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RELIABILITY ASSESSMENT OF FREE SPANNING OFFSHORE PIPELINE

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Reliability Assessment of Free Spanning Offshore Pipeline

by

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Dissertation submitted in partial fulfillment of
the requirements for the Bachelor of Engineering (Hons)
(Civil Engineering)

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CERTIFICATION OF APPROVAL

Reliability Assessment of Free Spanning Offshore Pipeline

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A project dissertation submitted to the
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(CIVIL ENGINEERING)

Approved by,

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(DR. ZAHIRANIZA MUSTAFA)

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TRONOH, PERAK

May 2014

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.

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RINOSHA A/P M SELVADURAI

ABSTRACT

Pipeline from offshore petroleum fields must have frequently prone to many threats such as corrosion, free spanning, extreme weathers and etc. This study will be only concentrated on free spanning of offshore pipeline. The presence of free span along the length of pipeline may result in excessive displacement and bending or vibration of the pipeline section. The research will begin with data gathering of pipeline from Malaysian Water Operation. All data related to the pipelines are gathered. This study is divided into three major parts which are the study of the length of pipeline span, bending moment capacity of pipeline and also the stress analysis in the pipeline. These are the three elements which can cause failure to the pipelines. Thus, an assessment analysis of free spanning pipeline is crucial in order to ensure the reliability of these pipelines. All equations are developed by using the data obtained f. Then, Limit State Function is developed for this research. From the limit state function, probability of failure of pipelines according to each category can be obtained. Software's were used to conduct the study. Software's that were used are BestFit, to get the distribution of the data and VaP to get the probability of the pipeline to fail. At the end of the research, all three failure modes is compared to get the best reliable mode according to the probability of failure for each mode.

Keyword: Free spanning pipeline; Span Length; Bending Moment; Vortex-Induced Vibration; Stress; Pressure

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Thousands of years back, pipeline was constructed to convey water for drinking and also usage for agriculture. The first recorded use of a pipe to transport a hydrocarbon was in China, about 2500 years ago. The Chinese used bamboo pipe to convey natural gas from shallow wells. Today's oil and gas pipeline industry has its own origin in the oil business (Hopkins, 2007). The offshore pipelines are divided into three categories which are liquid, gas and also multiphase. Figure 1 below explains the several type of offshore pipeline that is being used in the current oil and gas industry.

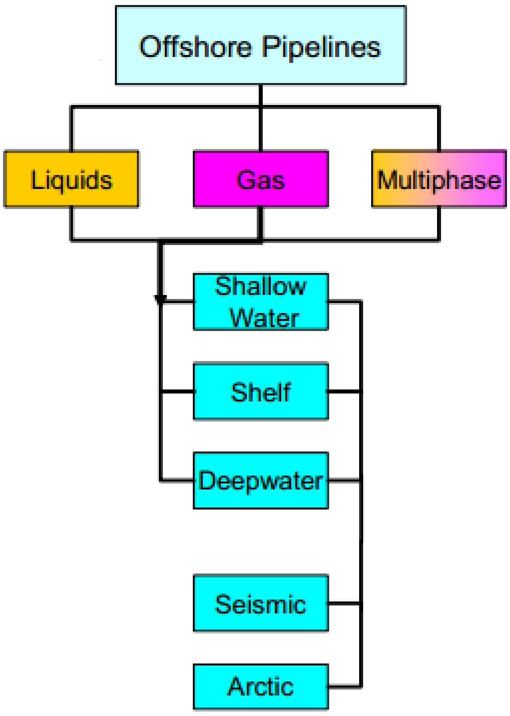


Figure 1: Types of offshore pipelines

Source: Hopkins (2007)

The development of an offshore industry is proportionally related to the development of offshore pipeline as well. As the industry expands towards deeper water depths, the pipelines are required to undergo improvement in material designs simply to withstand changes in the new environment. In oil and gas transportation, pipelines are one of the safest and economist methods of transportation. Pipelines are used to transport oil and gas from the wells to the shore. However, these pipelines are prone to many threats such as internal corrosion, external corrosion, erosion, spanning, trawl impact and many more, as sketched in Figure 2.

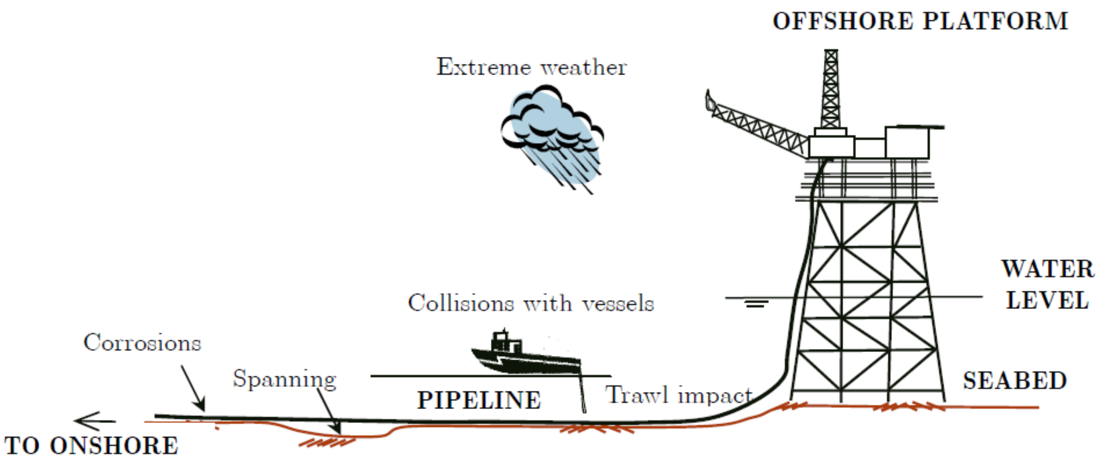


Figure 2: Different types of pipeline hazards
Source : Mustaffa.Z (2011)

1.2 Problem Statement

1.2.1 Problem Identification

The presence of free span along the length of pipeline may result in excessive displacement and bending or vibration of the pipeline section. Thus, an assessment analysis of free spanning pipeline is crucial in order to ensure the reliability of these pipelines.

1.3 Objectives and Scope of Study

1.3.1 Objectives

The objectives of this paper are identified as follows:

1. To create a Limit State Function (LSF) model that can be used in reliability estimate of pipeline span
2. To simulate different failure modes in the reliability prediction of pipeline spanning

1.3.2 Scope of Study

The scope of this research is to assess the reliability of free span in offshore pipeline by using the Limit State Function model. There are limitations for this research. The research is limited to, the pipeline is sitting on the seabed considering current is only from Vortex-Shedding which causes the dynamic stress to the pipeline and also the loading on operating pressure is fixed.

1.4 The Relevancy of the Project

The relevancy of this research is to optimize the reliability of pipeline failure. Reliability probabilistic is important to assess the free spanning pipeline so as to avoid overestimation or underestimation of the structural performance of the pipeline.

1.5 Feasibility of the Project within the Scope and Time frame

- *Scope of study* - This project was carried out within the scope of civil engineering course as it encompasses various aspects of this field of study.
- *Time allocation (2 semesters)* - The time frame is sufficient for a complete study on the literatures available on this topic as well as to develop a limit state function for various failure modes of offshore pipeline.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The review on the existing articles or literatures available for pipelines was done based on the development history of pipelines, free spanning, failure modes of pipeline, structural reliability analysis, as well as Probability Distribution Function. As such, the data with similar criteria were categorized together and explained based on its failure modes. As per the current analysis conducted, some of these failure modes include length of free span, bending moment, and also the stress analysis.

2.2 Free Span

Free span is a gap between the pipe and the supporting seabed as shown in Figure 3. The gap in between two span shoulders is called the span length. Pipeline spanning occurs when there is no contact between the pipeline and the seabed. An evaluation of an allowable free-span length is required in pipeline design. Should actual span length exceed the allowable length, then correction is then necessary to reduce the span to avoid pipeline damage. Free span can cause failure of pipeline. It is because of excessive yielding and also fatigue. Free spans normally occur in subsea pipelines (Guo et al, 2005). Figure 4 shows the terminology of free spanning of pipeline which causes the pipeline subject to bending. The length of the free span causes the pipeline subject to displacement, bending and also vibration of the pipeline section and eventually fails the pipeline structure.

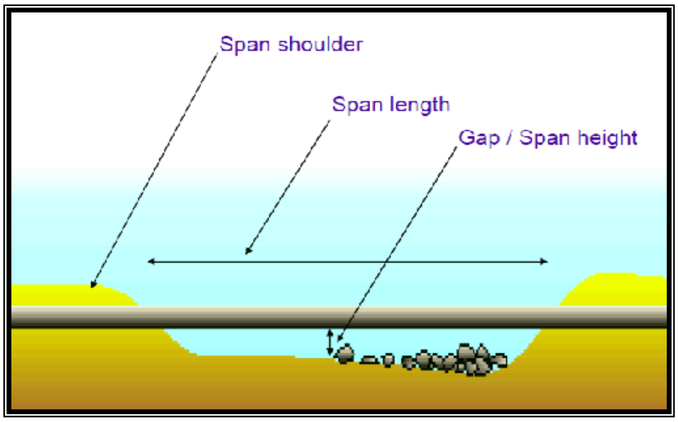
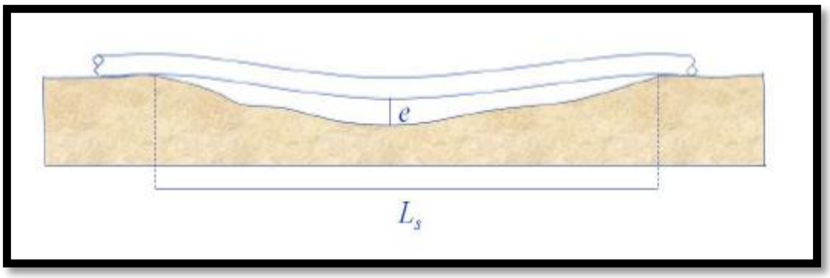


Figure 3: Free Spanning Terminology



Where,
e =distance between bottom of the pipe and seabed
Ls = span length

Figure 4: Free Spanning Terminology
Source:Sollund et al. (2012)

2.3 Types of Span

There are various types of spanning that has been occurring at the offshore pipeline system. As per the research conducted, there are six types of free span occurring. Some of the types of span includes, pipeline crosses seabed depression, pipeline crosses seabed with change in slope, pipeline crosses seabed depression with sloping ends, pipeline crosses seabed rock outcrop, pipeline touches down at centre of seabed depression and also pipeline crosses highly uneven seabed region. The most commonly occurred free span is the pipeline crosses seabed depression. Figure 5 shows the type of spans.

