SEA FORCES ON SUBSEA PIPELINES

by

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Dissertation submitted in partial fulfillment of the requirements for the

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CERTIFICATION OF APPROVAL

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Approved by,

(AP Dr Saied Saiedi)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

July 2008

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.

MOHD ASYRAFI BIN ABD HALIM

Abstract

Subsea is a general term frequently used to refer to equipment, technology, and methods employed to explore, drill, and develop oil and gas fields that exist below the ocean floors. This may be in "shallow" or "deepwater". Subsea production systems can range in complexity from a single satellite well with a flow line linked to a fixed platform, FPSO or an onshore installation, to several wells on a template or clustered around a manifold. Pipeline is one of the most important methods of transportation. It is widely used in fluid and gas transportation because of its cost-effectiveness. In the context of my research, 'Subsea Pipeline' means any type of pipelines that is laid on the seabed and anchored/tied to the soil and is located underwater. The pipeline can be of any type; gas pipeline, hydrocarbon pipeline, water/wastewater pipeline, etc. The target project for my project will be the Betty Revisit-4 Project, by Petronas Carigali Sdn Bhd. The purpose of my research is to determine the forces acting on the subsea pipeline coming from sea waves and current. For the current part, two forces are acting on the pipeline: lift and drag. As for the wave, there are drag and inertia forces. This research will focus on both effects on the pipeline. However, during further investigations, it is noted that the pipeline of my target project is located in a deepwater site, so wave effects are generally negligible. Effects of sea forces on a subsea pipeline is often a wave-current dynamic problem. To explore the mechanism of the effects, a series of experiments in the wave tank is conducted. In the end, the results will be compared to the results provided in the spreadsheet by PCSB and its consultant, RnZ and with previously investigated interactions – wave-soil-pipe and pipe-soil interactions, with manual calculations as a guide.

Acknowledgements

I would like to take this opportunity to thank my supervisor, Dr Saied Saiedi for guiding me throughout this project. My colleagues, Husna and Azam, who have always helped me in this project. The FYP Committee for organizing all the useful seminars and talks about preparing FYP presentations and reports. Not forgetting lab technicians who had been very helpful throughout the FYP I duration. The library staffs that always helped me when I'm in need of a very specific materials. My colleagues, who have motivated me and given me helpful thoughts and hints on how to manage an FYP projects. My father and mother, who have always given me unconditional love, thank you very much.

Abbreviations and Nomenclatures

DNV	Det Norske Veritas, Norway
Fr Number	Froude Number
KC Number	Keulegan Carpenter number
OGT	Oil and Gas Terminal
PTS	Petronas Technical Standards
Re Number	Reynolds Number
UTP	Universiti Teknologi Petronas

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Chapter 1: Introduction

In oil and gas production, pipeline transportation has been vital to the industry. Examples of prominent petroleum pipelines are The Greater Nile Oil Pipeline (1600km), Baku-Tbilisi-Ceyhan Pipeline (1768 km) and The Langeled Pipeline (1200 km). Most of the oil pipelines in the world are located underwater as it is a cost-effective mode of transportation for a long term oil production.

This project will focus on sea forces on subsea pipelines. Model pipeline is tested inside wave tank according to set parameters. Parameters are obtained from Betty Revisit-4 Project (New Pipeline). This project uses Froude Modeling Theory to scale down the prototype.

Since the study deals with deepwater environment, inertia effects of oscillating flow due to waves are ignored. Only force due to current is considered.(Jeoung, Park, & Jo, 2002).

Pipeline design

Designing pipelines requires advanced knowledge about hydraulics, ocean waves, currents and soil parameters. Many researchers have done studies on this topic, and a few design methods have been proposed, but until now, there's no perfect method that can be applied to all designs. Some design methods placed constrains in their parameters, which makes it difficult to determine a 'perfect' method of design.

However, almost all the design methods use wave and wind records as their main parameters. Wave records are usually measured in continuous surface height, i.e. a 10 minute record for every 3 hours. To reliably use wave data, an engineer must have access to wave data of 5 years or more. Then, by using extremal statistics, the extreme waves will be predicted. Sarpkaya (1981) already discussed about this in detail. All the issues involving external distributions are merely academic because all that is required is to fit the data and extrapolate it (Palmer & King, 2004). If no wave data available, an engineer could use wind data. However, this will not be elaborated as it is out of scope of this research.

Wave data

In designing using the wave data, the return time and extreme waves are generally related to each other. Return time is basically the average time interval between successive events in which design wave is exceeded (Palmer & King, 2004). The general equation used is:

$$E = 1 - e^{-L/T_R} \qquad \text{Equation 1}$$

Where, E = encounter probability

T_R = Return period

L = Design lifetime

For general pipeline design, using T_R 50-100 years is enough.

However, cautions should be taken as the extrapolation process is purely statistical and may lead to overdesign. The extreme wave may be limited by physical factors, notably by breaking.

