimensionless number which is also essential for the computation of drag, inertia and lift forces. On the other hand, the research done by V.Jacobsen in year 1988 suggested that the previously conduct by using Morison type equation often failed to give a good description of the measured forces. Therefore a more precise predictions is introduced which was the Fourier analysis by using the Fourier decomposition method. The V.Jacobsen's test results also shown that the Fourier analysis able to descript the hydrodynamic forces in the condition that irregular wave superimpose with current [17].

Besides that, there is WAKE II hydrodynamic force model which can predict forces on the pipelines with high accuracy. Wake II model proposed by Soedigdo *et al.* [18] with the consideration of wake and start-up effects of waves and currents. The model is able to describe the sharp and irregular characteristic in the measured force. Moreover, the model able to produce a good prediction of the magnitude and phase for horizontal and vertical force time series. Figure 3 shows the forces acting on the pipeline for the stability study which include hydrodynamic inertia, drag and lift forces, normal reaction forces exerted by seabed and weight of the pipeline.

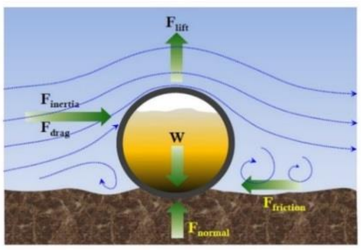

FIGURE 3. Forces Acting on Pipeline [3]

2.4 SUBSEA NON-METALLIC PIPELINE STABILIZATION METHODS

The stabilizing methods of submarine RTP also has been used in the metallic pipeline. In order to stabilize RTP on the seabed, additional weight is required to increase the pipeline weights per unit length. There are wide range of methods to stabilize RTP. The pipeline anchoring methods commonly found in the oil and gas industry are rock bolts, gravity anchor, concrete mattress, rock dumping, and chain.

The gravity anchors can be used for the whole design life for the RTP yet it is costly to manufacture and may cause local buckling of the pipeline. Rock bolts are easy to produce and install. Rock bolts also can be easily fit into variety size of RTP yet if may lead to local pipeline free span if the size of the ballast rock is too big or spacing are relatively small. [19] Furthermore, the bolts and nuts to secure the rock also required protection from corrosion in seawater. Concrete mattress not only increase the weight per unit length of the pipeline, it also allow the current flow above the pipeline smoothly. The only disadvantage of the concrete mattress is the high installation and manufacturing cost. The Figure 4 below shown the concrete mattress, rock bolts and gravity anchor methods.

Rock dumping method is using the seabed material that removed when forming the trench to cover on top of the subsea pipeline. This method maybe not reliable if soil liquefaction occur and causing the RTP destabilized. This method also sometimes causing minor to the outer layer of the pipeline. On the other hand, the upheaval buckling of the subsea is of increasing concern to the operators of flowlines in the North Sea and elsewhere [20]. Rock dumping have been used as protective measure for submarine pipeline upheaval buckling incidents in the Danish and Norwegian sectors in 1990. The protection measures such as rock dumping and concrete mattress combine with trenching of the pipe are recommended in engineering measures for preventing upheaval buckling of buried submarine pipelines by Run.L *et al.* [20]. The Figure 4 shows the rocking dumping process by using heavy machinery.

In most of the cases, permeable seabed, pipe penetrating the seabed and trenching also able to increase the stability of the subsea pipeline by reducing the hydrodynamic loading on the pipeline. For the alternative stabilization method, chain is used for temporary stabilized the subsea non-metallic pipeline during the hook up and installation period. The chain will increase the weight of the pipeline per unit length to prevent floatation. Other stabilization method will be used to stabilize the pipeline as the permanent solution after the commissioning. For this project, chain will be used as the anchoring method to increase the weight per unit length of the pipeline.

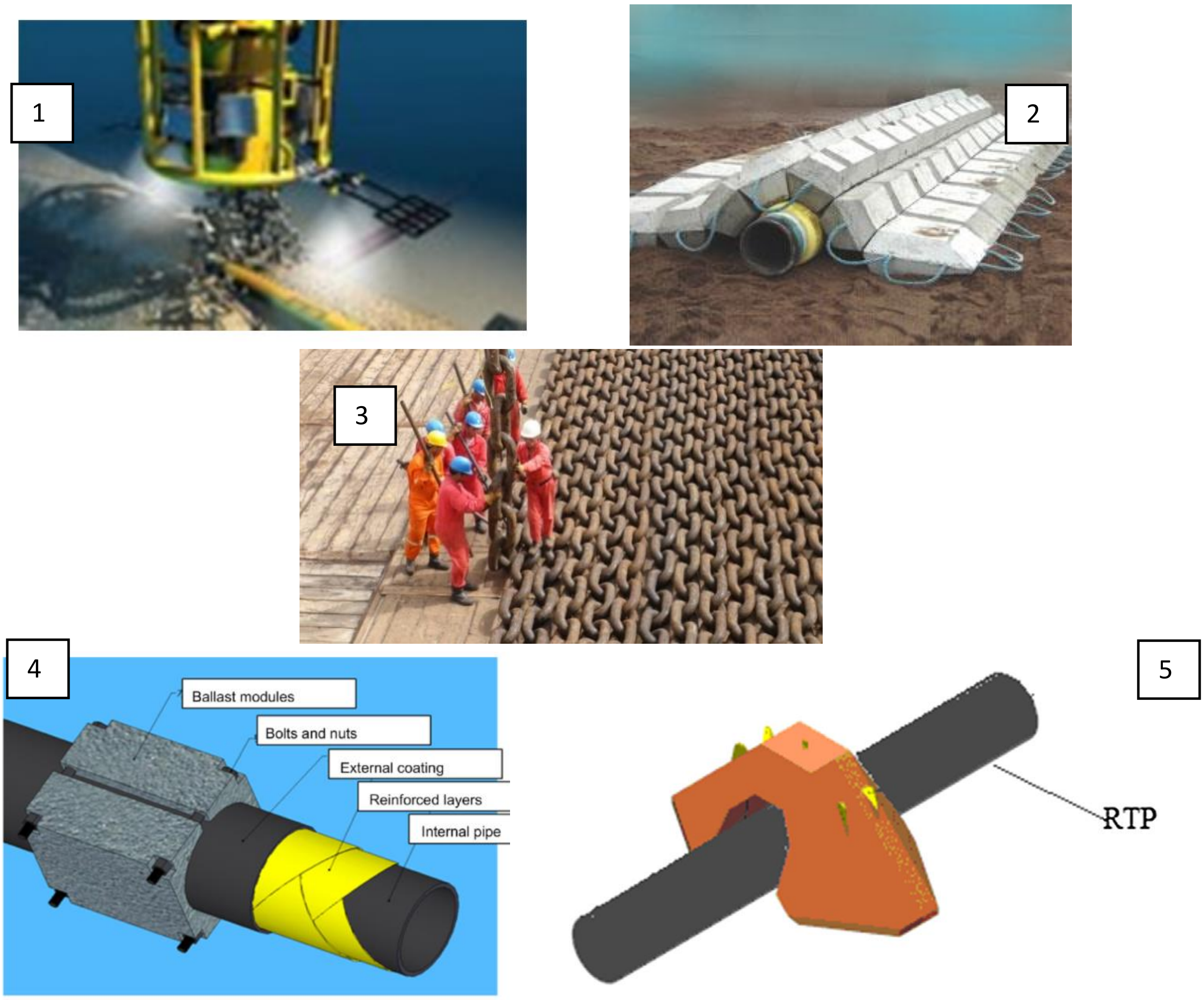

FIGURE 4. Offshore RTP anchoring methods (1-rock dumping, 2- concrete mattress, 3-chain, 4-rock bolts and 5-gravity anchor) [3]

2.5 CRITICAL ANALYSIS

All the on-bottom stability analysis methods described above are established based on steel pipeline. There is currently no industries standards available for the application of submarine non-metallic. However, these industries standards for on-bottom stability study is applicable to non-metallic pipeline as well in most aspects. The variable between steel metal to non-metallic is the mechanical properties which then will affect coefficients for loadings which include Coulomb friction between pipe-soil interactions, drag, lift and inertia coefficient in this project. Assumptions and adjustments of these coefficient in this project are different accordingly with the consideration of the non-metallic pipeline surface roughness.

Among all the three on-bottom stability design approaches which recommended by DNV practices, the dynamic lateral stability analysis is chosen for this research because the design methods take consideration of the random wave theories in the time domain simulation given a complete sea state. The dynamic lateral stability methods is not commonly used and replace the simplified methods in the industries due to limitation of the software availability decades ago. There are several commercial finite element software in the industries, such as ABAQUS and ANSYS. The ABAQUS software was chosen due to its ability to perform nonlinear analysis [21] and user defined function tools.

From the related works available in the literature shown in the table 1 that the research regarding computer aided on-bottom stability study of submarine metallic was started since the 1980s. Over 30 years the research works on the on-bottom stability study is still active due to the complexity of the stability issues. The variation between different oceans, locations, type of seabed, depth can affect the result of the stability study. Moreover, the interactions between pipe-soil, wave-soil and wave-pipe further increase the complexity of the stability study. From the literature of the related research, the on-bottom stability study for the non-metallic subsea pipelines can be found in literature materials from year 2013 onward. The on-bottom stability for non-metallic pipelines coated with concrete was first introduced by Bai et al. in 2014[5]. The related work with non-metallic pipeline on-bottom stability study is tabulated in the Table 1.

2.6 RELATED WORK

The project is focused on analyzing and comparing the related literatures design method, types of pipelines, finite element software used in the research and the anchoring method to stabilize the submarine pipelines.

TABLE 1. Literature of the related work

No	Author	Year	Title	Design Method	Materials	Software	Anchoring
1	K. Holthe and T. Sotberg, SINTEF, and J.C. Chao, Exxon Production Research Co. [22]	1987	An Efficient Computer Model for Predicting Submarine Pipeline Response to Waves and Current		Metallic	ABAQUS/ PONDUS	
2	T. Elsayed , H. Leheta & A. Yehya [23]	2012	Reliability of subsea pipelines against lateral instability	Absolute Lateral Static Stability	Metallic	ANSYS	Concrete Coating
3	Hezhen Yang & Aijun Wang [15]	2013	Dynamic stability analysis of pipeline based on reliability using surrogate model	Dynamic Lateral Stability	Metallic	ABAQUS	-
4	Qiang Bai, Yong Bai [3]	2014	30 - On-Bottom Stability of RTP, in Subsea Pipeline Design, Analysis, and Installation	Absolute Lateral Static Stability	Non-metallic	ABAQUS	Rock Dumping, Concrete Mattress, gravity anchors et. al
5	Yong Bai, Jiandong Tang, et al. [9]	2015	Reliability-based design of subsea light weight pipeline against lateral stability	Dynamic Lateral Stability	Non-metallic	ABAQUS	Concrete Coating
6	Yinghui Tian, Mark J. Cassidy, Chee Khang Chang [12]	2015	Assessment of offshore pipelines using dynamic lateral stability analysis	Dynamic Lateral Stability	Metallic	ABAQUS	-

CHAPTER 3

METHODOLOGY

3.1 METHODOLOGY

After reviewing three different on-bottom stability design approaches by DNV-RP-F109 [8] , dynamic lateral stability analysis is selected approaches for the non-metallic pipeline stability study. This is due to both ALSS and GLS methods will resulting a much larger required submerged weight for the non-metallic pipeline compare to DLS method. In this on-bottom stability analysis, the waves conditions in the given irregular sea state is calculated by using numerical wave theories of JONSWAP spectrum and Airy wave theory. The hydrodynamic loadings will be calculated by using WAKE II model. The calculation of the wave spectrums, theories and forces will be done in MATLAB.

The finite element analysis of the displacement of the non-metallic pipeline due to hydrodynamic loadings will be carry by using ABAQUS software. The project started with collecting the related work of regarding non-metallic pipeline, submarine pipeline and on-bottom stability study. The software required in the project such as Microsoft word, MATLAB and ABAQUS is prepared and installed. Next, finite element analysis will be carry out in ABAQUS with the assist of MATLAB.