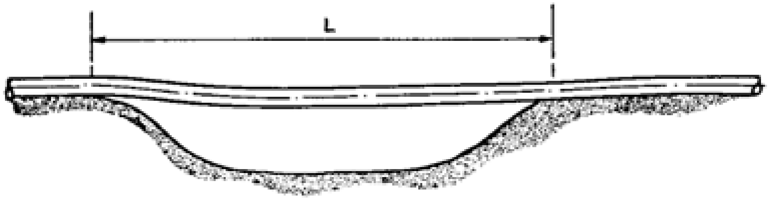
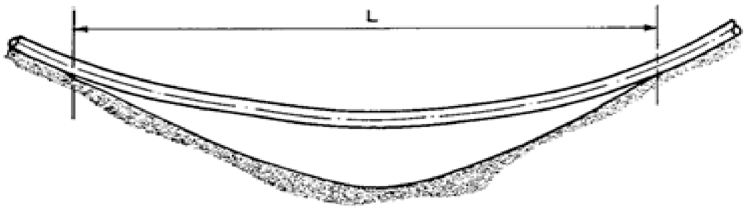
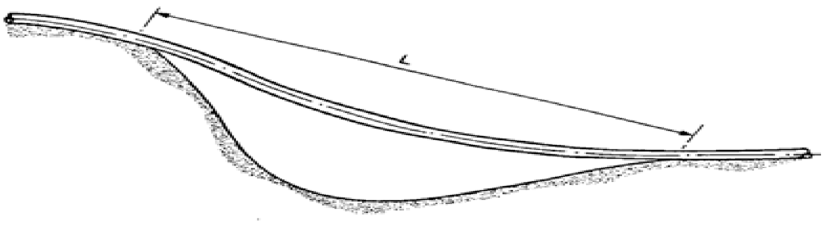
Types of Span	**Description**
	Pipeline crosses seabed depression
	Pipeline crosses seabed with change in slope
	Pipeline crosses seabed depression with sloping ends
	Pipeline crosses seabed rock outcrop
	Pipeline touches down at centre of seabed depression
	ipeline crosses ighly uneven eabed region

Figure 5: Types of span

2.4 Why do Free Span Occur?

Many studies have been conducted on the causes of free span. Most of the outcomes are divided into two which are natural causes and also dynamic causes. Natural causes such as seabed unevenness and artificial support. Dynamic causes such as change of topology (scouring) and also Vortex Induced Vibration (VIV). Figure 6 shows the main cause of the free span of offshore pipeline.

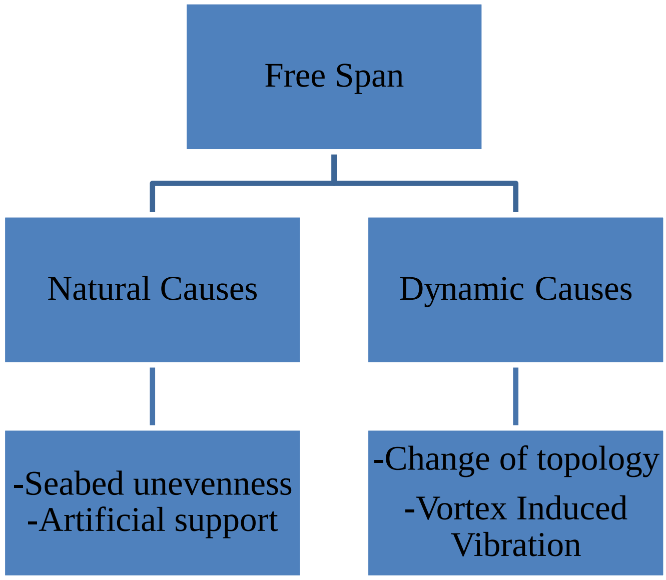


Figure 6: Causes of free span

2.4.1 Vortex – Shedding Frequency

Current from bottom of pipeline can cause dynamic stresses and it causes the pipeline to oscillate. The oscillation causes by the currents results in fatigue of the pipeline welds. Thus it reduces the life of the pipeline. Figure 7 shows the illustration of the occurrence oscillation caused by Vortex-Shedding Frequency inside the pipeline.

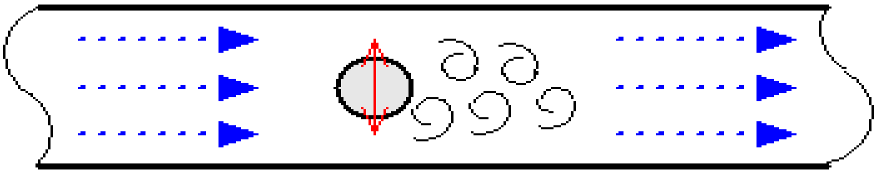


Figure 7: Oscillation causes by currents
Source : The Engineering Toolbox (2014)

The vortex –shedding frequency is the frequency at which pairs of vortices are shed from the pipeline and is calculates based on the following Equation 1:

$$fs = \frac{SUc}{D} \tag{1}$$

Where,

fs = vortex-shedding frequency

S = Strouhal Number

Uc = design current velocity

D = pipe outside diameter

2.4.2 Pipeline Natural Frequency

The natural frequency of the pipeline span depends on pipe stiffness, end conditions of the pipe span, length of the span, and effective mass of the pipe. The natural frequency and the shedding frequency of the pipelines are correlated:

i. Vortex shedding + Natural frequency = pipeline vibrates
ii. Vortex shedding far from natural frequency will prevent the pipeline failure.

The natural frequency for vibration of the pipe span is given by the following Equation 2:

$$fn = \frac{Ce}{2\pi}\sqrt{\frac{EI}{Me\ Ls^4}} \qquad (2)$$

where,

fn = pipe span natural frequency

Ls= span length

Me = effective mass

Ce = end condition constant

Source : Guo et al. (2005)

2.5 Theories on Free Span

2.5.1 Critical Span Length

The critical span length or the unsupported pipeline length at which oscillations of the pipeline occur for a specific current is based on the relationship between the natural frequency of the pipe free span and the reduced velocity. There are two types of critical span length category, which are, cross flow motion and also in-flow motion(Guo et al, 2005). Figure 8 shows the cross flow and inflow motions.

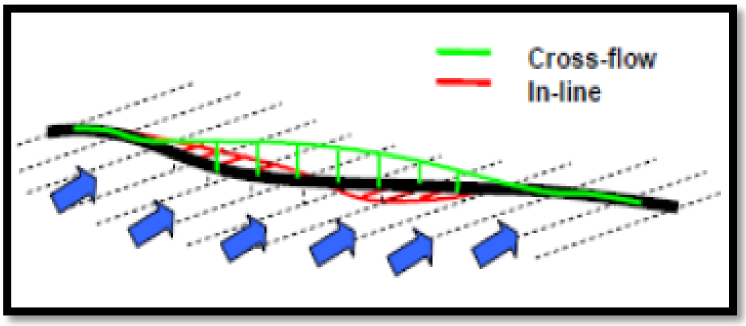


Figure 8: Cross-flow motion and In-flow motion
Source: Koushan, K. (2009)

The critical span length for cross flow motion is expressed in Equation 3:

$$Lc = \sqrt{\frac{Ce\ Ur\ D}{2\pi\ Uc}\sqrt{\frac{EI}{Me}}} \tag{3}$$

where,

Me = Effective Mass

Uc = design current velocity

D = pipe outside diameter

Ur = reduced velocity

The critical span length for in-line motion is expressed in Equation 4:

$$Lc = \sqrt{\frac{Ce\ fn}{2\pi}\sqrt{\frac{EI}{Me}}} \tag{4}$$

where,

fn = pipe span natural frequency

Me = effective mass

Ce = end condition constant

2.5.2 Bending Moment Capacity

Pipeline may be subjected to additional loads due to installation, seabed contours, impacts and high-pressure/high-temperature operating conditions for which the bending moment capacity is often the limiting parameter. A pipe subjected to increase bending may fail due to local buckling/collapse or fracture. Figure 9 shows a normal pipeline which is not subjected to any buckling an Figure 10 shows a pipeline that are subjected to buckling which can cause failure of the pipeline.