1.1 Background of Study

My project, titled "Sea Forces on Subsea Pipelines" will take an in depth look at effects of sea forces (wave, current etc.) to subsea pipelines. There are many types of pipelines; gas pipeline, hydrocarbon pipeline, water/wastewater pipeline, etc. The project will concentrate on the external forces acting on a subsea pipeline, regardless of its functions. There are 3 (three) major types of pipeline, namely Gathering Pipelines, Transportation Pipelines and Distribution Pipelines. Since my project's concern is only on subsea pipelines, the priority is given to Gathering and Transportation pipelines as most of subsea pipelines falls under this category.

This study will concentrate on two major forces: waves and currents, but neglect the soil-pipeline interaction. This is because there are many researchers that already worked on this interaction, for example (Xiaoyun, Fuping, & Qun, 2001).

1.2 Problem Statement

Many researchers have done studies on wave, wave-current, current-soil and wave current soil interaction. This project will focus on sea forces – wave and current. The measured experiment result will be analyzed and compared with theoretical/calculated values.

The theoretical values are obtained from manual calculations using hydrodynamic equations. This includes the current, drag, wave, lift and many other relevant parameters.

There is also a spreadsheet to calculate total force on the pipeline. This spreadsheet is based on DNV standards. A few important parameters are needed in order to yield the result for example, significant wave height, peak wave period, pipeline diameter, thickness and current speed.

In the end, the results from the practical experiment, theory and the spreadsheet will be discussed and compared to each other.

1.3 Objectives and Scope of Study

In order to achieve the goals set by this project, the scaled down model of the 18", 12" and 8" pipeline must be built. Factors taken into considerations are: self weight, diameter, coatings, and surface roughness.

The model is then tested inside the wave tank. The resultant force caused by the current is then recorded and plotted in the graph.

Apart from that, theoretical calculations are also completed. This includes modeling theories, wave-current force calculations and many other calculations.

The measured data is then compared to calculated data and the spreadsheet provided.

We want to identify and investigate sea forces on subsea pipelines. These forces are identified and included in calculations for the model and the prototype pipeline. Most of it comes from the current as the project pipeline is in deepwater site. One of the main objectives is to compare the measured results with theoretical values, obtained from spreadsheet (DNV) and our manual calculations.

This project also proposes modification for more accuracy in the experiment that has been done.

Chapter 2: Literature Review

To examine the effect of sea forces on a subsea pipelines, a series of experiments involving the usage of wave flume and pipeline model will be done in the hydraulics laboratory throughout the project duration. Since the actual pipeline is too big for the experiments, the pipeline sizes will be scaled down using certain formulas that will be determined later.

In my FYP I, the project chosen was the Resak Pipeline. However, due to internal difficulties and the condition of the problematic project, the plan to use the project is scrapped. Instead, the project is replaced with Betty Revisit-4 pipeline.