The analysis will be carried out for on-bottom stability for pipeline during operations with one year return currents with one year return wave. The wave attack angle and current attack angle of 90 degree will be considered for both conditions. The simulation or one hours of irregular waves. The simulations will carry out repeatedly with few iterations to ensure the reliability of the result. The comparative analysis will be done by conducting the simulations given the conditions in the case study of previous work. The result produced will be compared with the result of the previous work to ensure the analysis method result consistency and accuracy. The flow of project methodology is shown in Figure 1. The schedule and planning of activity for this project is shown in Appendix A.

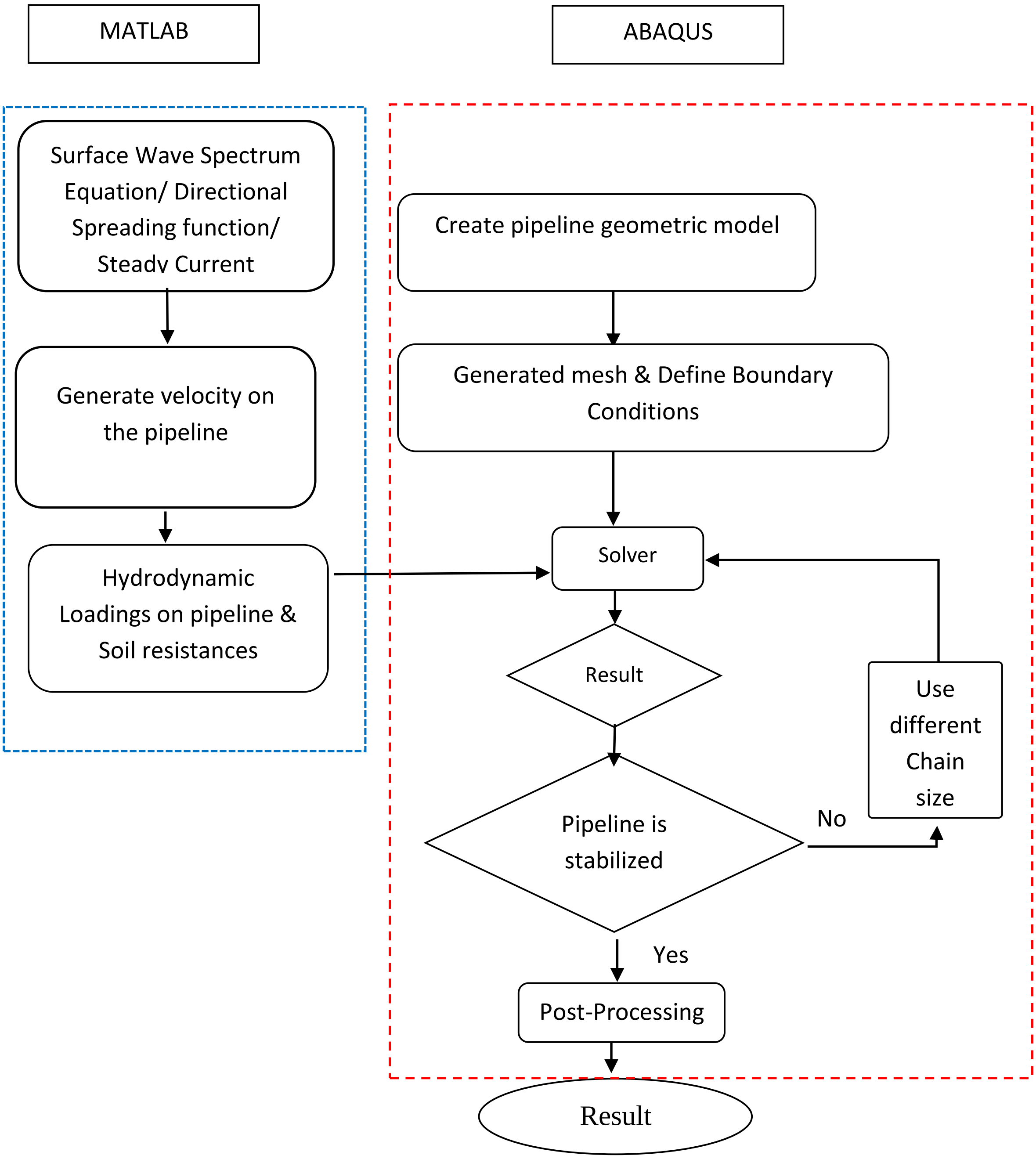

FIGURE 5. Project flow chart.

3.2 NON-METALLIC PIPELINE

The non-metallic pipeline (NMP) used in this project is reinforced composite thermoplastic pipeline from AIRBORNE Company. Figure 6: shows the cross section of non-metallic pipeline used in this project with three layers of polymer with different thickness.

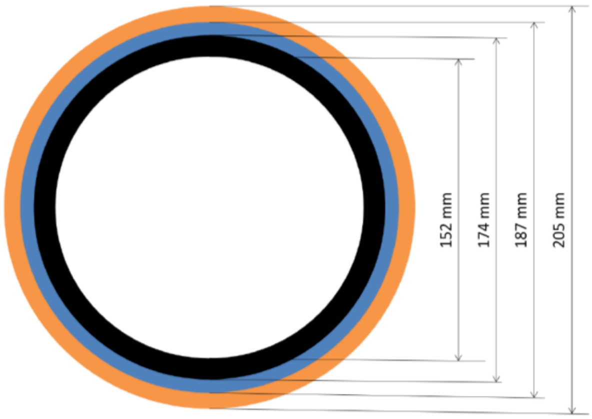

FIGURE 6. Non-Metallic Pipeline by AIRBORNE

Specifications:	
Inside Diameter	: 0.152 m
Outer Diameter, D	: 0.205 m
Cross Sectional Area	: 14848 mm^2
Length	: 400.0 m
Inclination	: 0^o
Empty Weight in air (total)	: 16.9 kg/m
Weight Full of Sea Water in air	: 35.357 kg/m
Weight Full of Sea Water in Sea Water	: 1.588 kg/m
Bulk Modulus	: 2.7 GPa
Poisson Ratio, ν	: 0.4
Young's Modulus, E	: 1.1 GPa
End conditions	: Fixed
Allowable Lateral Displacement (for 400m)	: 10 m
Surface roughness	: 7µ
Type of Each layer:	
Outer (Jacket)	: Polyamide (PE) 11 mm
Middle (Structural Layer)	: Glass Fiber/Polyethylene 6.5 mm
Inner (Liner)	: Polyamide (PE) 8 mm

*Assumed no marine growth at the outer layer of the pipeline
Complete data sheet for this pipeline is attached in Appendix B.

3.3 ENVIRONMENTAL DATA & PIPE-SOIL INTERACTION

The ocean environmental data is retrieved from one of the platform in South China Sea for the waves and currents design criteria. The significant wave height and peak period which are the importance for the calculation of on-bottom stability study can be retrieved from this ocean data.

The interaction between pipe-soil on the seabed can contribute to load reduction in several ways. In this project, only pure Coulomb friction part, F_F and passive resistance F_R due to initial penetration are included.

Load reduction due to penetration, $r_{pen,y}$ from DNV-RP-F109,

$$r_{pen,y} = 1.0 - 1.4 \times \frac{z_p}{D} \qquad \text{(Equation 3.1)}$$

Where,

D = Outer diameter

z_p = penetration depth

Total lateral resistance, [24]

$$F_{rt} = F_F + F_R \qquad \text{(Equation 3.2)}$$

Where,

Coulomb Friction F_F,

$$F_F = \mu(W_S - F_z) \qquad \text{(Equation 3.3)}$$

Where,

μ = Coefficient of friction

w_s = Submerged weight per unit length

F_z = Lift force

Passive friction on sand F_R,

$$\frac{F_R}{F_C} = \begin{cases} \left(5.0 \cdot \kappa_s - 0.15 \cdot \kappa_s^2\right) \cdot \left(\frac{z_p}{D}\right)^{1.25} & \text{if } \kappa_s \leq 26.7 \\ \kappa_s \cdot \left(\frac{z_p}{D}\right)^{1.25} & \text{if } \kappa_s > 26.7 \end{cases}$$ (Equation 3.4)

(Equation 3.5)

$$\kappa_s = \frac{\gamma_s' \cdot D^2}{w_s - F_Z} = \frac{\gamma_s' \cdot D^2}{F_C} \quad , \quad F_C = w_s - F_Z$$

Where the initial penetration on sand can be taken as,

$$\frac{z_p}{D} = 0.037 \times \kappa_S^{-0.67}$$ (Equation 3.6)

Where,

κ_s = Constant for passive soil resistance

γ_S' = Submerged unit soil weight

There are few assumptions made for this section which are:

1. Pipeline in the installation phase and hence only one year return waves and currents are considered
2. Waves and currents heading are acting perpendicular to the pipeline
3. Density of the seawater, ρ_w = 1025 kg/m^3
4. Sea State period is one hour
5. Seabed topography is assumed flat infinite surface
6. The total penetration is assumed as 0.2D
7. The seabed is impermeable after the initial penetration
8. No trenching, penetration due to dynamics during laying and embedment due to pipe movement
9. The type of seabed here is medium sand with grain size 0.5 mm
10. The site specific spreading parameter, s for South China Sea is assumed as 4, range 6 to 8 may use in the North Sea

Ocean Data:	
Wind Speed	: 19 m/s
Significant Wave Height, Hs	: 2.69 m
Peak Period, T_p	: 7.9 s
Maximum Wave Height, H_{max}	: 4.84 m
Current Speed V_c (At 0.5D)	: 1.11 m/s
Directionality	: 90^o
Sea State Period	: 3600 s
Water Depth, d	: 75 m
Peak Enhancement Factor, γ	: 1.2346
Added mass coefficient, C_{AW}	: 0.25
Drag coefficient, C_D	: 1.0
Lift coefficient, C_L	: 1.0
Inertia coefficient, C_M	: 2.5
Seabed:	
Submerged Unit Soil Weight, γ_S'	: 10000 N/m^3
*Typical γ_S' value for sand, 7000 (very loose) to 13500 N/m^3 (very dense)	
Coefficient of friction, μ	: 0.5
*General value for friction coefficient of polymer to sand is 0.3 to 0.5	
Initial penetration, z_p	: 0.041 m
Roughness, z_0	: 4x10^{-5}
Refer to Appendix C	

3.4 WAVES AND CURRENTS THEORY, SPECTRUM AND KINEMATICS

The interaction between the wave and current is commonly non-linear and irregular in nature. The Joint North Sea Wave Observation Project (JONSWAP) include the factor of the continuous developing wave spectrum through non-linear and wave-wave interaction by adding an extra peak enhancement factor gamma, γ into Pierson-Moskowitz spectrum (Hasselmann et al. 1973.)

JONSWAP, spectral density function of the sea surface elevation is given by:

$$S_{\eta\eta}(\omega) = \alpha \cdot g^2 \cdot \omega^{-5} \cdot \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) \cdot \gamma^{\exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma\cdot\omega_p}\right)^2\right)}$$

(Equation 3.7)

The Generalised Phillips' constant is given by:

$$\alpha = \frac{5}{16} \cdot \frac{H_s^2 \cdot \omega_p^4}{g^2} \cdot (1 - 0.287 \cdot \ln \gamma)$$ (Equation 3.8)

The spectral width parameter is given by:

$$\sigma = \begin{cases} 0.07 & if\ \omega \le \omega_p \\ 0.09 & else \end{cases}$$ (Equation 3.9)

In lieu of other information, the peak-enhancement factor may be taken as:

$$\gamma = \begin{cases} 5.0 & \varphi \le 3.6 \\ \exp(5.75 - 1.15\varphi) & 3.6 < \varphi < 5.0; \\ 1.0 & \varphi \ge 5.0 \end{cases} \quad \varphi = \frac{T_p}{\sqrt{H_s}}$$

(Equation 3.10)

Where,

$S_{\eta\eta}(\omega)$ = Spectral density function of sea surface elevation

H_s = Significant wave height

G = Gravitational acceleration

T_p = Peak Period

ω = Wave frequency

ω_p = Peak wave frequency

The wave induced velocity spectrum at the sea bed is derived from sea surface elevation by multiplied with transfer function G (ω),

Wave induced velocity spectrum $S(\omega) = G^2(\omega).S_{\eta\eta}(\omega)$ (Equation 3.11)

Significant flow velocity amplitude at pipe level (Equation 3.12)

$$U_m = 2\sqrt{M_0}$$

The transfer function, G

$G(\omega) = \frac{\omega}{\sinh(k.d)}$ (Equation 3.13)

Where,

d = Water depth

k = Wave number

The spectral moments of order zero, M_o

$M_0 = \int_0^\infty \omega. S(\omega) d\omega$ (Equation 3.14)

By substitute (Equation 3.11, 3.13 and 3.14) from DNV RP-F109 into (Equation 3.12)

Significant Wave Velocity, U_m

$U_m = 2\sqrt{\int_0^\infty \frac{\omega^2}{sinh^2(kd)} S(\omega) d\omega}$ (Equation 3.15)

The Airy wave theory or as known as linear wave theory which is suitable for the modelling of random sea states giving the high accuracy of the wave kinematics prediction. This theory produces a linearized description of the propagation of waves due to gravity. In this theory, the fluid flow is assumed as incompressible, irrotational and inviscid.