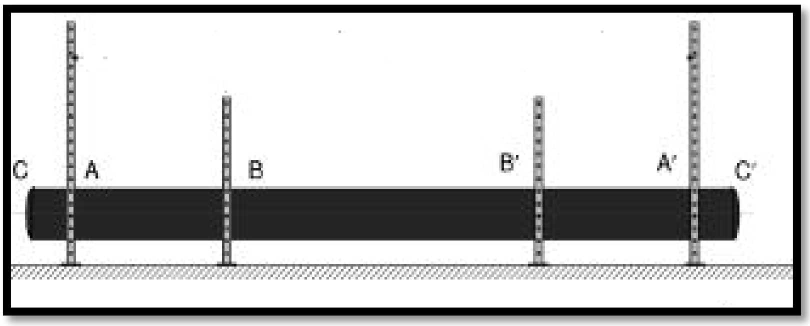


Figure 9: Normal pipeline (without buckling)

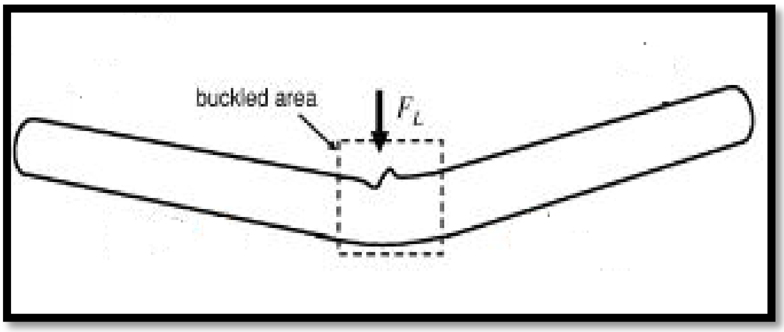


Figure 10: Pipeline that has buckling
Source : Guo et al. (2005)

The bending moment capacity of pipeline is expressed in Equation 5:

$$Bending\ Moment, My = \frac{q.Ls}{10} \quad (5)$$

where,

q = Pressure force per unit length

Ls= Span Length

2.6 Structural Reliability Analysis

2.6.1 Deterministic, Semi-Probabilistic and Probabilistic Models

Structural model and stress analysis is conducted using three different ways, which are deterministic, semi-probabilistic and also probabilistic method. For deterministic method, Allowable Stress Design (ASD) is used to determine the reliability of a pipeline. As for semi-probabilistic method, Load Factor Design (LFD) is used and last but not least for probabilistic method, Load and Resistance Factor Design (LRFD) is used to determine the reliability of a pipeline. The comparison of ASD, LFD and LRFD is shown in Table 2. Allowable Stress Design is categorized under a deterministic structural model, Load Factor Design is categorized under semi-probabilistic model and last but not least, Load and Resistance Factor Design is categorized under probabilistic model. For this research Probabilistic model has been used to run the simulation of the Limit State Function of several failure modes of the pipeline

Table 1: Comparison between ASD, LFD and LRFD

Method	Remarks
Allowable Stress Design (ASD)	**Advantage** >> Simple **Disadvantage** >> No risk assessment based on reliability theory >> Insufficient account of variability >> Factor of Safety is subjective
Load Factor Design (LFD)	**Advantage** >> Loads have different levels of uncertainty >> Load factor is applied to each load combination **Disadvantage** >> Complex >> No risk assessment based on reliability theory
Load Resistance Factor Design (LRFD)	**Advantage** >> Risk assessment based on reliability theory >> Uniform levels of safety >> Accounts for variability **Disadvantage** >> Requires statistical data >> Resistance factors vary

2.6.2 Limit State Function

All structures are designed to sustain loads that occur before and after construction of the structure. It has to be made sure that the structure must sustain load safely during its service life. A structure or a part of structure is considered unfit for use when it reaches a state called the limit state. Limit state is a state just before failure occurs (Mustaffa.Z (2011). The general equation of Limit State Function is,

$$\mathbf{Z = R - S}$$

where,

Z = Limit State Function

R = Strength

S = Load

This Limit State Function will be developed using a Probability Equation which is $Pf = P(Z<0)$where, the probability of failure of the pipeline is when $Z < 0$. The regions of survival and failure of limit state is described in Figure 11.

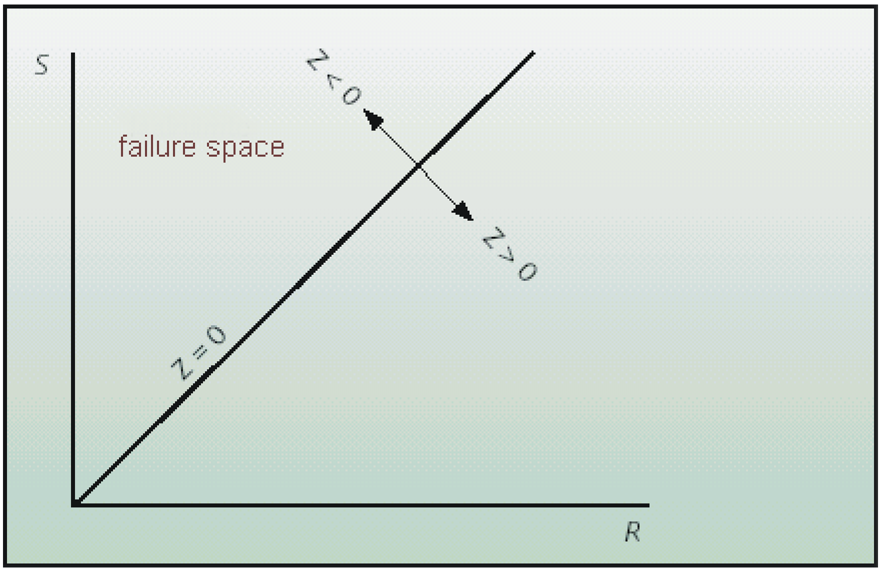
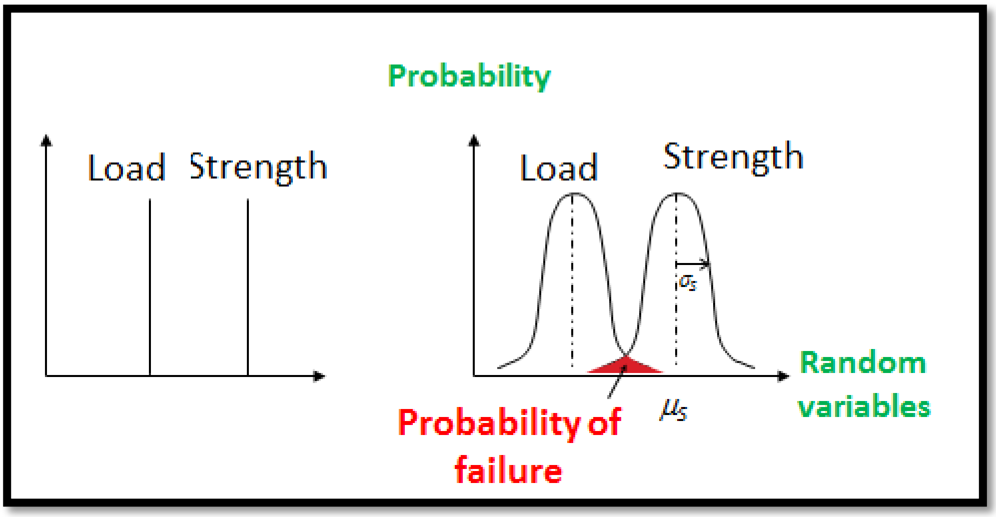


Figure 11: Regions of survival and failure in Limit State Function
Source : (Mustaffa.Z (2011).

2.6.3 Random Variables and Probability Density Function

When the value of a variable is determined by a chance event, that variable is called a random variable (Stat Trek, 2009). Random variables can be categorized into two which are discrete or continuous. Discrete random variable is within a range of numbers which can only take round values. Continuous random variable can take on any value within a range of values (decimal values).

The idea of this structural reliability analysis is to transform a single point value into random variables. Figure 12 shows the difference between deterministic and probabilistic model.



(a) Deterministic (b) Probabilistic

Figure 12: The difference between deterministic and probabilistic model
Source : Mustaffa.Z (2011)

There are several types of probabilistic distribution function (PDF). The suitability of a PDF is selected based on the nature of the problem, underlying assumptions associated with the distribution, shape of the graph after plotting the available data and also the convenience and simplicity in using PDF. Some of the common PDF's are Normal Distribution, Log Normal Distribution, Weibull Distribution, Binomial Distribution, Gumbell Distribution and also Pareto Distribution.

Normal Distribution

The normal distribution is most widely known and used of all distributions. Because the normal distribution approximates many natural phenomena so well, it has developed into a standard of reference for many probability problems. The characteristics of the Normal Distribution are it is symmetric bell-shaped curve, the shape depends on mean,μ and also the standard deviation, σ, the centre of distribution is μ,and the spread is determined by σ. Figure 13 shows an example of Normal Distribution graph.

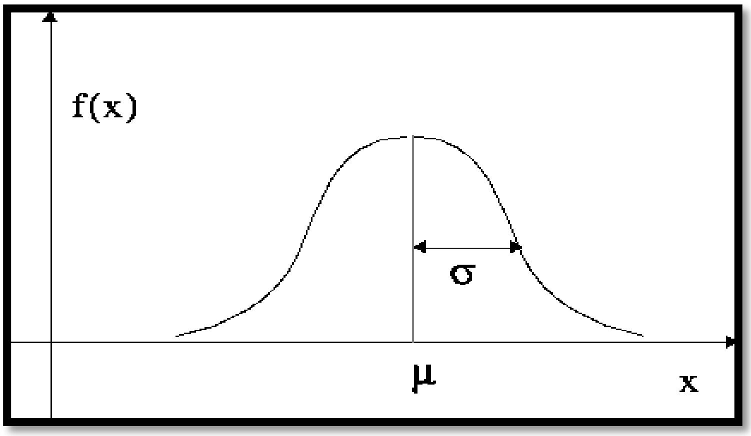


Figure 13: The Normal Distribution graph

Log Normal Distribution

The log normal distribution is a statistical distribution of random variables which have a normally distributed logarithm. Log-normal distributions can model a random variable *X* where log(*X*) is normally distributed. These distributions, under multiplication and division, are self-replicating. That is to say, multiplying or dividing log-normal random variables will result in log-normal distributions. Figure 14 shows an example of Normal Distribution graph.