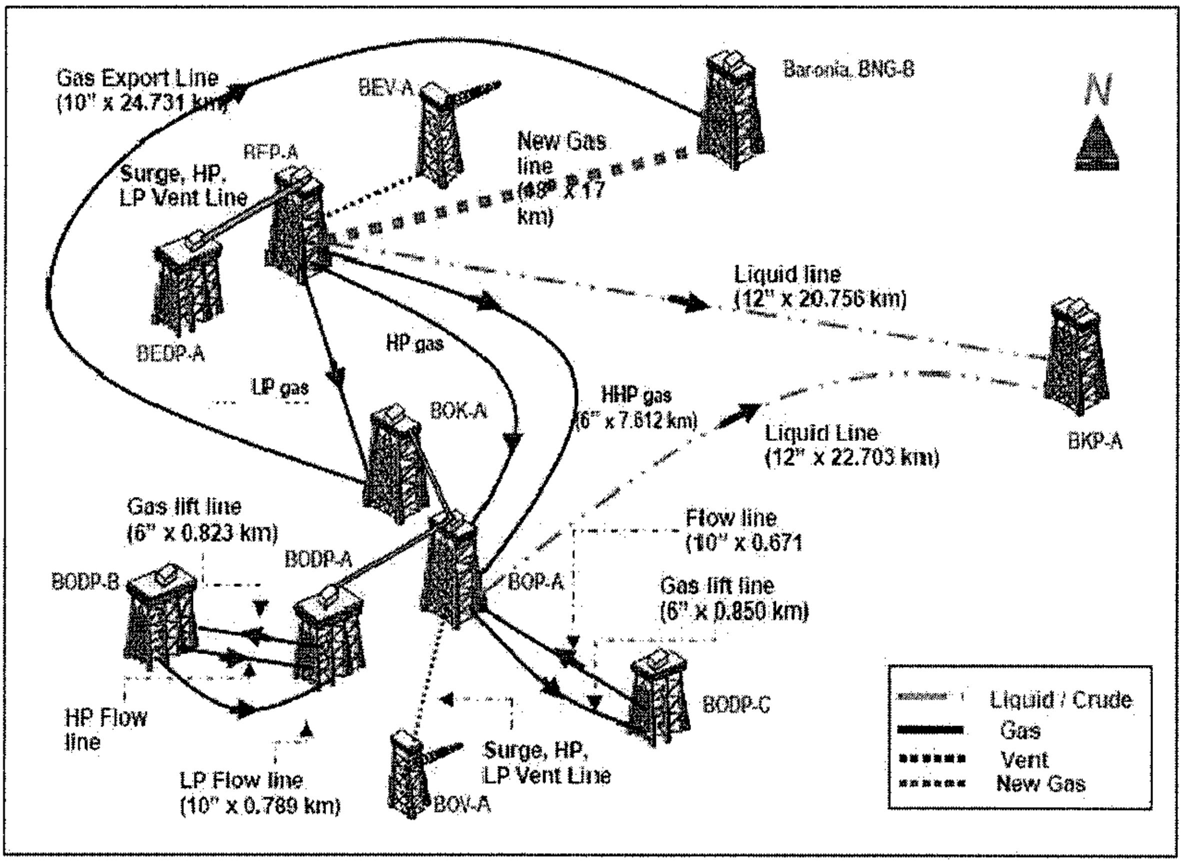

Figure 1: Betty Field

The purpose of the project is to redevelop Betty field 40km offshore NW of Lutong, Miri, Sarawak and constitutes SW part of Baram delta province.

New 18" wet gas pipeline from Betty to Baronia suitable for internal inspection. POGSB, a pipeline design consultant is responsible for the Detailed Design Engineering for the new 18" pipeline. The scope of this project is from BEP-A hanger flange to BNG-B platform hanger flange.

In designing this pipeline system, PTS 20.196 is used.

Table 1: System Design and Operating Parameters

Parameter	**BEP-A**	**BNG-B**
Coordinates	792880.30E, 510015.02N	802388.232E, 524435.623N
Nominal Diameter	18"	
Outside Diameter	457mm	
Service	Wet Gas	
Pipeline length	17.879km	
Design pressure	389 psig	
Design temperature	177^0F / 81^0C	

Overall density (kg/m^3)	
Phase 1 (2008)	14.0
Phase 2 (2009)	15.0
Phase 3 (2012)	18.0
Structural Damping coefficients	0.126

Table 2: Environmental parameters

Parameter	**BEP-A**	**BNG-B**
Water depths (ft) (m)	239 / 72.85	250 / 77.45
Tides (m)		
HAT	2.1	
MSL	1.2	
LAT	0.0	
Storm Surge (m)		
1 year	0.3	

10 years	0.4
100 years	0.6

For other parameters (Storm surge, wave and current criteria, seawater properties, splash zone, hydrodynamic coefficients, etc) please refer to Appendix I.

2.1 Theory

In this research, there are two parts of theories present. First the wave/current force part. This theory is used to predict the force that will affect the pipeline that is being used in the research. The second part of theory will discuss primarily on the modeling scale of the experiments. This is important, too as we are going to compare the model performance compared to the prototype performance.

2.1.1 Force Theory

This research revolves around the forces on the pipeline created by movement of water body. In general, there are two types of forces that this research is dealing with; wave forces and current.