Airy Wave Theory,

Wave number, $k = \frac{2\pi}{\lambda}$ (Equation 3.16)

$wavelength, \lambda = T\sqrt{gd}$ (Equation 3.17)

$Angular\ frequency, \omega = \frac{2\pi}{T}$ (Equation 3.18)

By substitute Airy wave theory (Equation 3.16 to 3.18) into (Equation 3.15)

The Significant Wave Velocity, U_m also equal to

$$U_m = 2\sqrt{\int_0^\infty \frac{\omega^2}{sinh^2\left(\frac{d}{\sqrt{gd}}\times\omega\right)} S(\omega)d\omega} \qquad \text{(Equation 3.19)}$$

The Wake II Model which proposed by Soedigdo et al. in 1999 [18] include the flow history effect which is also known as wake effects into the prediction of effective velocity on the submarine pipelines surface. Effective velocity is the summation of steady current velocity on the pipelines level and significant wave velocity with the wake velocity correction as shown in the following equations. Figure 7 below illustrate the wake on the pipeline produce by waves from Wake II model.

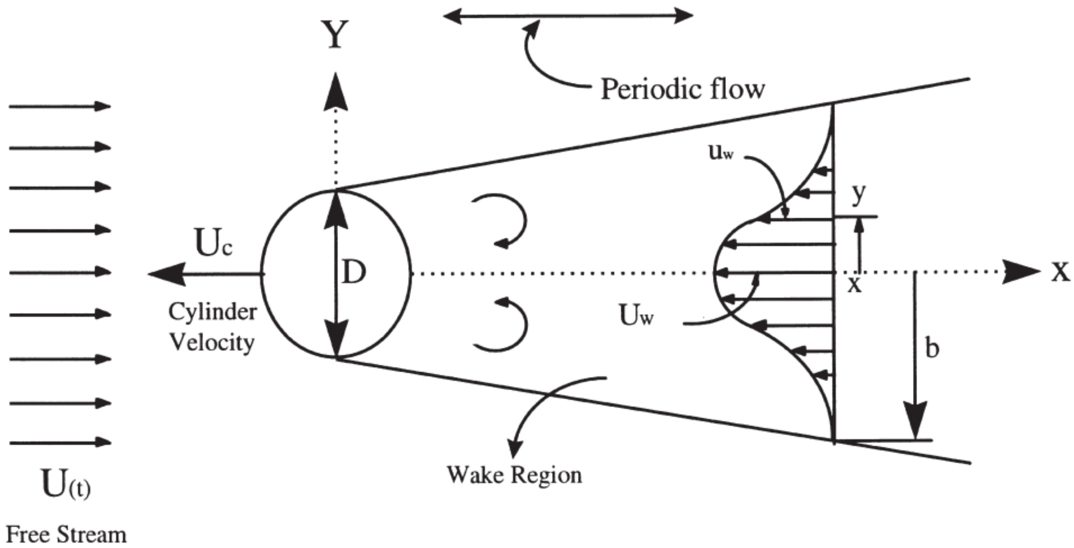

FIGURE 7. Velocity flow on pipeline on the seabed [18]

Effective velocity, $U_e(t) = U(t) + U_w(t)$ (Equation 3.20)

Where Wake velocity correction,

$$U_w(t) = \frac{\sqrt{\pi} erf\left(\frac{1}{2} C_2 \sin^n(\omega t + \phi)\right) U_m C_1}{C_2} \qquad \text{(Equation 3.21)}$$

Total ambient velocity or free stream velocity,

$$U(t) = V_c + U_1(t) \qquad \text{(Equation 3.22)}$$

Where,

C_1 = Empirical parameter for wake correction from figure 8

C_2 = Empirical parameter for wake correction from figure 8

n = Exponent parameter for wake correction from figure 8

V_C = Current speed at pipe level

U_1 = Oscillatory velocity

U_m = Significant flow velocity

Ø = phase angle from figure 8

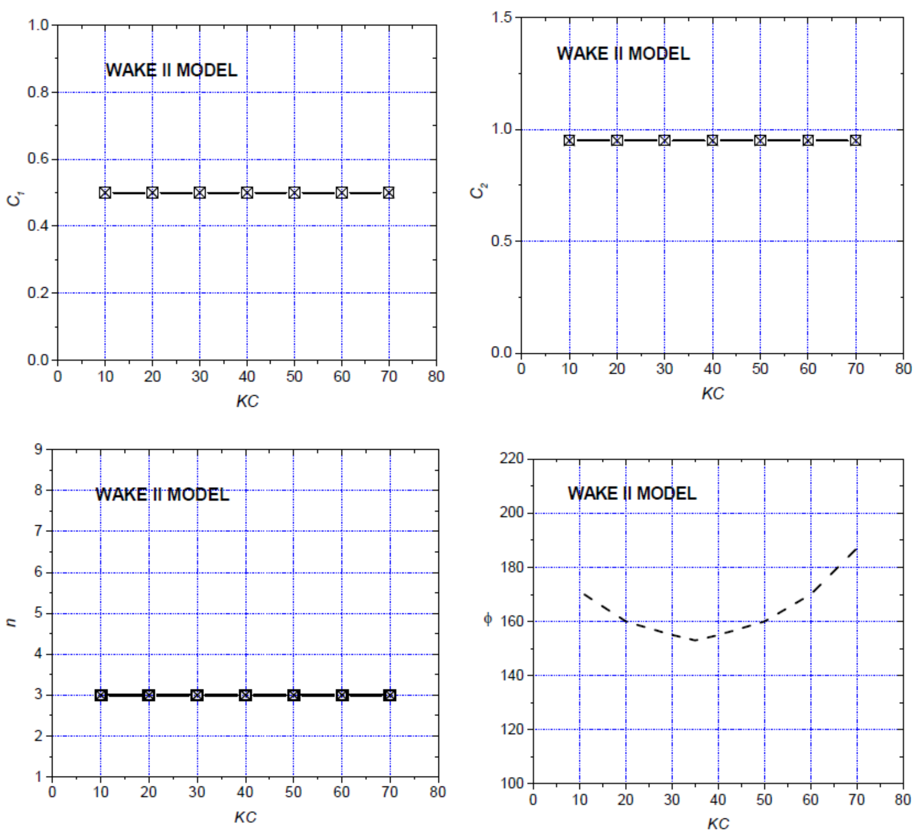

FIGURE 8 Coefficient of C_1, C_2, n and Ø [18]

Steady velocity, V_c which is also the steady current at pipe level.

Mean perpendicular current velocity over a pipe diameter

$$V_c = V_c(z_r) \cdot \left(\frac{\left(1 + \frac{z_0}{D}\right) \cdot \ln\left(\frac{D}{z_0} + 1\right) - 1}{\ln\left(\frac{z_r}{z_0} + 1\right)} \right) \cdot \sin\theta_c$$

(Equation 3.23)

Oscillatory velocity, $U_1(t) = U_m sin(\omega t)$ (Equation 3.24)

Where,

z_o =Bottom roughness parameter

z_r =Reference elevation

The wave speed reduction due to main wave directionality and wave spreading can be taking into account for calculation of significant flow velocity. The flow velocity is multiplied by a reduction factor R_D as shown in the equation (3.25) which retrieved from DNV RP-F109. The reduction factor R_D can be selected from Figure 9 based on the site specific spreading parameter, s and also the relative angle between wave and pipe. There is also load reduction due to pipe penetration into seabed. The load reduction factor equation is shows below as equation 3.26 and 3.27.

$U_w = R_D \times U_{w\theta}$ (Equation 3.25)

Where,

R_D = Load reduction factor

U_w = Velocity with wake velocity correction

$U_{w\theta}$ = Velocity at that attack angle relative to pipeline

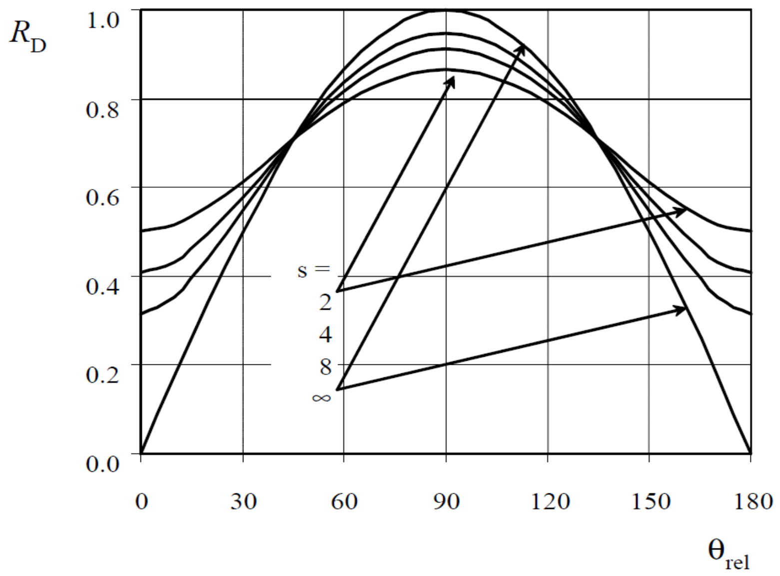

FIGURE 9. Reduction factor due to wave spreading and directionality [11]

$$r_{pen,y} = 1.0 - 1.4 \cdot \frac{z_p}{D} \quad \text{however} \quad \geq 0.3 \qquad \text{(Equation 3.26)}$$

$$r_{pen,z} = 1.0 - 1.3 \cdot \left(\frac{z_p}{D} - 0.1 \right) \quad \text{however} \quad \geq 0.0 \qquad \text{(Equation 3.27)}$$

3.5 HYDRODYNAMIC LOADINGS

The hydrodynamic loadings equation shown below from equation 3.28 to 3.30 total horizontal forces is the summation of drag and inertia forces. The lift force is the vertical forces. These force equations are retrieved from by Soedigdo *et al*. [18].

Drag force, $F_D = 0.5\rho_w D C_D |U_e| U_e$ (Equation 3.28)

Lift force, $F_z = 0.5\rho_w D C_L {U_e}^2$ (Equation 3.29)

Inertia force, $F_I = \frac{\pi D^2}{4} \rho_w [C_M \frac{dU}{dt} - C_{AW} \frac{dU_w}{dt}]$ (Equation 3.30)

Where,

U_e	= Effective velocity
ρ_w	= Density of sea water 1 025 kg/m3.
C_{AW}	= Added mass coefficient
C_D	= Drag coefficient
C_L	= Lift coefficient
C_M	= Inertia coefficient

3.6 TECHNICAL COMPUTING SOFTWARE – MATLAB

MATLAB R2015a software as shows in Figure 10 is used for all solving and calculation in this project. The curves generated by MATLAB will present in the Chapter 4. The complete coding of MATLAB is attached in Appendix F.