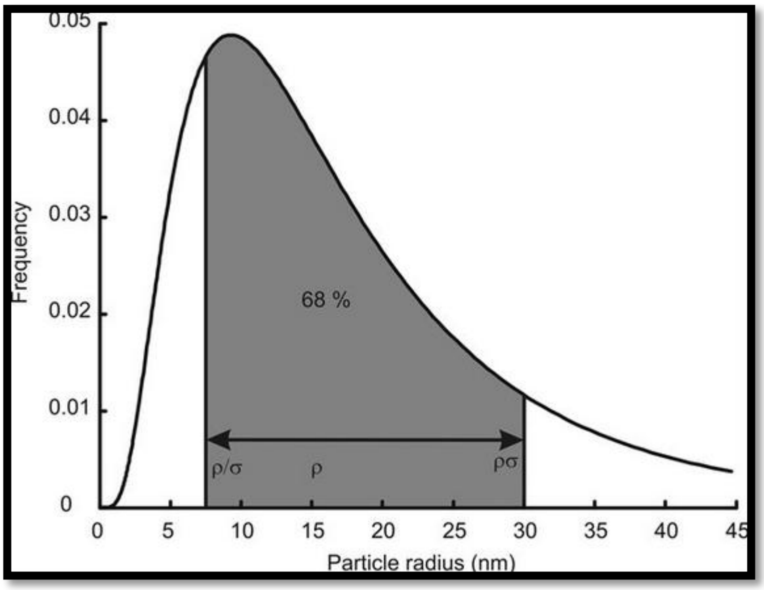


Figure 14: The Log Normal Distribution graph

Weibull Distribution

The Weibull Distribution is a flexible measurement that details the probable distribution associated with the lifetime characteristic of a particular part or service component, particularly focused on failure- rate. Weilbull distribution is used throughout reliability engineering anticipate and account for issues of wear out during development. . Figure 15 shows an example of Weibull Distribution graph.

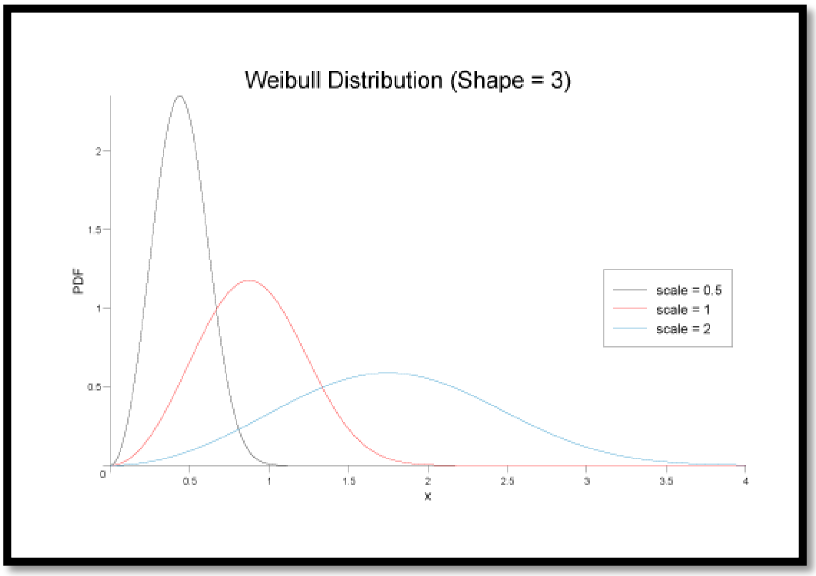


Figure 15: Weibull Distribution graph

Pareto Distribution

The Pareto distribution is a skewed, heavy-tailed distribution that is sometimes used to model the distribution of incomes and other financial variables. Pareto distribution, for a single such quantity whose log is exponentially distributed; the prototypical power law distribution. . Figure 16 shows an example of Pareto Distribution graph.

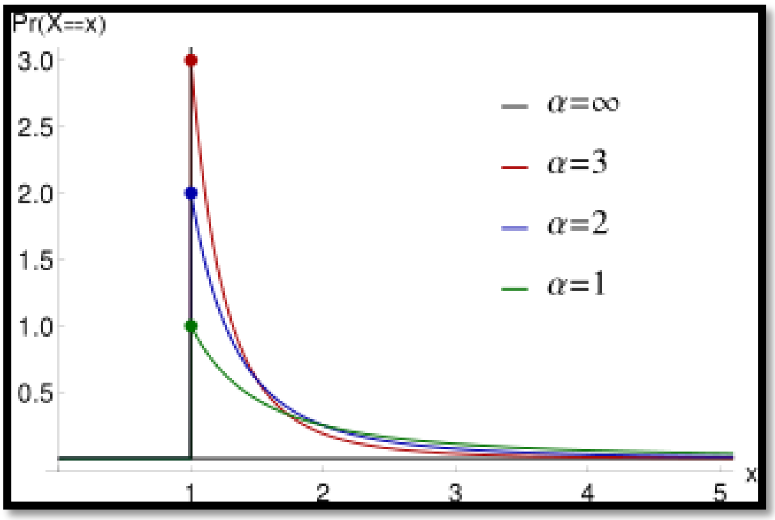


Figure 16: Pareto Distribution graph

2.7 Previous Studies Conducted by Researchers

Various studies has been conducted by many researchers on the free spanning of offshore pipeline, the system reliability of pipeline, the limit state design of structures, probabilistic analysis and etc. Table 2 shows the research conducted by some of the researchers on these elements.

Table 2: Previous Studies by Researchers

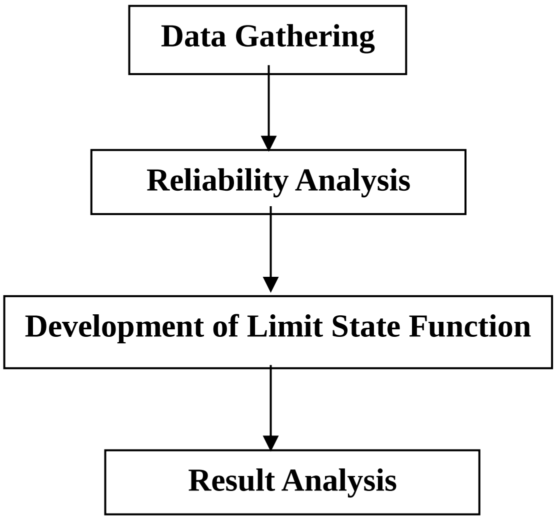
No	Author	Title	Remarks
1	Zimmerman et.al (1998)	Can Limit States Design be Used to Design a Pipeline Above 80% SMYS?	Design procedures for the large diameter pipelines by using LSF
2	Nielsen et al. (2002)	VIV Response of Long Free Spanning Pipelines	Model Test – setting up model by adding support. Observe the effect of free span length under VIV.
3	Mustaffa.Z (2011)	System Reliability Assessment of Offshore Pipelines	Probabilistic Analysis of Limit State Functions of Corroded Pipelines
4	Choi, H.S. (2000)	Free Spanning Analysis of Offshore Pipelines	Axial load of pipeline affects the natural frequency and allowable span length at the same time.
5	Elsayed et al. (2012)	A Finite Element Model for Subsea Pipeline Stability And Free Span Screening	Conducted FEM simulation using ANSYS and
6	Hauch.S et al. (1999)	Bending Moment Capacity of Pipes	Conducted simulation based on Limit State Function for bending moment capacity of pipes

CHAPTER 3

METHODOLOGY

3.1 Introduction

The research is began with data gathering of pipeline from Malaysian Water Operation, followed by reliability analysis, developing a Limit State function and last but not least analyse the result obtained.



3.1.1 Data Gathering

Data is gathered from Malaysian Water Operation. The pipeline properties are gathered. Some other important data that was gathered is the governing parameters of the pipeline, result validation of the pipe data, environmental data and also the general parameter calculation data. These data's are then used in calculations and also simulations that are involved in the research.

3.1.2 Reliability Analysis

The data that is gathered is then used to do some calculations based on the Equation 1 to Equation 6 and also by using the formula's listed in Table 3. These calculated parameters are grouped into few categories. These categories are named as Failure Modes. For this research, there are three types of failure modes which are Failure Mode 1: Span Length, Failure Mode 2: Bending Moment and also Failure Mode 3: VIV- Stress.