Current

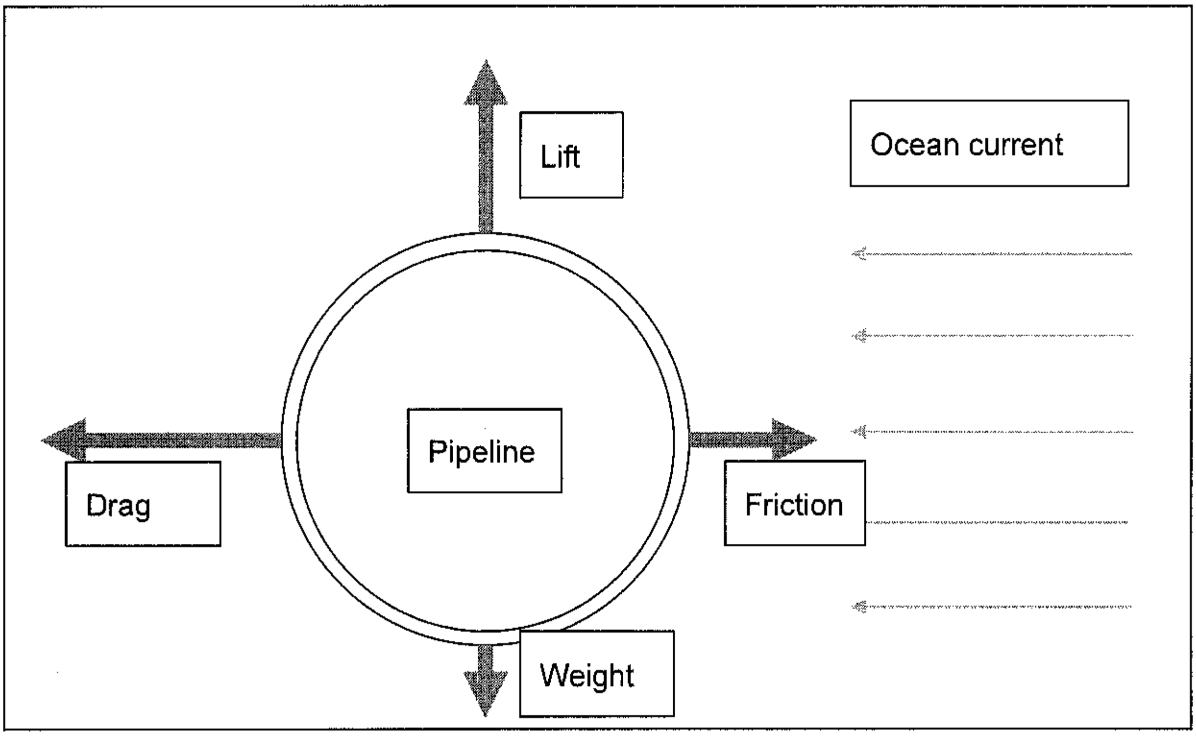

Figure 2: Forces on Pipeline due to Current

Current can be defined as continuous, directed movement of ocean water, often uni-directional. For any pipeline structure that is lying on the seabed, there are two forces acting on it under sea current, drag and lift forces. This is shown by Figure 1.

General equation for forces due to current is:

$$\boldsymbol{F} = \boldsymbol{F_x} + \boldsymbol{F_y}$$ **Equation 2**

F_x and F_y are the x and y component of the force, respectively. They can be solved as:

$$F_x = \frac{1}{2}\rho C_D D U^2$$ **Equation 3**

$$F_y = \frac{1}{2}\rho C_L D U^2$$ **Equation 4**

Where, F_x = horizontal force per unit length of pipeline

F_y = vertical force per unit length of pipeline

ρ = density of water

C_D = drag coefficient

C_L = lift coefficient

D = outside diameter of pipeline

U = velocity of water normal to pipe axis

Wave

Waves are created when there are unsteady flows around the pipeline. The pipeline may be in an oscillatory wave-induced current, from tide, storm and ocean circulation.

Most of the analysis uses the Morison equations. These equations are almost universally used in the offshore industry (Palmer & King, 2004).

$$F_x = \frac{1}{2}\rho C_D Du|u| + \left(\frac{\pi}{4}\right)\rho D^2 C_M \left(\frac{du}{dt}\right) \quad \textbf{Equation 5}$$

$$F_y = \frac{1}{2}\rho C_L DU^2 \quad \textbf{Equation 6}$$

Where, F_x = horizontal force per unit length of pipeline

F_y = vertical force per unit length of pipeline

ρ = density of water

CD = drag coefficient

CL = lift coefficient

CM = inertia coefficient

D = outside diameter of pipeline

U = instantenous velocity of water

du/dt = horizontal acceleration of water

|u| = u absolute

The first part of this equation is similar to Equation 3 and 4, except for the modulus part. This is to ensure that the sign changes according to the direction of forces. The second term of Morison Equation is called the *inertia* equation. A body in an accelerating fluid is subjected to a force equal to the mass of fluid displaced times acceleration. This is called the Froude-Krylov force. Imagine the pipe is moving, instead of the water moving. As we can see in figure, the accelerating pipe will create a void space where it should have been located. This space will be replaced by water and this, in turn, will create a force, equal to the water mass.