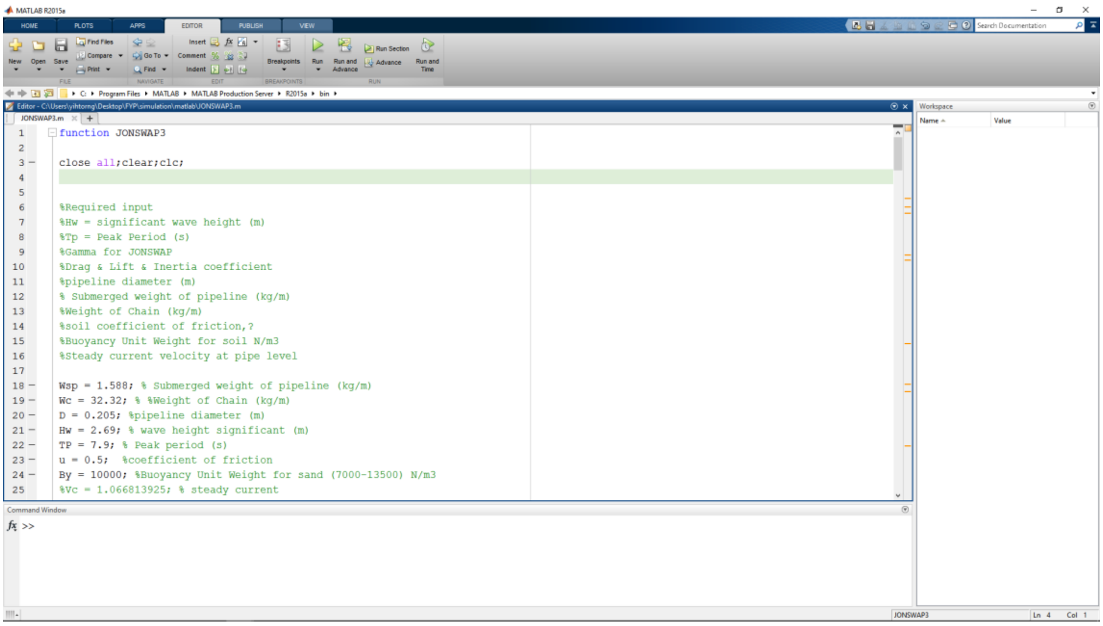

FIGURE 10 MATLAB R2015a

3.7 FINITE ELEMENT SOFTWARE-ABAQUS

The finite element software use in this project is Abaqus/CAE 6.13-1. Abaqus is suitable to carry out finite element analysis on on-bottom stability study of pipeline because it is able to perform non-linear analysis.

The submarine NMP is modeled in 3D planar with deformable pipe base feature in 50 m long. The beam element PIPE31H is assigned to the pipeline with the given pipeline profile of pipe radius and pipe thickness. The general and mechanical properties of the non-metallic is then assigned to the beam element. The original full sized pipeline length is 400 m. The boundary conditions at the both pipe end will be pinned which only allow rotational.

The chain size selected is 32.32 kg/m, the downward force of the pipeline will become 332.52 N/m. Horizontal force and soil resistance is applied to the pipeline as show in the Figure 12 and 13 respectively.

Input Parameters:

Pipe: Internal diameter ID: 0.152 m Outer diameter OD: 0.205 m Length: 50 m
Material properties: Density: 1138.20 kg/m^3 Young's modulus = 1.1 GPa Poisson Ratio = 0.4
Meshing (as shows in Figure 10) : Element type: C3d8r Mesh size: 0.029 No. of elements: 137920
Loads: Drag & Inertia force(U1 axis): 215.1N/m in form of surface traction Soil resistance (U1 axis): 87.85 N/m in form of surface traction
Boundary condition: Pinned (as shows in Figure 11)
Condition: Pipeline filled with seawater at water depth 75m

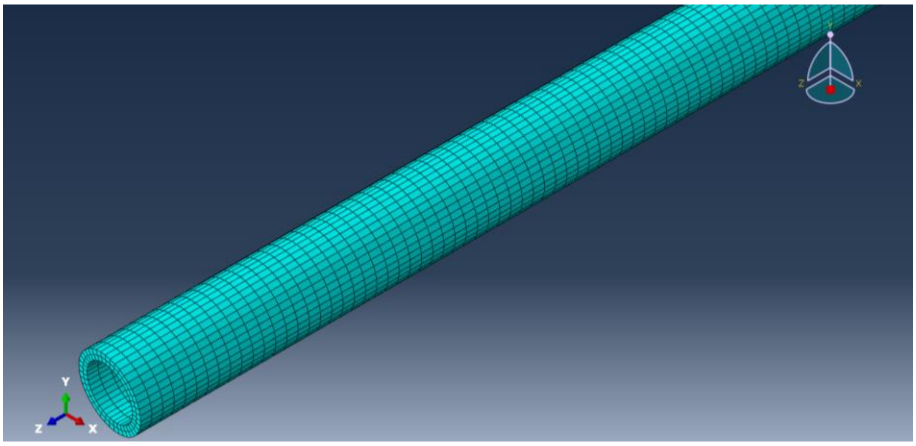

FIGURE 11 Pipeline meshing

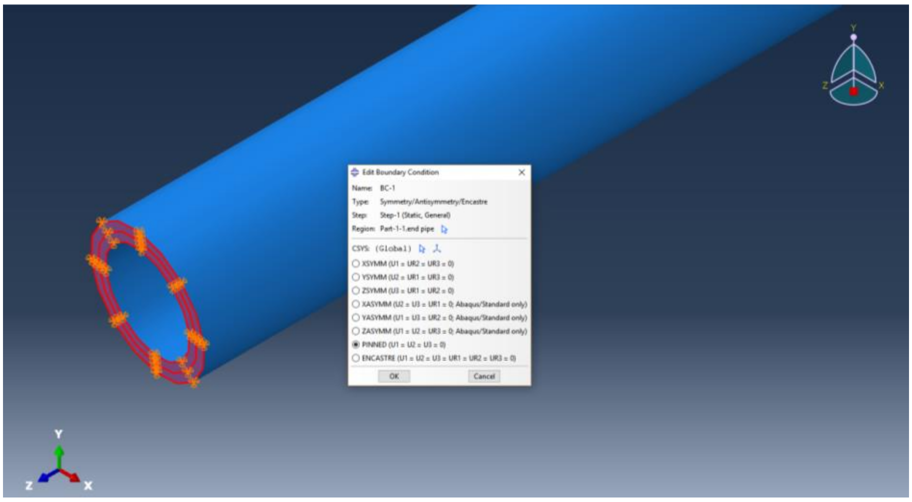

FIGURE 12 Both end pipe boundary conditions

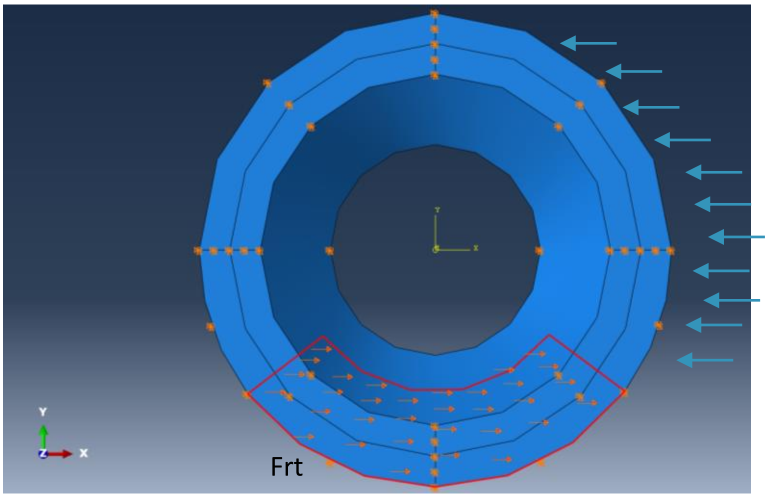

FIGURE 13 Soil resistance as surface traction on the pipeline

CHAPTER 4

RESULTS AND DISCUSSION

4.1 HYDRODYNAMIC LOADINGS AND FORCES

The following curves are generated by using MATLAB R2015a. Since only one hour sea state is consider in the design parameter, the time series curves is generated until 3600 seconds. Figure 14 shows the randomness fluanction of the sea surface over a time period generated with given environmental data. Figure 15 shows the time series of significant flow velcoity at the pipeline level which peak at 2361 seconds with 0.6747 m/s. Figure 16 shows the time series for free stream velocity which also known as ambient velocity which peak at 2570 seconds with 1.646 m/s. Figure 17 shows the time series for wake velocity generated at the pipeline which peak at 1964 seconds with 0.3028 m/s. Figure 18 and 19 shows the time series for effective velocity exerted on the pipeline which peak at 2361 seconds with 1.451 m/s.