Table 3 : Formula's used in parameters calculation

Parameters	Formula
Pipe diameter with concrete coating = D_{cc}	$D_{cc} := D + 2(t_{ec} + t_{cc})$
Pipe diameter with concrete coating = D_t	$D_t := D_{cc} + 2 \cdot t_m$
Pipe diameter with external coating = D_{ec}	$D_{ec} := D + 2t_{ec}$
Pipe internal diameter = D_i	$D_i := D - (2t)$
Cross sectional area of pipe = A	$A_c := \frac{\pi \cdot D^2}{4}$
Pipe steel mass = m_{st}	$m_{st} := \frac{\pi}{4} \cdot \left(D^2 - D_i^2\right) \cdot \rho_{st}$
Internal coating mass = m_{ic}	$m_{ic} := 0 \frac{kg}{m}$
External coating mass = m_{ec}	$m_{ec} := \frac{\pi}{4} \cdot \left(D_{ec}^2 - D^2\right) \cdot \rho_{ec}$
Concrete coating mass = m_{cc}	$m_{cc} := \frac{\pi}{4} \cdot \left(D_{cc}^2 - D_{ec}^2\right) \cdot \rho_{cc}$
Marine growth mass = m_m	$m_m := \frac{\pi}{4} \cdot \left(D_t^2 - D_{cc}^2\right) \cdot \rho_m$
Unit mass of pipe including coatings = m_p	$m_p := m_{st} + m_{ic} + m_{ec} + m_{cc} + m_m$

Unit mass of contents = m_c	$m_c := \frac{\pi \cdot D_i^2 \cdot \rho_{cont}}{4}$
Added unit mass = m_a	$m_a := \frac{\pi \cdot D^2 \cdot \rho_{sw}}{4}$
Total mass = m_t	$m_t := m_p + m_c + m_a$

The failure modes are then simulated according in BestFit Software to identify the best Probability Density Function (PDF). Figure 17 below shows the data that has been input into the software.

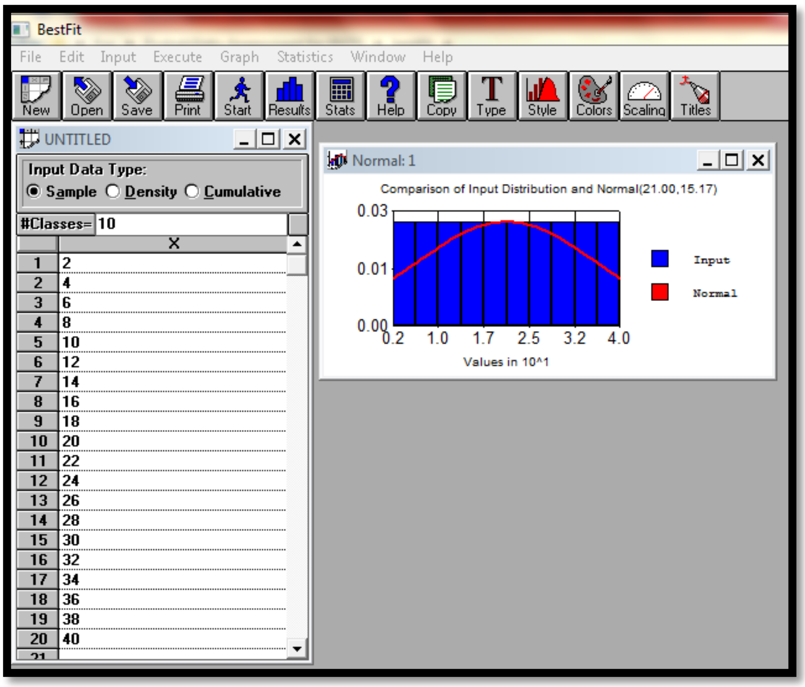


Figure 17: Data input in BestFit Software

As mentioned in 2.5.3, the best Probability Density function is used to obtain the distribution of the data. Figure 18 shows the basic result that has been simulated from the BestFit. It displays the minimum and maximum length of span, mean, mode, standard deviation and also the variance. Figure 19 shows the most suitable Probability Density Function (PDF) for the data that has been input in BestFit Software

Statistics for UNTITLED	
A	B
Minimum=	1.0
Maximum=	30.0
Mode=	3.0
Mean=	9.252199
Std Deviation=	6.648819
Variance=	44.206797
Skewness=	0.988834
Kurtosis=	3.23992

Figure 18: Result Simulated from BestFit

Best Fit Results					
Function	Chi-Square	Rank	K-S Test	Rank	A-D Test
NegBin(2.00,0.18)	0.09023	1.0	N/A		N/A
Weibull(1.44,10.23)	0.101404	2.0	0.068679	2.0	1.564426
Gamma(1.94,4.78)	0.103007	3.0	0.062292	1.0	1.389834
Lognormal2(1.94,0.82)	0.129761	4.0	0.078567	3.0	2.615887
Lognormal(9.68,9.45)	0.129761	5.0	0.078567	4.0	2.615887
Erlang(1.00,9.25)	0.147472	6.0	0.161507	8.0	11.471351
Expon(9.25)	0.147472	7.0	0.162559	9.0	11.528176
Geomet(9.75e-2)	0.159728	8.0	N/A		N/A
Logistic(5.89,4.61)	0.268279	9.0	0.257398	10.0	31.35337
Normal(9.25,6.65)	0.38478	10.0	0.129138	6.0	10.542083
Beta(1.00,1.08) * 29.00 + 1.00	0.531525	11.0	0.343654	11.0	90.4304
Erf(6.26e-2)	0.777552	12.0	0.555449	13.0	163.788571
Chisq(8.00)	1.866311	13.0	0.155633	7.0	30.68099
Pareto(1.00,1.00)	3.238812	14.0	0.552468	12.0	210.554743
Poisson(9.25)	626.763903	15.0	N/A		N/A
Binomial(36.00,0.21)	3.333138e+9	16.0	N/A		N/A
HyperGeo(54.00,30.00,2.14e+2)	2.284755e+16	17.0	N/A		N/A
Triang(-1.16,2.11,30.00)	1.0e+34	18.0	0.12892	5.0	6.786511

Figure 19: Result Simulated from BestFit

3.1.3 Development of Limit State Function

The result that is simulated in BestFit is then used in VaP Software. To simulate using VaP Software, Limit State Function is created for each of the failure modes. From this Limit State Function, the probability of failure for each failure mode is obtained. Simulation was run using 100000 counts to obtain a better curve of the graph. The result that is obtained from the graph is the probability of failure of the pipeline. The simulation will be repeated for various parameters and also failure modes. Figure 20 shows the graph or curve that is obtained from the Monte Carlo (VaP) simulation. The highlighted in yellow is the probability of failure of the pipeline.