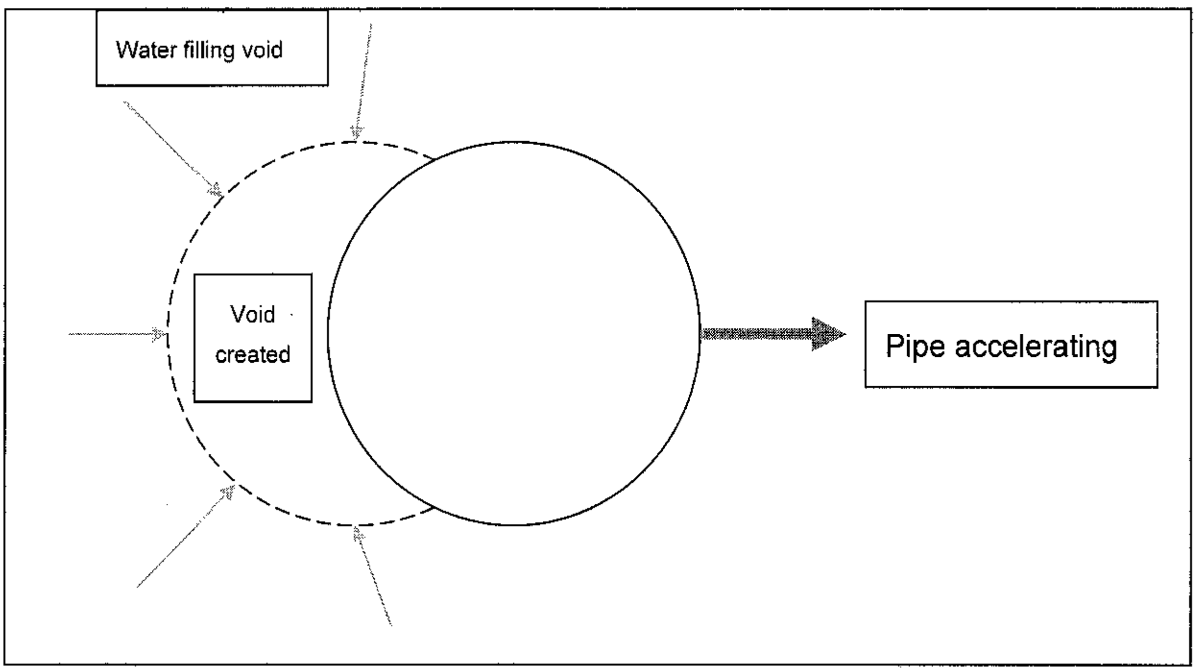

Figure 3: Inertia in Accelerating Body in Fluid

Normally the value of C_M is 1, but sometimes an additional acceleration of fluid around the pipeline caused the value of C_M to be more than 1.

There is no inertia term for Equation 6 because there is no vertical acceleration.

The horizontal acceleration du/dt is given by

$$\frac{du}{dt} = \frac{\delta u}{\delta t} + u\left(\frac{\delta u}{\delta x}\right) + v\left(\frac{\delta u}{\delta y}\right) \qquad \textbf{Equation 7}$$

Coefficient values

There are a few coefficients in equations 3-6. To be exact, the coefficients are C_D, C_L and C_M. What are these coefficients and what are their values? C_D and C_L depend on roughness of pipe and the kinematic viscosity of water. Both are functions of Reynolds number.

As per recommended by (US Army Coastal Engineering Research Center, 1984), drag and inertial coefficients are as follows:

Table 3: US Army Coastal Engineering Research Center recommendation (Cd)

$Re < 10^5$	$C_D = 1.2$
$10^5 < Re < 4x10^5$	$C_D = 1.2$~0.6
$Re > 4x10^5$	$C_D = 0.6$~0.7

Table 4: US Army Coastal Engineering Research Center (Cm)

$Re < 2.5x10^5$	$C_M = 2.0$
$2.5 \times 10^5 < Re < 5x10^5$	$C_M = 2.5\text{-}Re/5x10^5$
$Re > 5x10^5$	$C_M 1.5$

Therefore, as per recommended by US Army Coastal Engineering Research Center, Reynolds numbers for 4" and 3" pipe are calculated.

Assume kinematic viscosity of fresh water = $1x10^{-6}$

u = 0.14 m/s (see Methodology)

D = 4" = 0.106m

$$\therefore Re = \frac{Du}{\vartheta} = \frac{0.106(0.14)}{10^{-6}} = 14840$$

D = 3" = 0.076

$$\therefore Re = \frac{Du}{\vartheta} = \frac{0.076(0.14)}{10^{-6}} = 10640$$

Therefore, both are recommended to use C_D = 1.2 and C_M = 2.0.

Values recommended by other prominent authors on this subject can be seen in Table 5.

Table 5: Nominal values for coefficients

Coefficient	(Palmer & King, 2004)	(Sorensen, 1997)
C_D	0.7	2.0
C_L	0.9	3.0
C_M	3.29	2.5

As we can see, (Sorensen, 1997) is a bit conservative in selecting coefficients compared to (Palmer & King, 2004). However, we will use the values provided by the Betty Revisit-4 documents:

- $C_D = 0.7$
- $C_L = 0.9$
- $C_M = 3.29$

2.1.2 Modeling Theory

For a model scale of 1:100 to 1:200, it is virtually impossible to maintain the Reynolds similitude (Chakrabarthi, 1994).

According to (Chakrabarthi, 1994), flow characteristics in the boundary layer are most likely to be laminar at $Re<10^5$, while the boundary layer is turbulent at $Re>10^6$. Thus, small model would yield laminar flow while full-scale conditions are evidently turbulent. Therefore, we use Froude similitude, by allowing variations in Reynolds number (Gao, Gu, & Jeng, 2002). Chakrabarthi later explains that the dependence of drag coefficients on Reynolds number is quite strong because it characterizes the flow as laminar, transition or turbulent. However, this only goes as far as transition flow. Once the flow becomes turbulent, the dependency is reduced to the extent it is negligible.