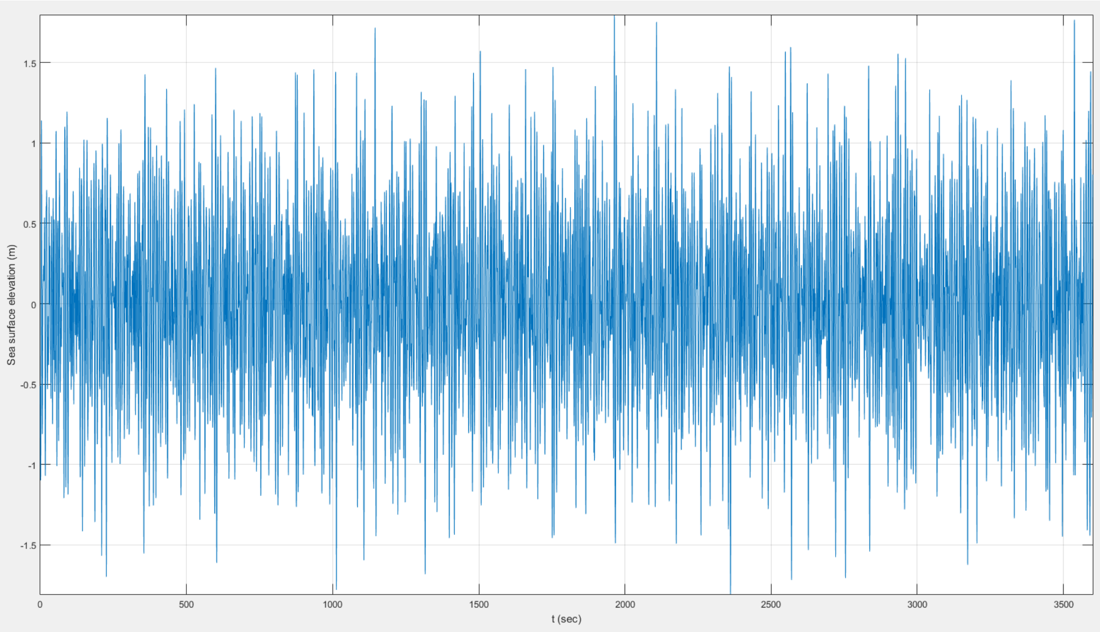

FIGURE 14 Time Series for sea surface elevation

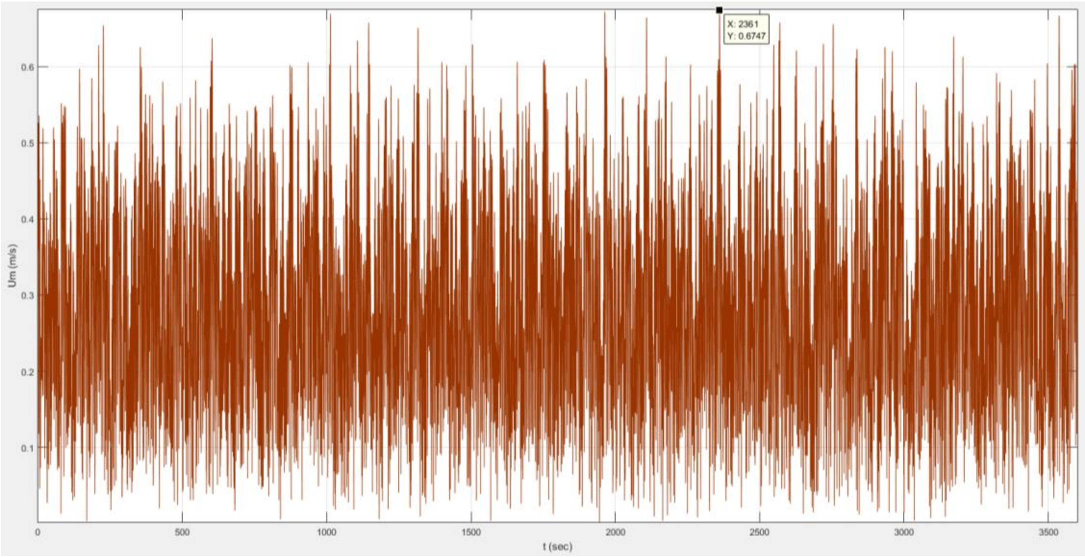

FIGURE 15 Time series of significant wave velocity

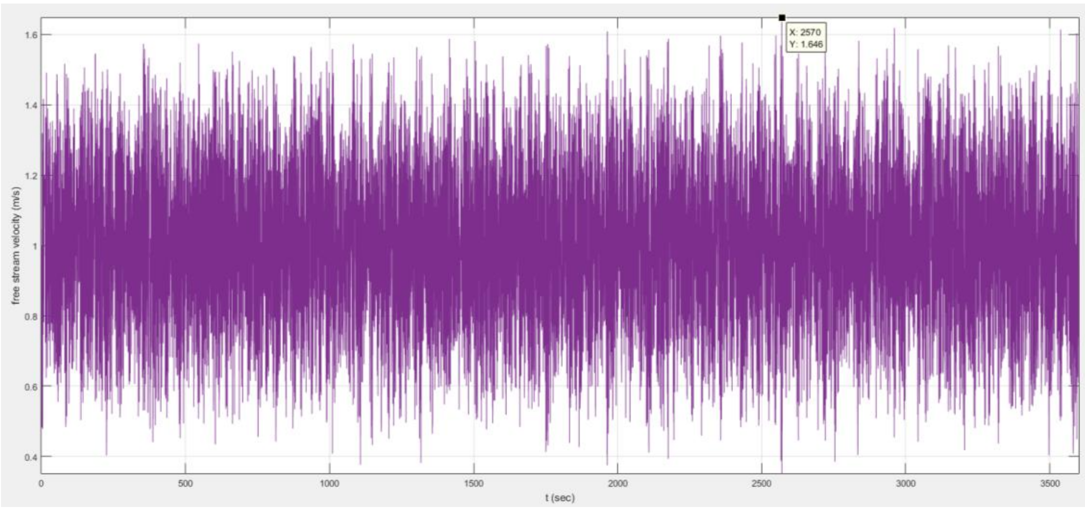

FIGURE 16 Time series of free stream velocity

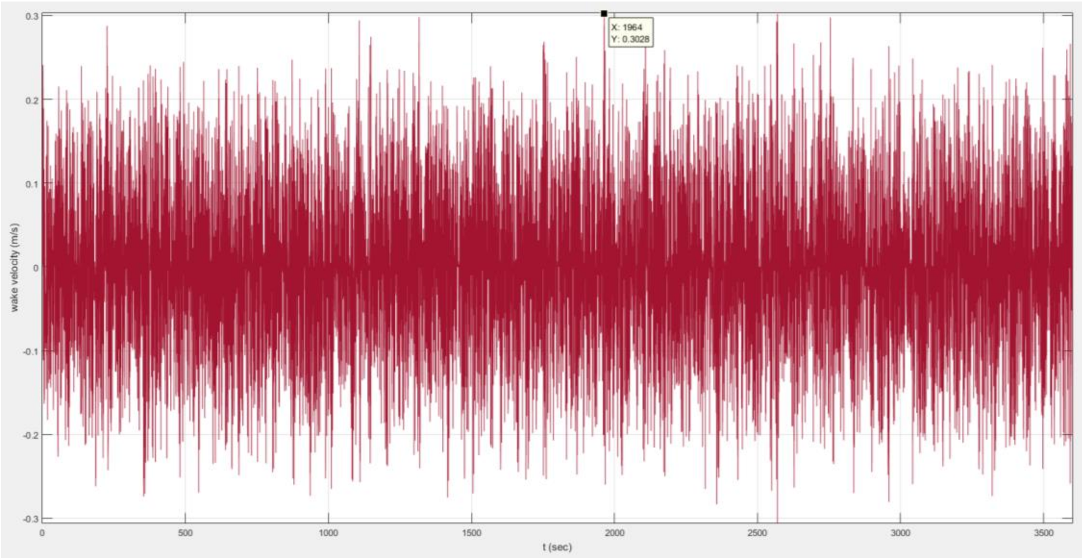

FIGURE 17 Time series for wake velocity

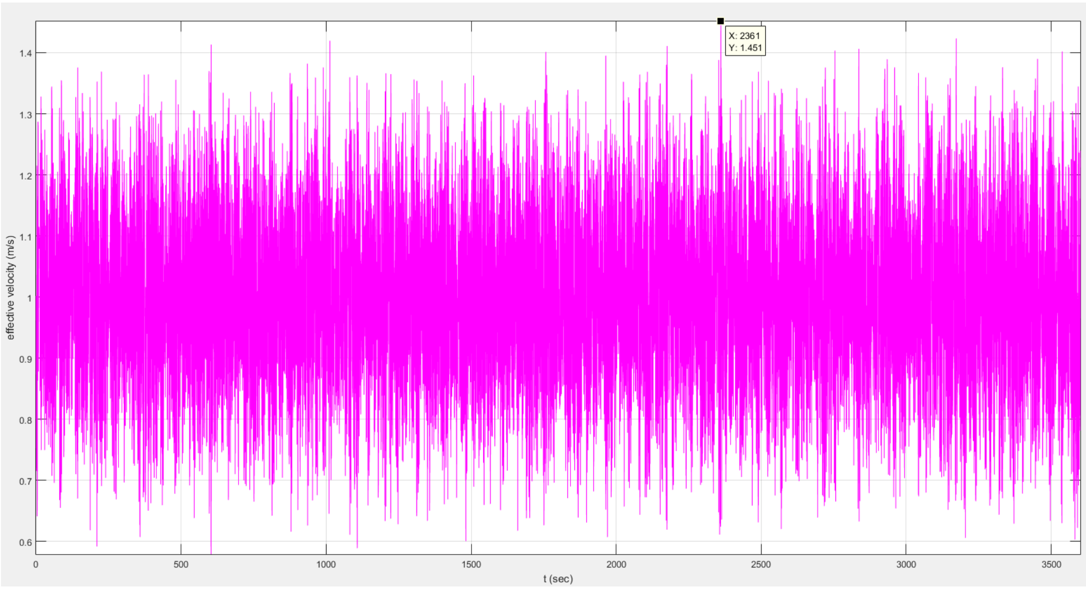

FIGURE 18 Time series for effective velocity

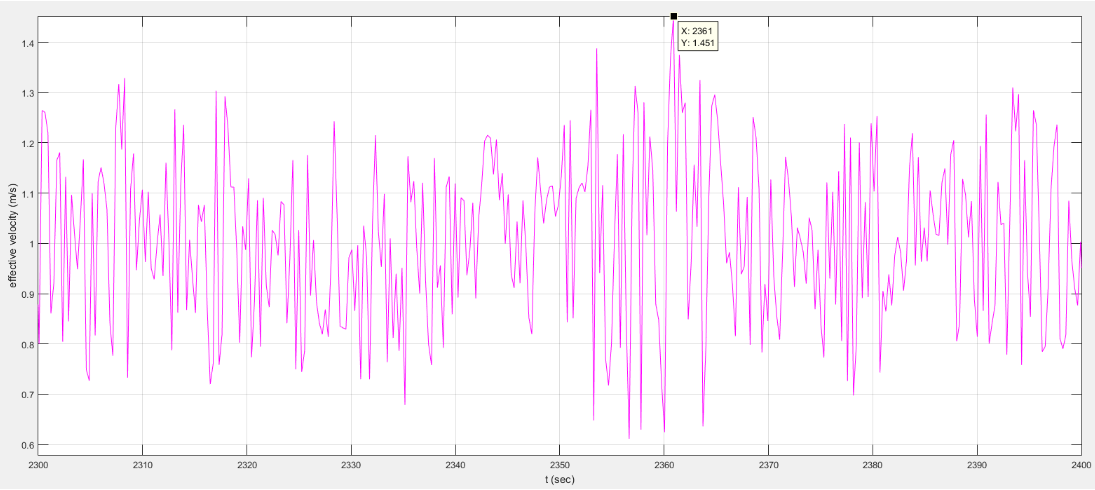

FIGURE 19 Time series for effective velocity from 2300 to 2400 seconds

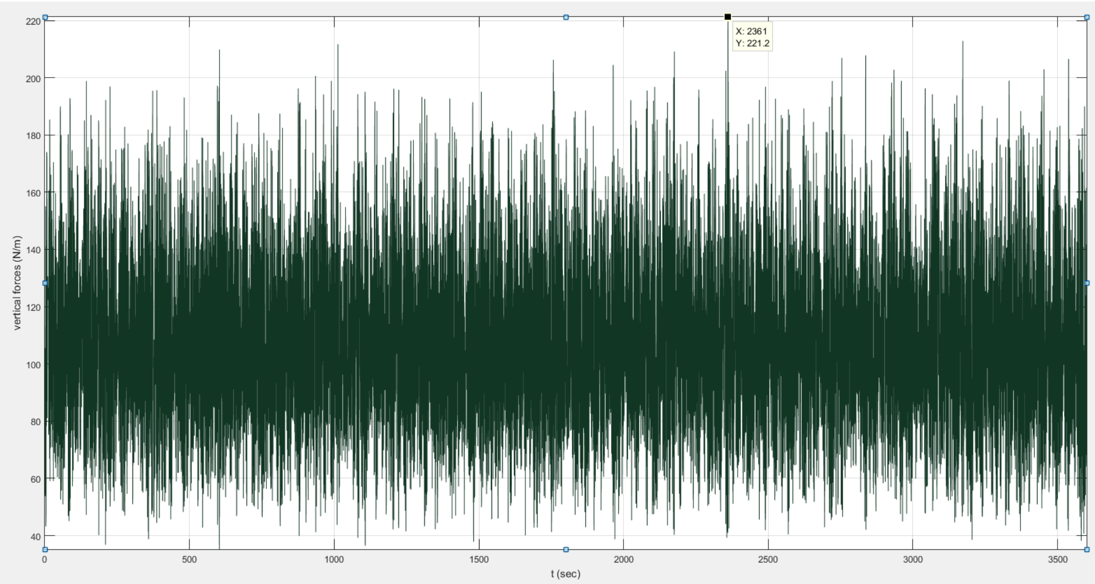

FIGURE 20 Time series for vertical forces

The peak of lift force is 221.2 N/m at 2361 seconds which is lower than the downward forces due to weight of the pipeline and chain 332.52 N/m as mention in the section 3.7. The resultant vertical forces is 112.324 N/m with downward direction, hence no floatation will occur in this condition. The resultant vertical forces can assumed equal to the normal force from the seabed. Hence, vertical forces can be excluded from the ABAQUS simulation.