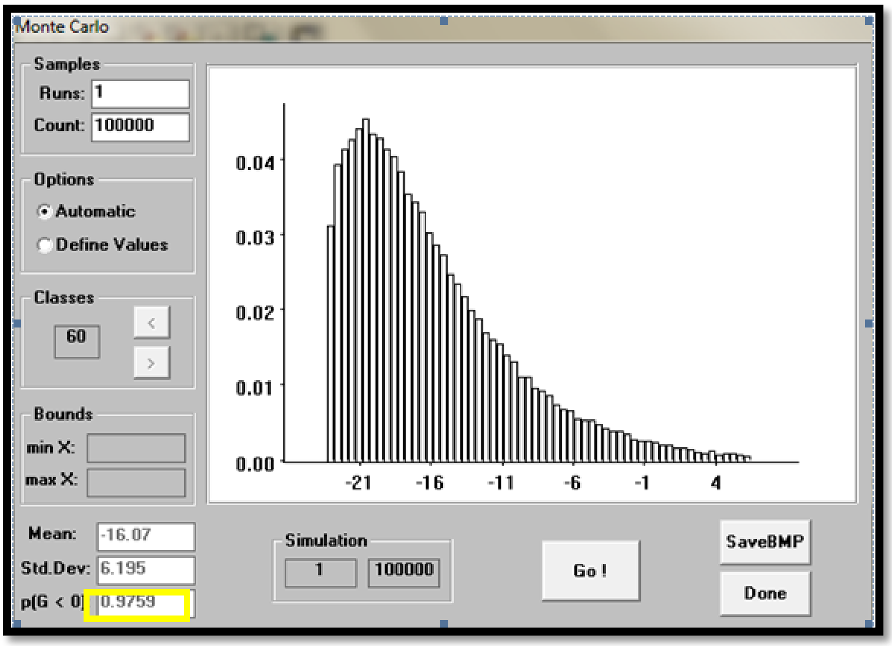


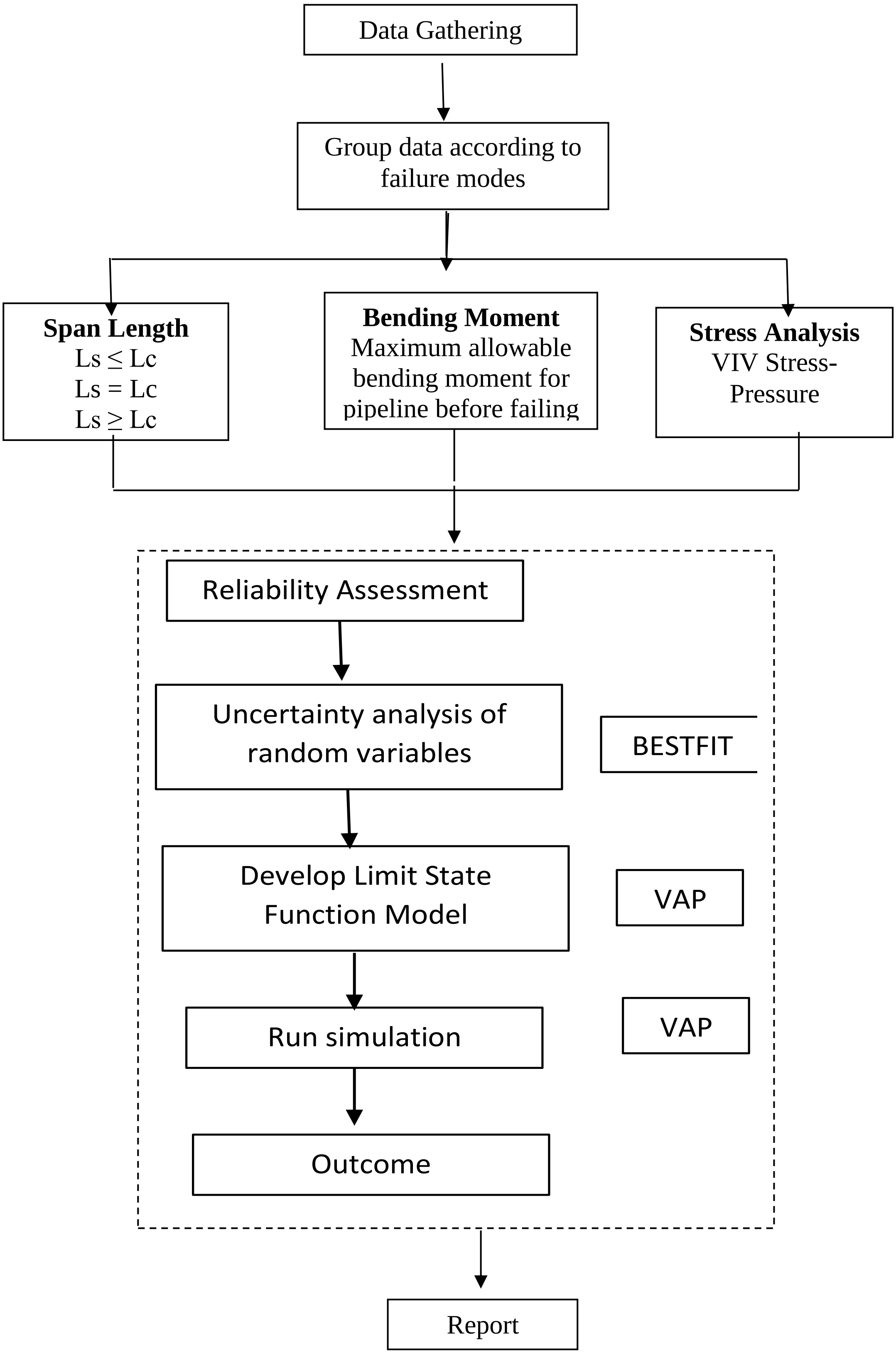
Figure 20: Result Simulated from VaP

3.1.4 Result Analysis

The probability of failure that is obtained from the Monte Carlo simulation is then tabulated in to Microsoft Excel and a curve is produced. The curve shows the probability of failure at 50% and the maximum level the pipeline can withstand.

3.2 Research Flow

The flow below shows the summarization of the research methodology in 3.1.

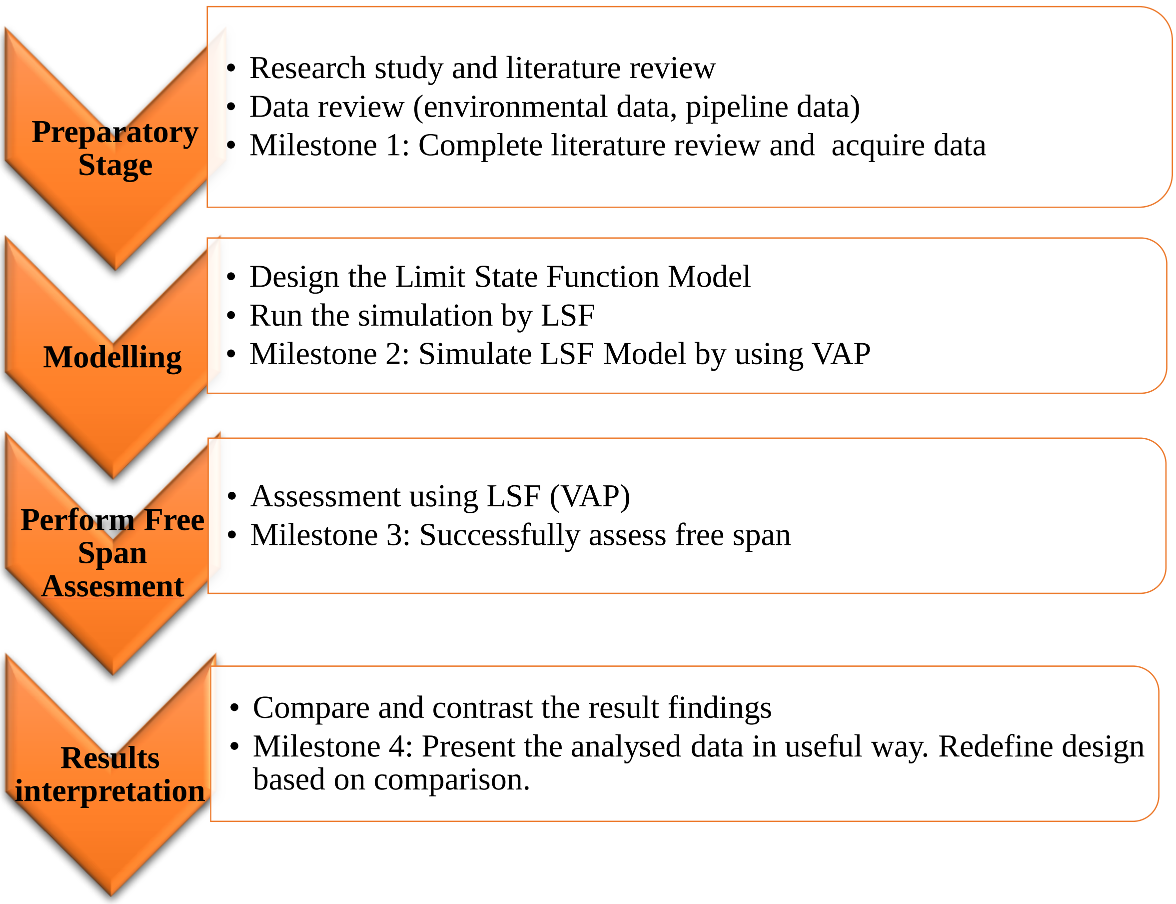


3.3 Research Tools

Internet – Studies on literature review was conducted by the aid of internet. Previous research papers are obtained from internet and studies were performed. Video aid from YouTube is also used to understand about the free spanning and Limit State Function.

Simulation Software – For this research purpose two types of software are used. The software are BestFit and also the VaP. Bestfit is used to get the probability distribution of data and VaP is used to simulate the probability of failure of the pipeline.

3.4 Key Milestone



3.5 FYP I Gantt Chart

NO	WEEK DETAIL	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Title														
2	Preliminary Research Work and Literature Review														
3	Submission of Extended Proposal								●						
4	Preparation for Oral Proposal Defense														
5	Oral Proposal Defense Presentation											●			
6	Project Work														
7	Preparation of Interim Report														
8	Submission of Interim Draft Report													●	
9	Submission of Interim Final Report														●

3.5 FYP II Gantt Chart

NO	WEEK DETAIL	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Work Continues														
2	Submission of Progress Report								●						
3	Project Work Continues														
4	Pre Sedex											●			
5	Submission of Draft Report												●		
6	Submission of Dissertation													●	
7	Submission of Technical Paper													●	
8	Oral Presentation													●	
9	Submission of Dissertation (Hardbound)														●

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Data has been obtained from Malaysian Water Operation. These data's are used to conduct the research. Some information has been extracted from the data given by Malaysian Water Operation. The data that was given by Malaysia Water Operation is for the pipeline material grade API 5L X52 with the wall thickness of 8mm and the outer diameter of 168.3. The data that has been obtained is the governing parameters and result validation of pipe data, environmental data and also the general parameter calculation of the pipeline. Table 4 shows the parameters that have been used for this research. Some of the results are obtained based on some basic calculation. For this research, data has been collected for three types of failure modes. Limit State function is created for each of the failure mode. The result obtained is then shown is a graph. Each result is compared at the probability of failure at 50%. The reliability of the pipeline is obtained from the best comparison of the failure modes.

Table 4: Parameters that has been used

Parameters	Symbol	Unit	Value
Pipe Outer Diameter	D	mm	168.3
Wall Thickness	t	mm	8
Wall Thickness Corrosion Allowance	CA	mm	3
Corrosion Coating Thickness	t_c	mm	5
Corrosion Coating Density	ρ_c	kg/m^3	1400
Concrete Coating Thickness	t_{cc}	mm	25.4
Concrete Coating Density	ρ_c	kg/m^3	3044
Product Density	ρ_{pr}	kg/m^3	50
Corrosion Coating Thickness	t_c	mm	5
Maximum Allowable Operating Pressure	-	MPa	7.7
Young's Modulus	E	MPa	207000
Pipe external diameter with external coating	D_{ec}	m	0.335
Pipe external diameter with concrete coating	D_{cc}	m	0.405
Total pipe external diameter + Marine growth	D_t	m	0.405
Pipe Internal Diameter	D_i	m	0.309
Second moment of inertia of	I	m^4	9.102E-05

pipe			
Mass of pipe steel	M_{st}	kg/m	57.00
Mass of internal pipe coating	M_{ic}	kg/m	0
Mass of external pipe coating	M_{ec}	kg/m	7.29
Mass of concrete coating	M_{cc}	kg/m	123.81
Mass of marine growth	M_m	kg/m	0
Mass of empty pipe	M_{pe}	kg/m	188.09
Mass of pipe content	M_{cont}	kg/m	2.86
Mass of displaced water	M_w	kg/m	131.98
Maximum Allowable Static Span Length	L_c	m	14
Bending stress due to horizontal force	s_{bh}	MPa	117.49
Bending stress due to vertical force	s_{bv}	MPa	125.61
Effective Mass	M_e	kg/m	361.20
IN-LINE VORTEX VIBRATION			
Stability Parameter	Ks		0.54
Reduced Velocity	V_r^{IL}		1.75
Dynamic In-line Span Length	L_{dyn}^{IL}		24.08
CROSS-FLOW VORTEX VIBRATION (due to Current)			
Reynold's Number	Re		2.88E+05
Reduced Velocity	V_r^{CF}		4.69
Dynamic Cross-flow Span Length	L_{dyn-c}^{CF}		39.43
CROSS-FLOW VORTEX VIBRATION (due to Current + wave)			
Reynold's Number	Re		4.80E+05
Dynamic Cross-flow Span Length	L_{dyn-c}^{CF}		29.84