The equations used are as follows:

Froude Number:

$$\mathbf{Fr} = \frac{\mathbf{U_m}}{(\mathbf{gD})^{1/2}} \qquad \text{Equation 8}$$

Froude number is the ratio of inertia force to gravitational force.

For KC number:

$$KC = \frac{U_m T}{D} \qquad \text{Equation 9}$$

KC number is the Hydrodynamic force on the pipe under wave loading.

For Reynolds number:

$$\boldsymbol{Re} = \frac{\boldsymbol{U_m D}}{\boldsymbol{v}}$$ **Equation 10**

Since both Fr and Re cannot be satisfied concurrently on model test, Froude scaling is used mainly and variations are allowed for Re up to 2 magnitudes (Chakrabarthi, 1994).

According to Froude's Law

$$\frac{\lambda_{U_m}}{\lambda_g^{1/2}\lambda_D^{1/2}} = 1$$ **Equation 11**

Since $\lambda_g = 1$

$$\lambda_{U_m} = \lambda_D^{1/2}$$ **Equation 12**

$$\lambda_T = \frac{\lambda_D}{\lambda_{U_m}} = \lambda_D^{1/2}$$ **Equation 13**

Therefore;

$$\lambda_{KC} = \frac{\lambda_{U_m}\lambda_T}{\lambda_D} = 1$$ **Equation 14**

This proves that Froude and KC number can be satisfied concurrently in our model test. The range for Froude and KC number for the South China Sea are 0-0.5 and 0-20, respectively. If the experimental values fall between these ranges, they can be accepted. The Reynolds number is smaller than the actual value by two orders (Gao, Gu, & Jeng, 2002).

However, the use of Froude Modeling scale is limited because in this project, there will only be current acting on the pipeline. Since Froude only accommodates wave and current, we have to use Reynolds similitude anyway. The modeling theory will only become important when we're going to compare the prototype with the theoretical values from the actual pipeline.

According to (Chakrabarthi, 1994) the model to prototype scale factor of Froude model can be summarized in the next table:

Table 6: Scale factor of Froude model

Variable	**Unit**	**Scale Factor**
Length	L	λ
Area	L^2	λ2
Velocity	LT^{-1}	$\lambda^{1/2}$
Force/Thrust/Resistance	MLT^{-2}	λ^3

When using Froude's Law, the Reynolds law becomes:

$Re_p = \lambda^{3/2} Re_m$

Thus, as C_M and C_D are strong functions of Re, results from model tests are not directly applicable to the design (Chakrabarthi, 1994). Some modifications have to be made to the results.

2.3 Scour Protection

When a structure is considered vulnerable to scour that may result in loss of stability, protective measures are taken to ensure that stability is maintained. Scour protection can be classified as passive or active (Chakrabarthi, 1994). Active scour protection is, by definition, protecting structure from scour by reducing disturbing forces. The protection is called passive when the foundation ability to resist scouring is increased.

Many commercial devices are available to reduce flow at the structure's base.

2.4 On-bottom Stability Analysis

A pipeline has to be stable on the seabed. If it's too light, it'll sway sideways under current and waves. If it's heavy, it will be expensive and difficult to construct.

There are a few solutions available in increasing the stability of the pipeline. External concrete coating can be added to the pipeline. Another alternative is to increase the diameter of the pipeline. This is expensive, especially if we're using corrosion-resistant alloy. Other options, by manipulating environment, are to trench the pipeline into the seabed or burying it in the seabed/covering it with rock.

Basically, the on-bottom stability analysis of submarine pipeline is performed to determine the stability of pipeline resting on the seabed. The submarine pipeline resting on the seabed is subjected to environmental forces which can result in instability of pipeline. Therefore, these analyses need to be carried out in order to determine the stability requirement of the submarine pipeline. The On-Bottom Stability analysis covers the aspects such as wave mechanics, hydrodynamic forces and pipeline-soil interaction. The aspect of hydrodynamic forces already mentioned in the previous subsection while the pipeline-soil interaction can be defined as the interaction of the contact between the pipeline and the seabed and this interaction consists of seabed stiffness and friction definition. The contact pressure between the pipeline and the seabed governs the friction force keeping the pipeline stable on the seabed. However, the study will focus on the effect of waves and current loading and will not include the pipeline-soil interaction aspects.

2.5 Stability Design

The process of stability design brings together the methods of wave/current prediction, hydrodynamic force calculations from currents and lateral resistance analysis (Palmer & King, 2004). When designing, the engineer must confirm that the stability condition is satisfied. If not weight has to be added to generate more lateral resistance. However, there's a catch. By adding the weight externally, the hydrodynamic force has to be recalculated. This can be easily computed by a computer program thus assisting in rapid designing process.