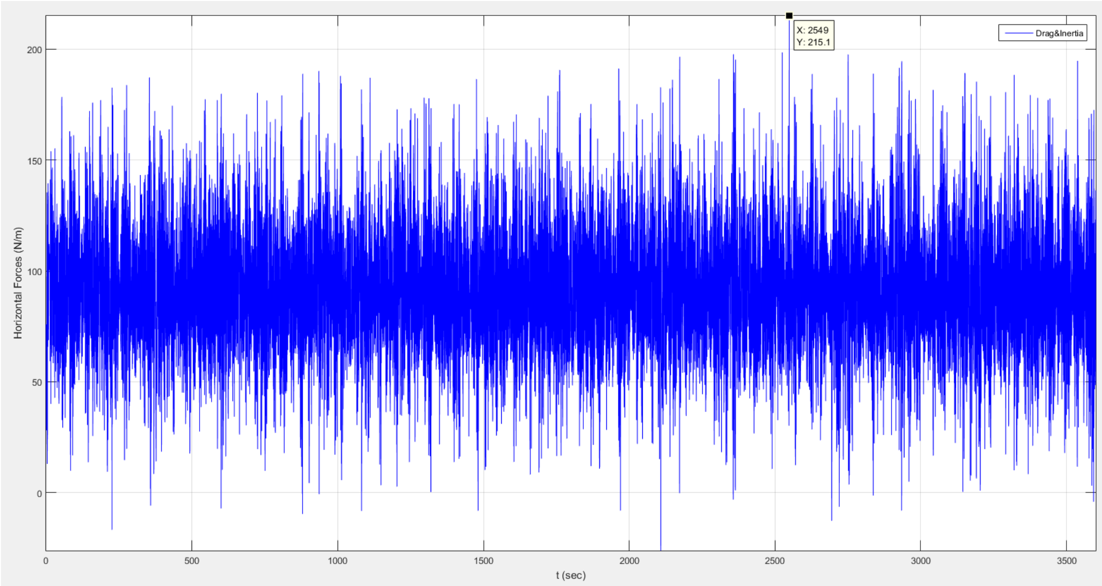

FIGURE 21 Time series for horizontal forces

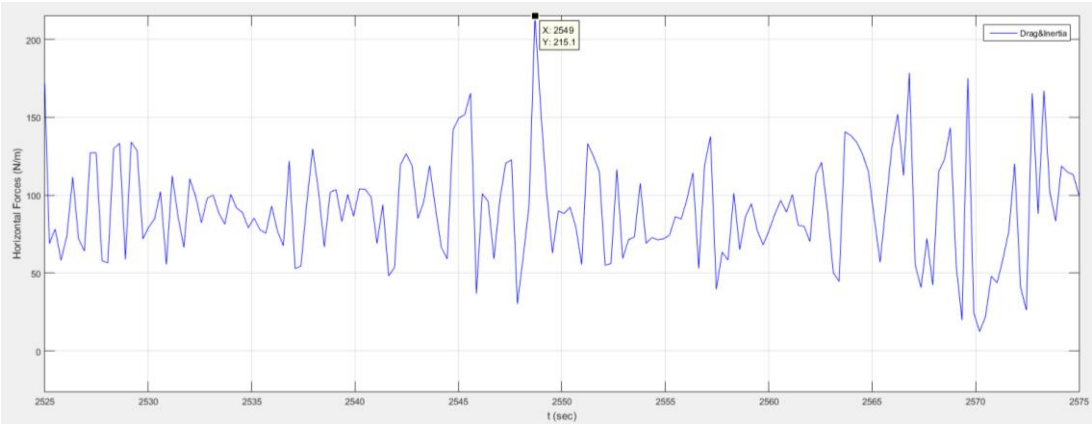

FIGURE 22 Time series for horizontal forces from 2525 to 2575 seconds

The Figure 21 and 22 time series for horizontal forces on the pipeline midpoint show the horizontal force peak at 215.1 N/m at 2549 seconds over the 50 m length of pipeline. Hence, this force will be input in to the finite element software in form of surface traction through surface of 2 pipeline.

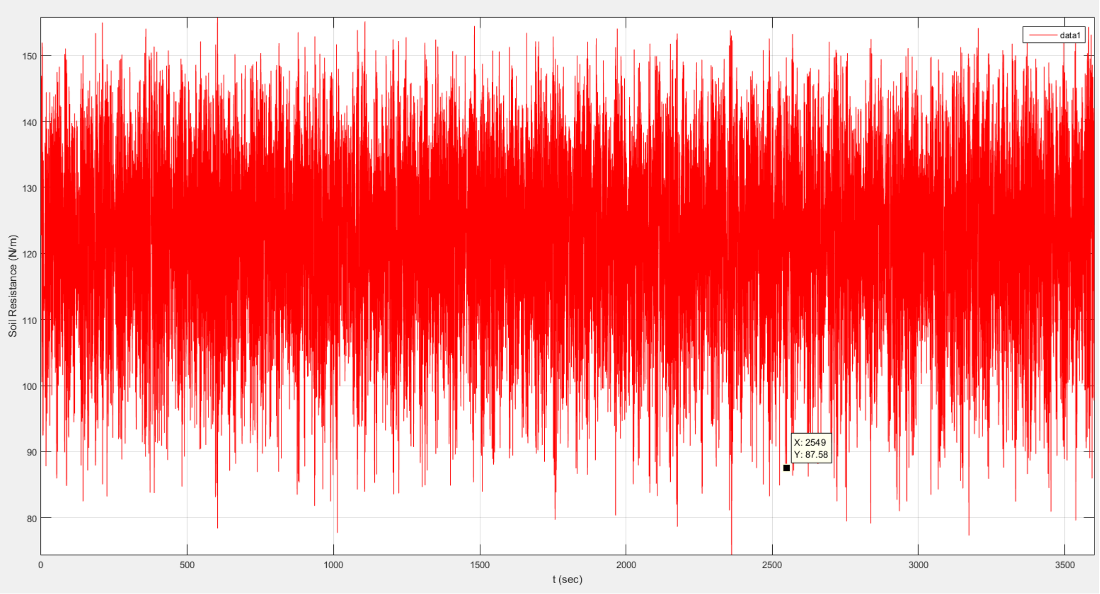

FIGURE 23 Time series of soil resistances

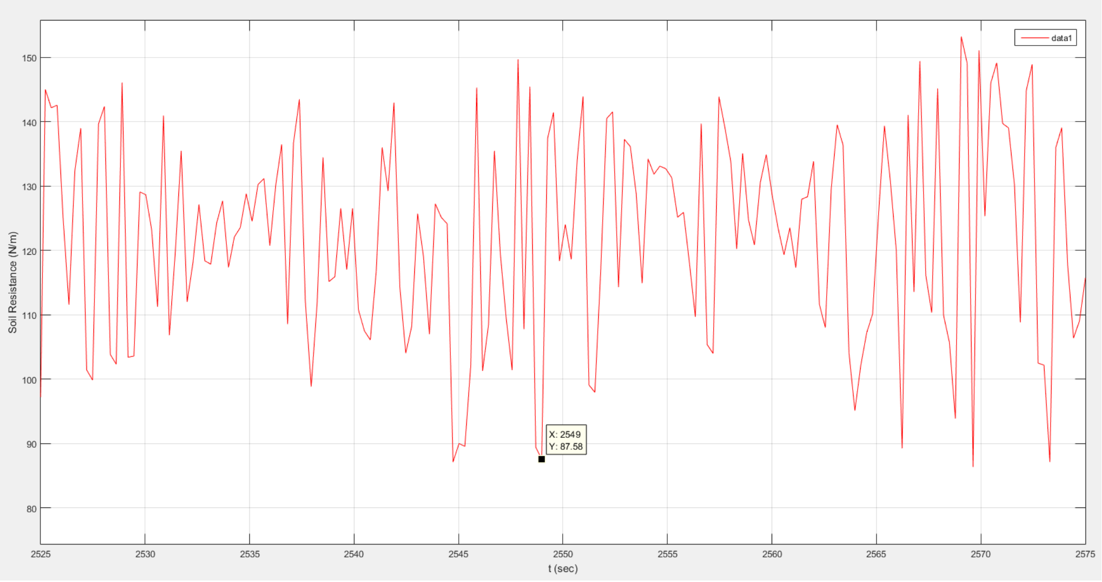

FIGURE 24 Time series of soil resistance from 2525 to 2575 seconds

Since the pipeline penetration into the seabed is assumed at 0.2D which is 0.041 m the arc length inside the seabed is 0.3434m. Hence, the contact surface area between pipe-soil is 17.17m^2 over a 50 m length pipeline. The horizontal force peak at 2549 seconds which at this point the soil resistance is 87.58 m. The soil resistance which is the summation of passive and pure coulomb friction forces is then input into the finite element software in form of surface traction.

4.2 DISPLACEMENTS FROM FINITE ELEMENT ANALYSIS

This is the displacement contour generated by ABAQUS which shows the maximum lateral displacement. In this study, the lateral displacement is 0.7654 m when stabilize by 32.32kg/m chain.