4.2 Result from Simulation

4.2.1 Failure Mode 1: Length of Free Span

As discussed in methodology, length of free span is the first failure mode that is simulated. Length of span is chosen as the failure mode because it is one of the contributing factors for pipeline failure. The cross-flow motion and also the in-flow motion is taken into account for the calculation of maximum allowable span length. The calculated maximum allowable span length is 14m. The data that has been extracted from Malaysia Water Operation data is simulated in BestFit and also VaP software's. This is to identify the distribution of the data. According to the simulation that was computed, it shows that the data is well distributed in Weibull Distribution function. The distribution for Weibull Distribution chosen in order to obtain an accurate result of the reliability of pipeline. The mean and standard deviation result from the Best Fit is then used to run the simulation in VaP software using the Limit State Function equation. The input distribution graph (BestFit) and Monte Carlo (VaP) simulation is attached in Appendix 1. The distribution of the failure model according to mean, standard deviation and Probability Density Function (PDF) is described in Table 5.

A Limit State Function has been created in order to obtain the expected result. Limit State Function that is created for this failure mode is

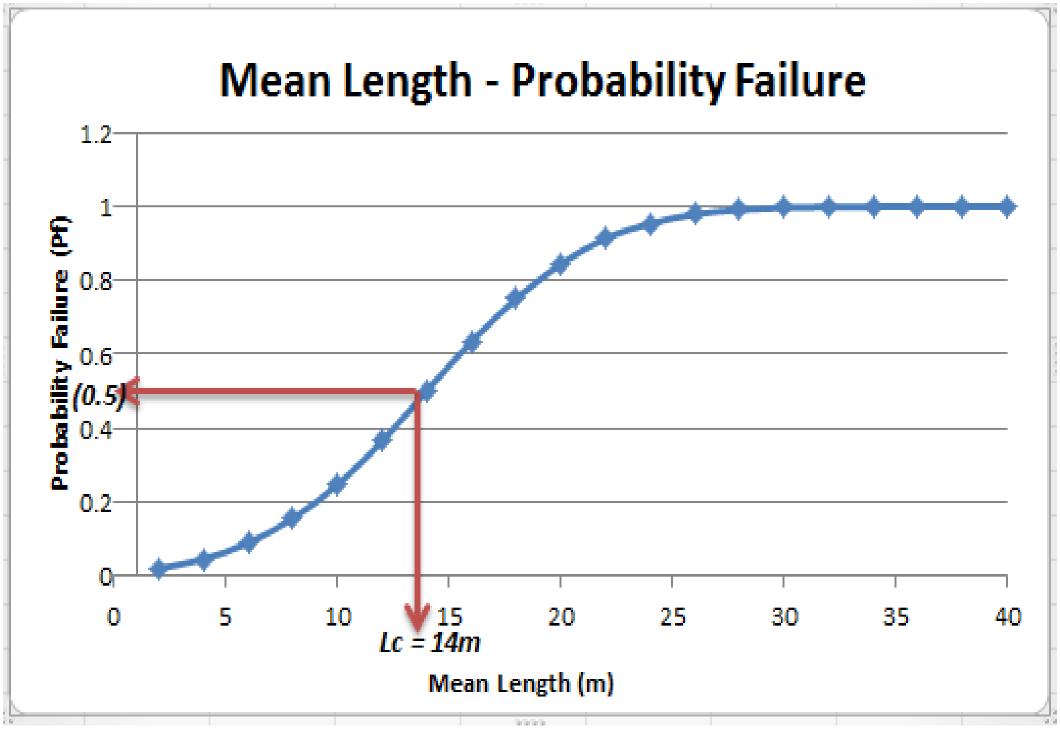
$$Z = Lc - Ls \tag{6}$$

where
Lc = Maximum Allowable Span Length (m),
Ls = Mean Span Length, Ls (m)

Lc represents the strength (R) and the Ls represents the load (S) . it is known that, when Z falls below 0, it indicates failure and when the value of Z is higher than 0, the pipeline is said to be under survival region. Graph 1 shows the result that has been computed for failure mode 1. The data for the graph obtained is attached as Appendix 1.

Table 5: Distribution of failure mode – Span Length

Random Variables	Unit	Symbol	PDF	Mean, μ	Standard Deviation
Effective mass	kg/m	M_e	-	361.20	-
Outer Diameter	mm	D	Normal	168.3	20.5
Wall Thickness	mm	t	Normal	8	2.1
Maximum Allowable Span Length	m	Lc	-	14	-
Span Length	m	Ls	Weibull	2-40	5.91608



Graph 1: Computed result for failure mode 1

The result shows that, at Lc = 14m, the probability of the pipeline to fail is about 50%. This shows that, under this failure mode, the pipeline still can be used although it has reached its maximum allowable span length. The pipeline still can be used up to the span length of 24m with the probability of failure of the pipeline is reaching 90%.

4.2.2 Failure Mode 2: Bending Moment

Bending moment is chosen as one of the failure mode because it is also one of the major contributions for pipeline failure. Pipeline that is subjected to additional loads due to temperature, installation purposes n etc are subjected to bending causing the pipeline to buckle and fail. As the length of the span increases the deformation of the pipeline increases causing the pipeline to laterally buckle and instable. Thus, the buckling is then developed into bending moment to know the probability of the pipeline to fail. For this failure mode, the data is well distributed in Normal Distribution function. The mean and the standard deviation obtained from the Normal Distribution function is then used in VaP simulation. The distribution of the failure model according to mean, standard deviation and Probability Density Function (PDF) is described in Table 6. Limit State Function that is created for this failure mode is,

$$Z = My - Mb \qquad (7)$$

where,

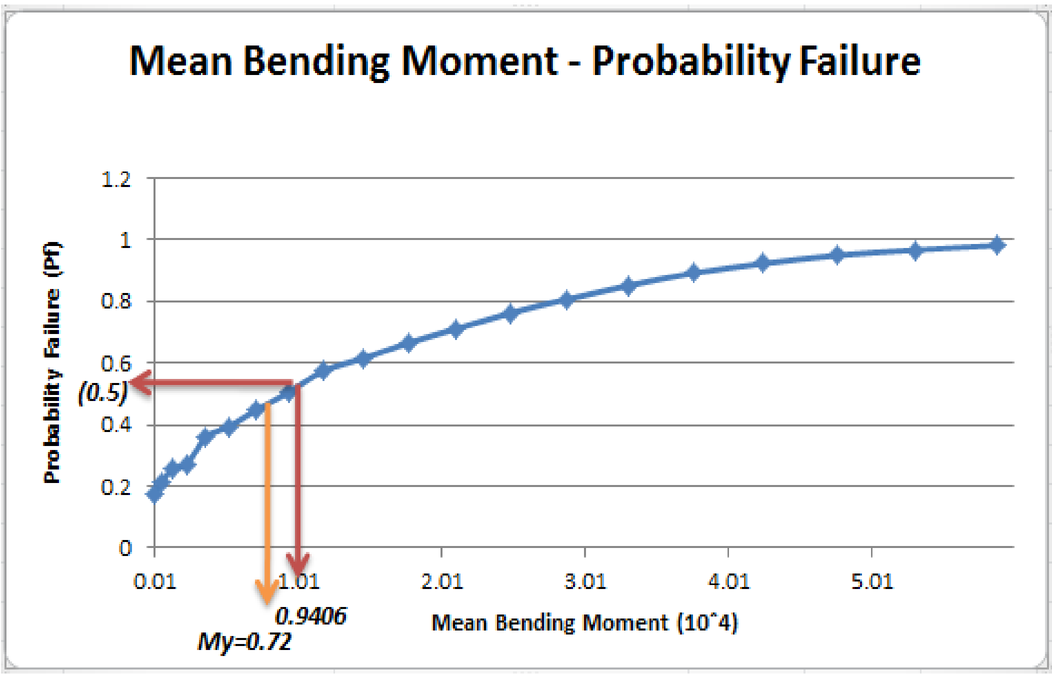
My = Maximum Allowable Bending Moment ($m^2.kg/s^2$)

Mb = Mean Bending Moment ($m^2.kg/s^2$)

My represents the strength (R) and the Mb represents the load (S) . As mentioned above, it is known that, when Z falls below 0, it indicates failure and vice versa. Graph 2 shows the result that has been computed for failure mode 2. The data for the graph obtained is attached as Appendix 2.

Table 6: Distribution of failure mode – Bending Moment

Random Variables	Unit	Symbol	PDF	Mean, μ	Standard Deviation
Effective mass	kg/m	M_e	-	361.20	-
Wall Thickness	mm	t	Normal	8	2.1
Pressure force per unit length	MPa	q	-	7.7	-
Span Length	m	Ls	Weibull	2-40	5.91608
Maximum Allowable Bending Moment	$m^2.kg/s^2$	My	-	0.72×10^4	-
Bending Moment	$m^2.kg/s^2$	Mb	Normal	0.015×10^4 - 5.9×10^4	2.48×10^4



Graph 2: Computed result for failure mode 2

The result shows, at Mb = $0.9406x10^4$ $m^2.kg/s^2$ the probability of the pipeline to fail is only 50%. This shows that, under this failure mode, the pipeline still can be used although it has reached its maximum allowable bending moment. The maximum allowable bending moment is $0.722x10^4$. As calculated, at 50% of probability of failure, the span length is 16m. As compared to the failure mode 1,at the probability of failure of the pipeline of 50% the span length is 14m. This shows that the pipeline still can be used up to 16m of span length, whereby 2m more than the maximum allowable span length. As compared to the failure mode 1 (span length = 14m), failure mode 2 (span length = 16m) is more reliable by 14.3%.

4.2.2 Failure Mode 3: Stress Analysis

Stress Analysis due to Vortex-Induced Vibration. Vortex-Induced Vibration is chosen as 1 of the failure mode mainly because of the current produced at the bottom of the pipeline causes dynamic stress to the pipeline. Thus, the dynamic stresses cause the pipeline to oscillate. The oscillation on the other hand causes the pipeline to fatigue and reduces the life of the pipeline. For this failure mode, the data is well distributed in Normal Distribution function. The mean and also the standard deviated is obtained by running simulation in BestFit The distribution of the failure model according to mean, standard deviation and Probability Density Function (PDF) is described in Table 7. Maximum Allowable Operating Pressure (MAOP) is a fixed variable in this case. Limit State Function that is created for this failure mode is,

$$Z = Sc - Ss \qquad (8)$$

where,

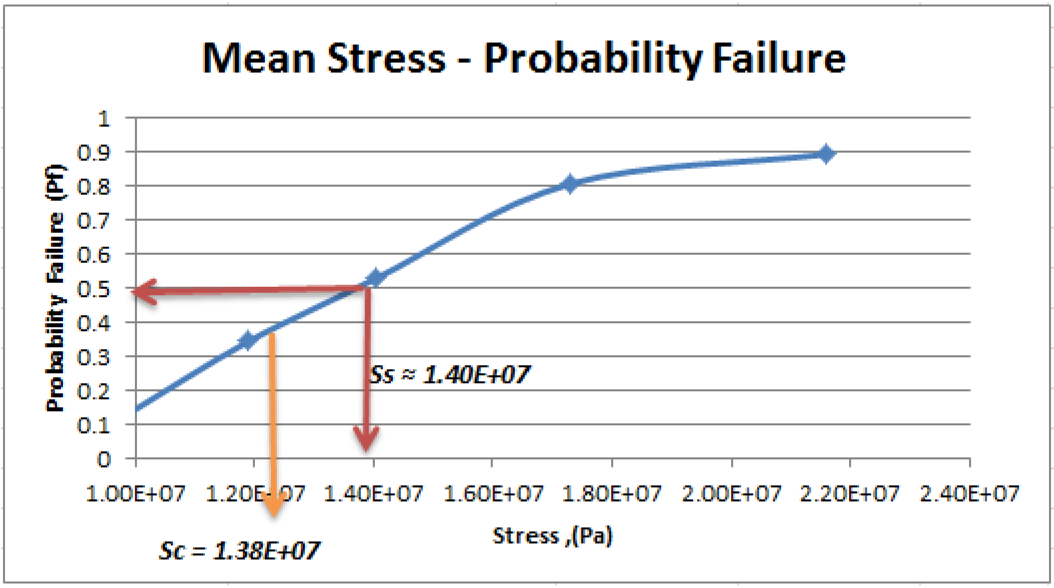
Sc = Maximum Allowable Stress (Pa)

Ss = Mean Stress (Pa)

Sc represents the strength (R) and the Ss srepresents the load (S). Graph 3 shows the result that has been computed for failure mode 3. The data for the graph obtained is attached as Appendix 3.

Table 7: Distribution of failure mode – VIV-Stress

Random Variables	Unit	Symbol	PDF	Mean, μ	Standard Deviation
Effective mass	kg/m	M_e	-	361.20	-
Wall Thickness	mm	t	Normal	8	2.1
Pressure force per unit length	MPa	q	-	7.7	-
Span Length	m	Ls	Weibull	10-36	5.91608
Maximum Allowable Stress	MPa	Sc	-	13.8	-
Stress	MPa	Ss	Normal	9.00 - 22.00	3.45



Graph 3: Computed result for failure mode 3

The result shows, at Ss ≈ 14.0MPa the probability of the pipeline to fail is only 50%. This shows that, under this failure mode, the pipeline still can be used although it has reached its maximum allowable stress. The maximum allowable stress is 13.8MPa. As calculated, at 50% of probability of failure, the span length is 20m.The span length at maximum allowable stress is at 14m which is also the probability of failure of 50% in failure mode 1. This shows that the pipeline still can be used up to 20m of span length, whereby 6m more than the maximum allowable span length in failure mode 1. As compared to the failure mode 1 (span length = 14m), failure mode 2 (span length = 20m) is more reliable by 42.9%. As compared to the failure mode 2, the bending moment, the span length that was obtained for probability of failure of 50% is at 16m. Thus, the difference of span length between failure mode 2 and failure mode 3 is by 4m. Failure mode 3 (span length = 20m) is more reliable by 28.6% as compared to failure mode 2 (span length = 16m). This shows that the pipeline still can operate although it has reached its maximum allowable span length (14m).

Table 8 below shows the reliability summarization of all three failure modes. Failure mode 3, the VIV-stress is the most reliable failure mode. This is because pipeline still can operate until it reaches a span length of 20m. It can operate at the reliability of 42.9% as compared to failure mode 1 and reliability of 28.6% as compared to failure mode 2.

Table 8: Reliability of pipeline

Type of Failure Modes	Reliability of Pipeline (%)		
	Failure Mode 1	Failure Mode 2	Failure Mode 3
Failure Mode 1		14.3	42.9
Failure Mode 2			28.6
Failure Mode 3			

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In conclusion, this project revolved around the theoretical research and analysis of Limit State Function model. This Limit State Function can be used to determine the reliability of pipeline. The Limit State Function model has been created for different failure modes. Different failure modes show different probabilities of failure of the pipeline. To consider a pipeline to failure, all possible probability of failure due to failure modes must be considered. This Limit State Function can be used to determine the reliability of pipeline. Failure mode 3, stress analysis is the most reliable failure mode with the reliability percentage of 42.9%. The maximum allowable span length, 14m is too stringent to be used as the limit for free span.

5.2 Recommendations

The suggested future work for this project will be the continuation of different type of failure mode. There are many types of failure mode that can be taken into consideration such as rate of corrosion, weather condition and etc. The reliability of pipeline can be known more accurately when all the failure modes are taken into consideration. Apart from that, the criteria used in the classification of the research can be further divided into more specific parameters such as Specified Minimum Yield Strength can be varied. A better result can be achieved through the establishment of more parameters or criteria. Besides that, the research can be furthered by performing mathematical modeling to obtain a more complete representation of Limit State Function.

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APPENDIX

Appendix 1

Mean Length	SD	Pf	Pf(%)
2	5.91608	0.021421	2.14214
4	5.91608	0.046577	4.65766
6	5.91608	0.09032	9.03203
8	5.91608	0.156687	15.6687
10	5.91608	0.247808	24.7808
12	5.91608	0.365986	36.5986
14	5.91608	0.501812	50.1812
16	5.91608	0.634665	63.4665
18	5.91608	0.750641	75.0641
20	5.91608	0.843934	84.3934
22	5.91608	0.913143	91.3143
24	5.91608	0.953714	95.3714
26	5.91608	0.978689	97.8689
28	5.91608	0.990951	99.0951
30	5.91608	0.996557	99.6557
32	5.91608	0.998859	99.8859
34	5.91608	0.99961	99.961
36	5.91608	1	100
38	5.91608	1	100
40	5.91608	1	100

Appendix 2

Mean Length (m)	Mean Bending Moment(10^4), ($m^2.kg/s^2$)	Standard Deviation (10^4), (m)	Pf (Length)	Pf (Bending Moment)
2	0.01469688	2.48	0.021421	0.17658
4	0.05878752	2.48	0.046577	0.209845
6	0.13227192	2.48	0.09032	0.255364
8	0.23515008	2.48	0.156687	0.271985
10	0.367422	2.48	0.247808	0.358671
12	0.52908768	2.48	0.365986	0.393674
14	0.72014712	2.48	0.501812	0.448148
16	0.94060032	2.48	0.634665	0.503834
18	1.19044728	2.48	0.750641	0.574575
20	1.469688	2.48	0.843934	0.616016
22	1.77832248	2.48	0.913143	0.664925
24	2.11635072	2.48	0.953714	0.711411
26	2.48377272	2.48	0.978689	0.761291
28	2.88058848	2.48	0.990951	0.806717
30	3.306798	2.48	0.996557	0.850761
32	3.76240128	2.48	0.998859	0.891642
34	4.24739832	2.48	0.99961	0.922392
36	4.76178912	2.48	1	0.948609
38	5.30557368	2.48	1	0.966707
40	5.878752	2.48	1	0.981832

Appendix 3

Mean Length	MAOP (10ˆ6)	Maximum Allowable Stress Stress	Mean Stress	SD	Pf	Pf(%)
10	7.70E+06	1.38E+07	9.83E+06	3.44E+06	0.1254	12.54
14	7.70E+06	1.38E+07	1.19E+07	4.70E+06	0.3431	34.31
20	7.70E+06	1.38E+07	1.40E+07	3.55E+06	0.5252	52.52
25	7.70E+06	1.38E+07	1.73E+07	4.12E+06	0.804	80.4
36	7.70E+06	1.38E+07	2.16E+07	6.32E+06	0.8905	89.05