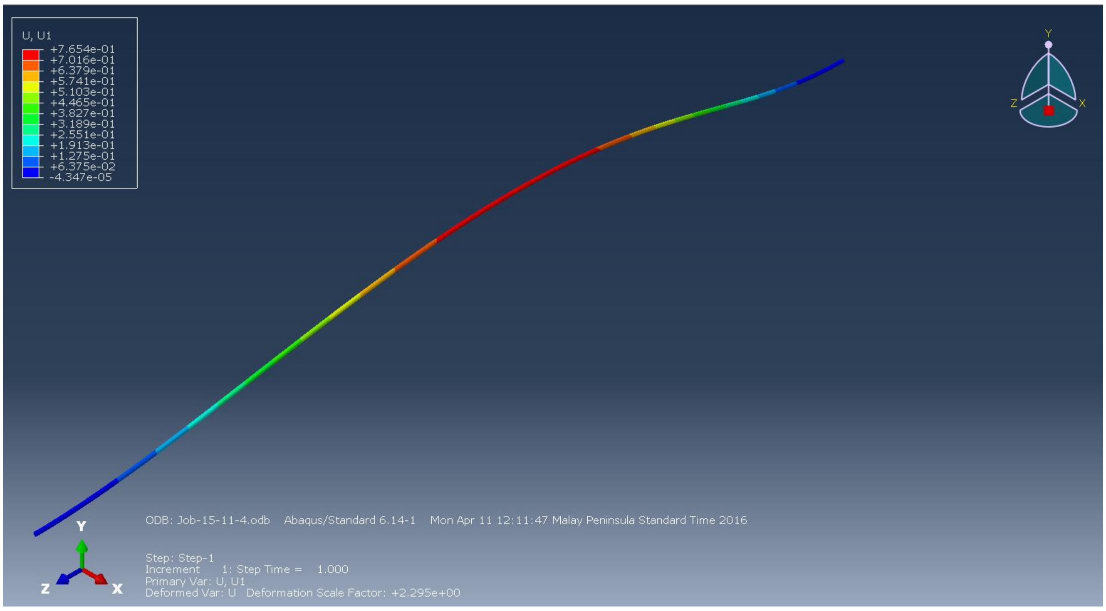

FIGURE 25 Displacement contour

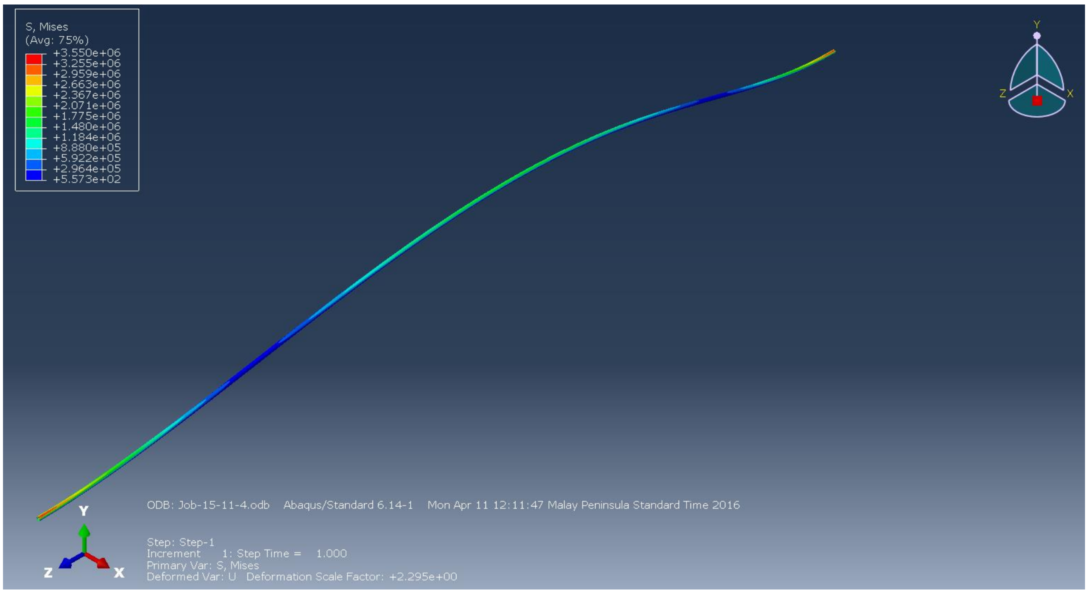

FIGURE 26 Von Mises Stress

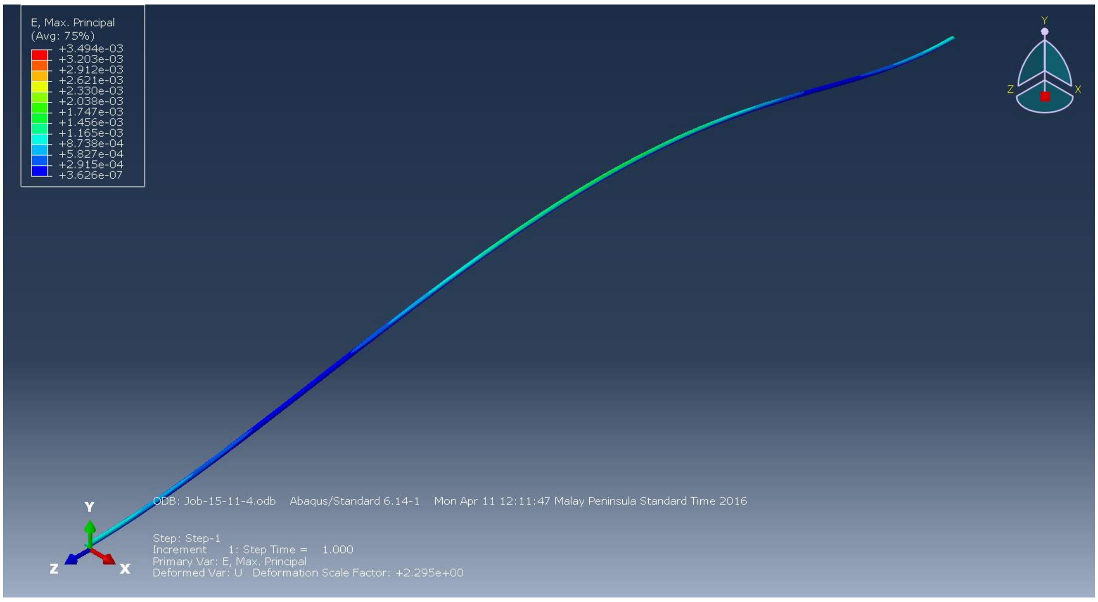

FIGURE 27 Strain

The Result:

Maximum Horizontal Displacement: -: 0.7654 m
Maximum Von Mises Stress: 3.55MPa
Maximun strain: 3.494e-03
Weight of chain added: 32.32 kg/m
Simulation Run Time: 3 hours

4.3 COMPARISON WITH PREVIOUS RESEARCH

This is the comparison of generated forces from in house developed in MATLAB by using JONSWAP spectrum, Airy wave theories and Wake II model to the result from Y.Tian *et al.* [12]. From Figure 10 and 11, the time series pattern for vertical forces is vary from intensity and curve shape over 10800 s. This is due to different forces of model and wave theories is used. The random number generator function in MATLAB and ABAQUS subroutine causing the vertical forces peak at different time. Both theories predict the maximum vertical forces at the pipeline midpoint in the given condition is around 2.1 kN to 2.2 kN. The percentage of difference for this two value is around 4.04 %.

These are parameters used in the research by Y.Tian *et al.[12]:*

Diameter: 1 m

Current speed: 1m/s

Significant wave height: 14.5 m

Peak period: 14.2 s

100 years return period of waves and currents

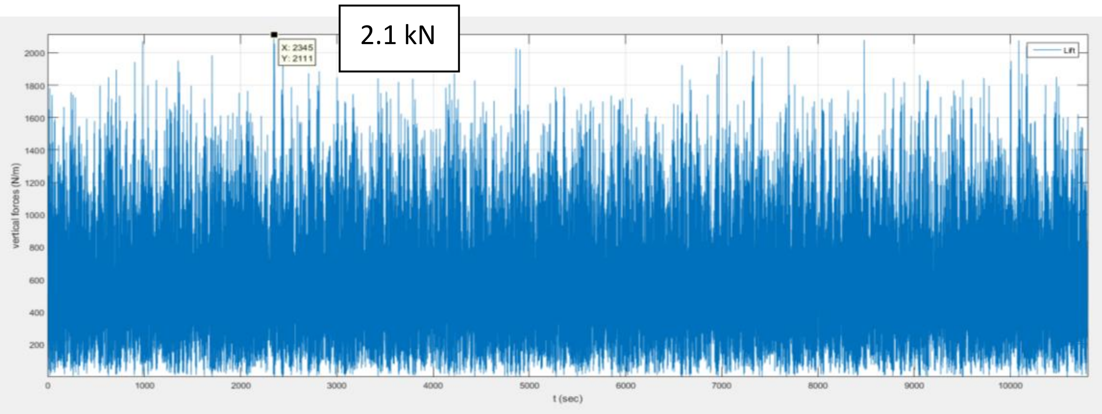

FIGURE 28. Time series of Vertical forces over 10800s from MATLAB at pipeline midpoint

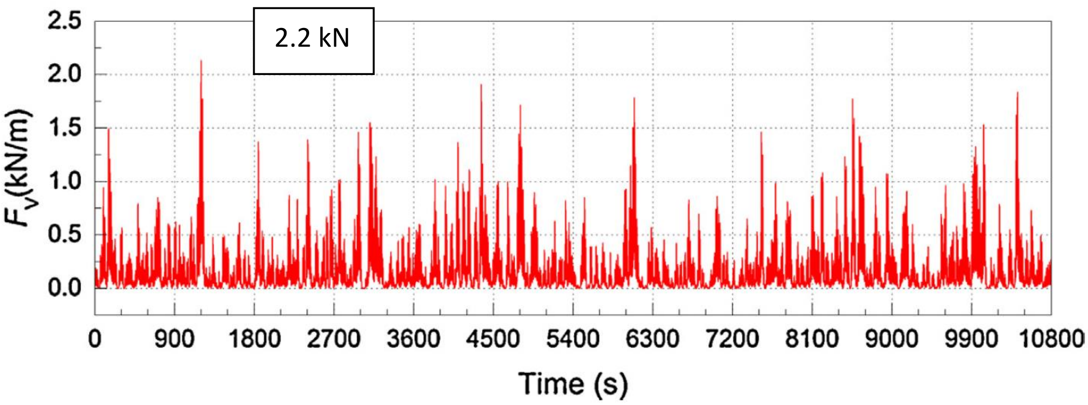

FIGURE 29 Times series of Vertical forces over 10800s at the pipeline midpoint from ABAQUS Subroutine

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 SUMMARY OF PROJECT PROGRESS

In conclusion, the finite element analysis is carried out by using ABAQUS standard which the result of the simulation shown the lateral displacement due one year return waves and currents is 0.7654 m. Due to scaling effect due to the full length of 400 m pipeline reduced to 50 m, the actual displacement for the pipeline can be up to 6.1332 m. The acceptable lateral displacement for this model is 10 m, hence this result is acceptable.

5.2 FUTURE WORK

Through the results shown above, the on bottom stability analysis is recommended to carry out and compare with different method of analysis and different method of calculation of hydrodynamic loadings at pipeline level to increase the quality of the result. Besides that, higher computational power is desirable to achieve more comprehensive and accurate result for the on-bottom stability analysis in a shorter simulation running time.

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APPENDIX A GANTT CHART AND KEY MILDSTONE

Referring to Table 1 and 2, the project timeline within 14 weeks for both Final Year Project I and Final Year Project II has been shown.

TABLE A1 Timeline for FYP I

No.	**Details/ Week**	**FYP 1**													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Selection of Project Topic	■	■												
2	Installation of Required Software			●											
2	Study of Waves Theories and ABAQUS software				■	■	■	■	■	■	■				
3	Development Pipeline Model											■	■		
4	Generate mesh & Define Boundary Conditions													■	■

TABLE A2 Timeline for FYP II

No.	**Details/ Week**	**FYP II**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Trial Simulations	●	■	■				■	■	■						
2	MATLAB & User Defined functions			■	■	■										
3	Repeat Simulations				■	■	■	■	■	■	■	■				
4	Comparative analysis								●	■	■	■				
5	Post-processing										●	■	■			
6	Analyze and Summarize Results											■	■	●		

● - Key Milestone

■ - Process

APPENDIX B DATE SHEET FOR NON-METALLIC PIPELINE

TABLE B Datasheet for non-metallic pipeline

Item	Required Data / Properties	Details	Value
1	NMP Physical properties	Type of Each Layer	Liner: Polyamide (PE) Structural Layer: Glass Fibre / PolyEthylene Jacket: Polyamide (PE)
		Diameter (outside and inside)	ID: 152 mm OD: 205 mm
		Wall Thickness (each layer)	Liner: 11 ± 1 mm Structural Layer: 6.5 ± 1 mm Jacket: 8 ± 2 mm
		Cross Sectional Area	14848 mm^2
		Material Density (each layer)	Liner: 950 kg/m^3 Structural Layer: 1693 kg/m^3 Jacket: 950 kg/m^3
		Unit Weight	16.9 kg/m, in air 1.5 kg/m, in and filled with water
		Bulk Modulus (collapse)	2.7 – 2.8 GPa
		Poisson Ratio	ν = 0.4
		Young's Modulus	1.1 GPa (Liner & coating)
		Allowable Dent	To be determined
		Pipe Yield Strength	Not applicable
		Pipe Bending Stiffness (EI)	67 $kN*m^2$
		Pipe Axial Stiffness (EA)	16438 kN
		Pipe Torsional Stiffness (GI)	186 $kN*m^2$
		Contact Stiffness	Not applicable
		Rayleigh Damping Coefficients	Unknown
		Surface Roughness Parameters	Liner roughness: 7µ
		S/N or T/N curves	Airborne property
		Thermal Coefficients	Axial direction: 46 µ/°C Radial direction: -4 µ/°C
		Minimum Bend Radius (Transport)	2.7 m
2	Material properties	Strength of Reinforced Layer	765 MPa
		Stiffness of Reinforced Layer	32800 MPa
		Shore Hardness D	62 (PolyEthylene)
		Material Toughness	2.3 – 2.4 MPa*√m
		Plastic Strain	Not applicable
3	NMP Jointing Details (connector)	Stiffness – Axial	See end-fitting design report
		Stiffness – Bending	See end-fitting design report
		Stiffness – Torsion	See end-fitting design report
		Flange width	See end-fitting design report
		Lip Length	See end-fitting design report
4	Outer Coating / Inner Liner details		See item 1
			See item 1

APPENDIX C SEABED ROUGHNESS (RETRIEVED FROM DNV RP-F109)

TABLE C Seabed roughness

Table 3-1 Seabed roughness		
Seabed	*Grain size d_{50} [mm]*	*Roughness z_0 [m]*
Silt and clay	0.0625	$\approx 5\cdot10^{-6}$
Fine sand	0.25	$\approx 1\cdot10^{-5}$
Medium sand	0.5	$\approx 4\cdot10^{-5}$
Coarse sand	1.0	$\approx 1\cdot10^{-4}$
Gravel	4.0	$\approx 3\cdot10^{-4}$
Pebble	25	$\approx 2\cdot10^{-3}$
Cobble	125	$\approx 1\cdot10^{-2}$
Boulder	500	$\approx 4\cdot10^{-2}$

APPENDIX D ENVIRONMENTAL DATA FOR SOUTH CHINA SEA

TABLE D 1 Extreme waves

4.2.1 Independent Extreme Waves

RP	1 YR	10 YR	50 YR	100 YR
Hs (m)	2.69	3.41	3.86	4.05
Tz (lower) (s)	5.1	5.7	6.1	6.2
Tz (Central) (s)	5.6	6.3	6.7	6.8
Tz (Upper) (s)	6.0	6.8	7.2	7.4
Tp (lower) (s)	6.2	6.9	7.4	7.5
Tp (central) (s)	7.9	8.8	9.4	9.6
Tp (upper) (s)	9.9	11.2	11.9	12.2
Hmax(m)	4.84	6.08	6.84	7.17
Tass (s)	7.3	8.2	8.7	9.0

TABLE D 2 Extreme current

4.3.1 Independent Extreme Currents

Layer Above Seabed	1 YR	10 YR	50 YR	100 YR
1*D	1.40	1.50	1.70	1.80
0.5*D	1.11	1.19	1.35	1.43
0.1*D	0.65	0.70	0.79	0.84
0.01*D	0.30	0.32	0.37	0.39

APPENDIX E WAVES AND CURRENTS CALCULATIONS

The following data taken from independent extreme waves in South China Sea with one year return period and one hour sea state. From the environmental data Appendix B.

Significant wave height during a sea state, Hs = 2.69m

Peak period for design spectrum, T_p = 7.9s

Water depth is assumed, d = 75m

Peak wave frequency, ω_p $= \frac{2\pi}{Tp}$ $= \frac{2\pi}{7.9}$ =<u>0.79534Hz</u>	Reference Period, T_n $= \sqrt{\frac{d}{g}}$ $= \sqrt{\frac{75}{9.80665}}$ = <u>2.7655s</u>

T_n/T_p = 2.7655/7.9

= <u>0.35</u>

For Peak-enhancement factor, γ (retrieved from DNV-RP109)

$$\gamma = \begin{cases} 5.0 & \varphi \le 3.6 \\ \exp(5.75 - 1.15\varphi) & 3.6 < \varphi < 5.0; \\ 1.0 & \varphi \ge 5.0 \end{cases} \quad \varphi = \frac{T_p}{\sqrt{H_s}}$$

Phi, φ $= \frac{Tp}{\sqrt{Hs}}$ $= \frac{7.9}{\sqrt{2.69}}$ = <u>4.8167</u>	Hence Peak-enhancement factor, γ = exp(5.75-1.15*4.8167) = <u>1.2346</u>

Mean perpendicular current velocity over a pipe diameter

$$V_c = V_c(z_r)\cdot\left(\frac{\left(1+\frac{z_0}{D}\right)\cdot\ln\left(\frac{D}{z_0}+1\right)-1}{\ln\left(\frac{z_r}{z_0}+1\right)}\right)\cdot\sin\theta_c$$

Assume, V_c is a steady current therefore,

Steady current velocity associated with design oscillation, perpendicular to pipeline,

$V^* = V_c$

Reference measurement height over sea bed, z_r is taken as 0.5*D which is diameter of the NMP, D = 0.205m

The current velocity at reference height, $V(z_r)$ = 1.11 m/s

The seabed is assume as medium sand, hence roughness, $z_0 = 4x10^{-5}$

*current velocity retrieved from Appendix C and roughness from Appendix B

$Directionality\ of\ current, \theta_c = 90^o$

$$V^* \quad = 1.11 \times \left[\frac{\left(\frac{4x10-5}{0.205}+1\right)\times In\left(\frac{0.205}{4x10-5}+1\right)-1}{In\left(\frac{0.205}{4x10-5}+1\right)}\right]\times \sin 90^o$$

$= \underline{1.066813925\ m/s}$

Keulegan-Carpenter number for single design oscillation,

$$K^* \quad = \frac{\text{Um}\times T^*}{D}$$

$$= \frac{0.8565\times 9.875}{0.205}$$

$= \underline{41.2582}$

Steady to oscillatory velocity ratio for single design oscillation,

APPENDIX F MATLAB CODE FOR JONSWAP, SIGNIFICANT WAVE VELOCITY, EFFECTIVE VELOCITY, HYDRODYNAMIC FORCES AND SOIL RESISTANCES

```
function JONSWAP3

close all;clear;clc;


%Required input
%Hw = significant wave height (m)
%Tp = Peak Period (s)
%Gamma for JONSWAP
%Drag & Lift & Inertia coefficient
%pipeline diameter (m)
% Submerged weight of pipeline (kg/m)
%Weight of Chain (kg/m)
%soil coefficient of friction,?
%Buoyancy Unit Weight for soil N/m3
%Steady current velocity at pipe level

Wsp = 1.588; % Submerged weight of pipeline (kg/m)
Wc = 32.32; % %Weight of Chain (kg/m)
D = 0.205; %pipeline diameter (m)
Hw = 2.69; % wave height significant (m)
TP = 7.9; % Peak period (s)
u = 0.5;  %coefficient of friction
By = 10000; %Buoyancy Unit Weight for sand (7000-13500) N/m3
Vc = 1.066813925; % steady current

d = 75;
g = 9.80665;
Rd = 0.9;



Wsp = Wsp*g; % Submerged weight of pipeline (N/m)
Wc = Wc*g; % %Weight of Chain (N/m)
%-------generate random frequency
w=linspace(0.2,2.5,50);
delta_w = w(2)-w(1);
w = w + delta_w .* rand(1,length(w)); % random selection of frequencies
w3=w;

%----- Jonswap spectrum ------ code retrieved from  Baharuddin Ali (2013)

gama  = 1.2346;
fp    = 2*pi/TP;
fac1  = (320*Hw^2)/TP^4;
sigma = (w<=fp)*0.07+(w>fp)*0.09;
Aa    = exp(-((w/fp-1)./(sigma*sqrt(2))).^2);
fac2  = w.^-5;
fac3  = exp(-(1950*w.^-4)/TP^4);
fac31 = exp(-5/4*(w/fp).^-4);
fac4  = gama.^Aa;
S     = fac1.*fac2.*fac3.*fac4;
%--------------------------------
skl  = 50;   % use scale model to reduce time consume in calculation..!!
tend = 520; % example : about 3 hours for model scale 1:50
sfr   = 25;   % sampling frequency (Hz)
t = [0: 1/sfr: tend]*sqrt(skl); % time vector
phi = 2*pi*(rand(1,length(w))-0.5); % random phase of ith frequency
A = sqrt(2*S.*delta_w); % amplitude of ith frequency
%-----------------------------------------
for i = 1:length(t)
    wave(i) = sum(A .* cos(w*t(i) + phi));
end
```

```
[S2,W2]=HitSpek3(wave',length(wave),400,sfr,skl); % 400 :hamming variabel, custom,
can be modified

smax=(max(S)<=max(S2))*max(S2)+(max(S)>max(S2))*max(S);
figure;
subplot(1,1,1)
plot(W2,S2,w3,S,'r');xlabel('w (rad/s)');ylabel('Spectral (m^2.s)');
legend('measured','theoretical');
grid;

%maximum water particle velocity = Um from Wake II model proposed by Soedigdo et al.
(1999)
%Um is same as Significant flow velocity = Us from DNV 2011

%--------------------------------------------------------------------

%Significant flow velocity,Us calculation from JONSWAP & DNV by Hea Yih Torng
fun= @(x)(x.^2)./(sinh((d/sqrt(g*d).*x)).^2);


%fun= @(x)(x.^2)./((sinh(3.08056)).^2);
q = integral(fun,0,Inf);

for i = 1:length(t)
if wave(i) < 0

   Us(i) = 2.*sqrt(abs(q.*wave(i)));

else

   Us(i) = 2*sqrt(q.*wave(i));

end
end



axis([w3(1) w3(end) 0 smax*1.2]);
figure(11)

plot(t,Us);xlabel('t (sec)');ylabel('Us (m/s)');grid;
axis([0 3600 -inf*1.2 inf]);
%subplot(4,1,3)
%plot(t,K);xlabel('t (sec)');ylabel('Keulegan-Carpenter number');grid;

%--------------------------------------------------------------------

%free stream velocity
%end
Ut = Vc + Us.*sin(wave.*t);
figure(2);

plot(t,Ut);xlabel('t (sec)');ylabel('free stream velocity (m/s)');grid;
axis([0 3600 -inf*1.2 inf]);

%wake velocity

Uw = ((0.5*sqrt(pi)/0.95)*Us.*erf(0.475*((sin(wave.*t+150)).^3)));

figure(3);

plot(t,Uw);xlabel('t (sec)');ylabel('wake velocity (m/s)');grid;
axis([0 3600 -inf*1.2 inf]);

%Effective velocity on pipeline
Ue= Uw+Ut;
Ue = Rd.*Ue;
figure(4);

plot(t,Ue);xlabel('t (sec)');ylabel('effective velocity (m/s)');grid;
axis([0 3600 -inf*1.2 inf]);
```

```
%-----------------------------------------------------------------------

%HYDRODYANMIC forces from Wake II model

Fd= 0.5*1025*D*1.*abs(Ue).*Ue;

figure(5);
%subplot(3,1,1)
%plot(t,Fd);

t2=t;



%lift vetrical force
Fl= 0.5*1025*D*1.*Ue.*Ue;
Fl = 0.87.*Fl;  %due to penetration

plot(t,Fl);xlabel('t (sec)');ylabel('vertical forces (N/m)');grid;
legend('Lift');
axis([0 3600 -inf*1.2 inf]);

%couloumb friction and passive friction

Ks = By*(D^2)./(Wc + Wsp - Fl);
 % initial penetration
Zpi = 0.2*D;
Ff = u*(Wc + Wsp - Fl);



if Ks <= 26.7

    Fr = (5.*Ks - 0.15.*(Ks.^2).*((Zpi/D).^1.25));

else

    Fr = Ks.*((Zpi/D).^1.25);

end

Frt =  Ff + Fr ;

dUt=Us.*wave.*cos(wave.*t);

zz = sin(wave.*t + 150);
Zx = (1.60794.*wave.*(exp(-0.225625.*(zz.^6))).*(zz.^2).*(cos(wave.*t+150)));

dUw=((0.5*sqrt(pi)./0.95).*Us.*(Zx));
dUw = abs(dUw);

%Cd = ((1.1+0.38*(St./0.205).*exp(-0.016.*((St./0.205).^4)))/(St./0.205));
%Cd and CL are assume as 1.0 (drag and lift coefficent)
Fi=((pi)*(D^2)/4)*1025*(2.5.*dUt-0.25.*dUw);


figure(6);
%horizontal(drag and inertia forces)
Fh= Fd+Fi;

Fh = (1-1.4*(Zpi/D))*Fh;
Fh = abs(0.72.*Fh); %due to penetration

plot(t,Fh);xlabel('t (sec)');ylabel('Horizontal Forces (N/m)');grid;
legend('Drag&Inertia');
axis([0 3600 -inf*1.2 inf]);



 figure(8);
plot(t,Frt);xlabel('t (sec)');ylabel('Soil Resistance (N/m)');grid;
axis([0 3600 -inf*1.2 inf]);

figure(9);
plot(t,Fh-Frt);xlabel('t (sec)');ylabel('Horizontal Resultant Forces(N/m)');grid;
axis([0 3600 -inf*1.2 inf]);
```

```
figure(12);

plot(t,wave);xlabel('t (sec)');ylabel('Sea surface elevation (m)');grid;



axis([0 3600 -inf*1.2 inf]);


function [S,W]=HitSpek3(z,n,m,sfr,skl);
% HitSpek2 : generate wave spectrum from time signal /code retrieved from  Baharuddin
Ali (2013)
%
zf = fft(z);
R  = zf.*conj(zf)/n;
fr = (0:n-1)/n*sfr;
P  = 2*R/sfr;
w  = hamming(m) ;
w  = w/sum(w) ;
w  = [w(ceil((m+1)/2):m);zeros(n-m,1);w(1:ceil((m+1)/2)-1)];
w    = fft(w) ;
pavg = fft(P) ;
pavg = ifft(w.*pavg) ;

S = abs(pavg(1:ceil(n/2)));
F = fr(1:ceil(n/2));

S=S/(2*pi)*sqrt(skl);% Spectral (m^2.s)



W=2*pi*F/sqrt(skl); % w (rad/s)
```