Chapter 3: Methodology

3.1 Methodology

The experiments will be conducted in a wave tank. The models are constructed by using a simple PVC pipe filled with gravel. The pipe was laid freely on the bottom of the wave tank. It was connected to a 5N scale with 0.5N sensitivity (Salter).

The subsea pipe generally has a large span, so the model might be treated as a two-dimensional structure in a wave tank test.

The experiment will be conducted by using slow flow, and increasing incrementally, before decreasing at the same rate. Data obtained are in the form of force vs. time/velocity.

The results for the model will then be translated into prototype data that will be plotted in a graph and compared with the spreadsheet/theoretical calculations.

A few variables have been identified for the experiment. They are:

1. Pipe diameter (3", 4")
2. Pipe weight (12kg, 14kg, 16kg, 20kg, 22.5kg, 25kg)
3. Current (0.1-0.2m/s)

These variables will be adjusted according to their respective model diameters.

3.2 Facilities and Instruments/Model

3.2.1 Facilities and instruments

Wave Tank

The wave tank is basically a water tank with a dimension of 22.86m x 12m and maximum water level of 1.0m. For wave generation, however, a maximum of 0.6m water level is allowed to avoid splashes. For this project, we use 0.5m water depth.

The first run of the wave tank was conducted and a spot was chosen as the place of experiment setup based on a few criteria:

1. Current speed
2. Stability of current
3. Variation of vertical current profile
4. Matched with experimental setup

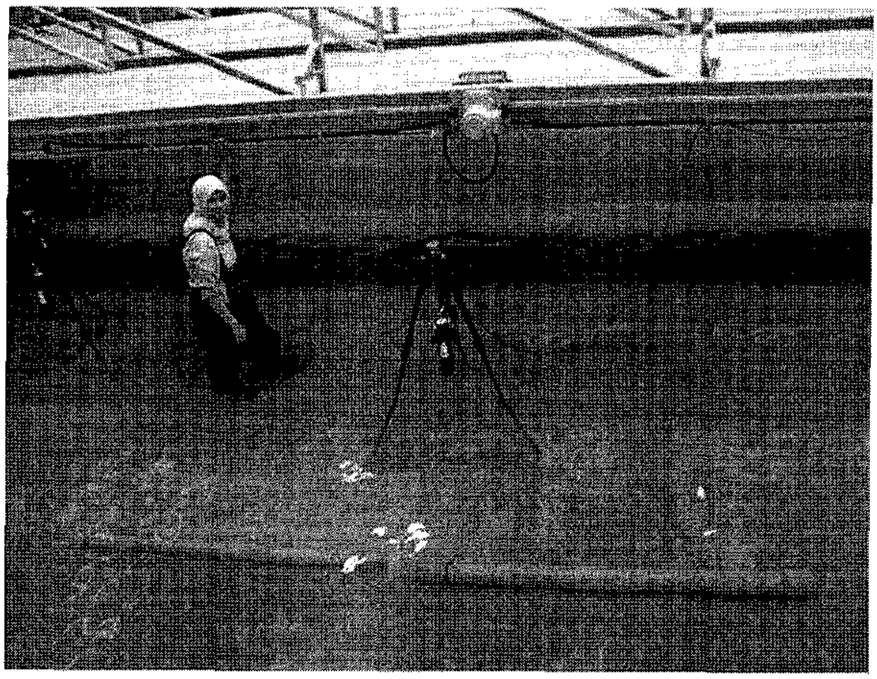

Figure 4: Two tested pipes on the floor

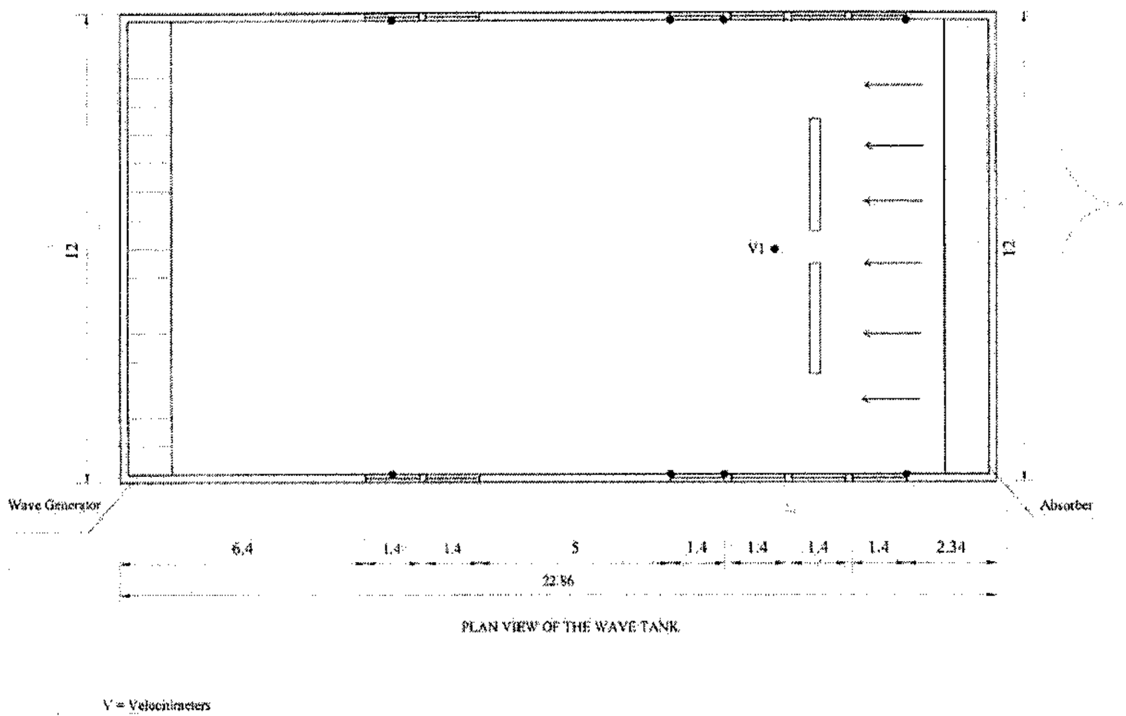

Figure 5: Plan view of experimental setup

As for the current generation, a profile has been established for the surface, middle and bottom of flow. The flows can be seen in appendix 4. v_{rms} for bottom profile is 14.3891m/s.

Scale

Salter scale was used with maximum weight 50N. Its sensitivity is 0.5N. This scale will be recorded with a camcorder for further studies of the data.

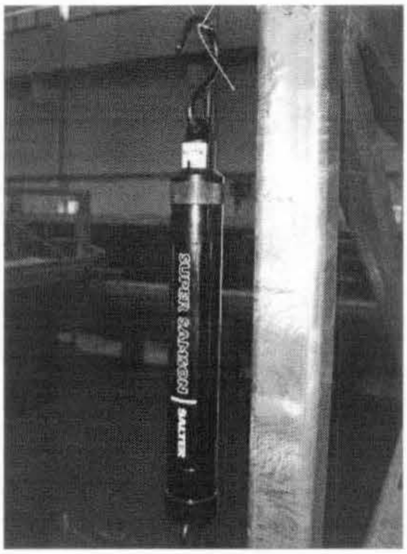

Figure 6: Salter scale (up to 50N)

3.2.2 Pipeline model

The model is rested on the wave tank bed. The pipeline models are PVC pipes, 1.5m long each. Three different diameters are used; 6", 4" and 3". Sand and stones are used to fill up the pipeline model to simulate self weight of the pipeline.

Two scales are hanged as illustrated in Figure 8, connected to the model pipeline using a wire. Since the project only involves currents, the unidirectional force can be directly measured by the digital scale.

The pulley's mechanism used in the set up is shown in Figure 7.

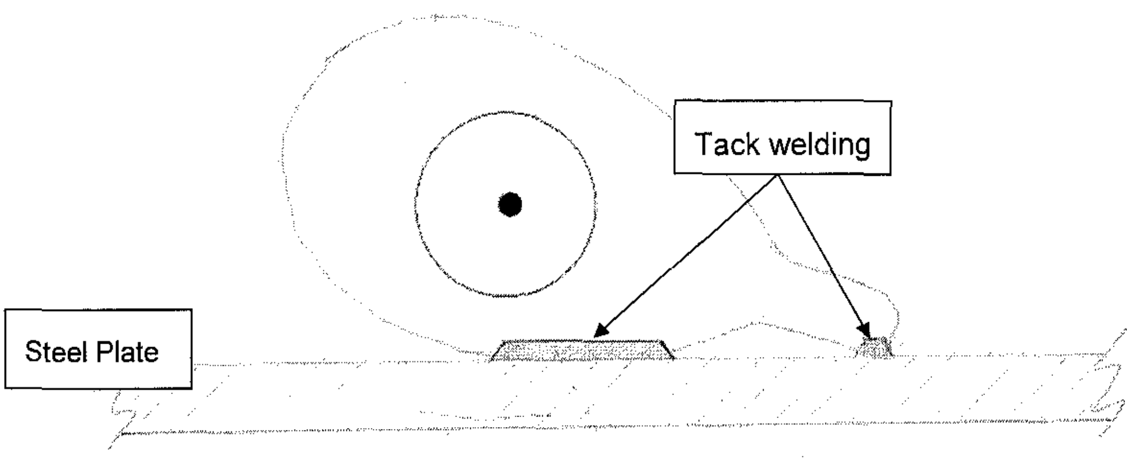

Figure 7: Pulley Mechanism

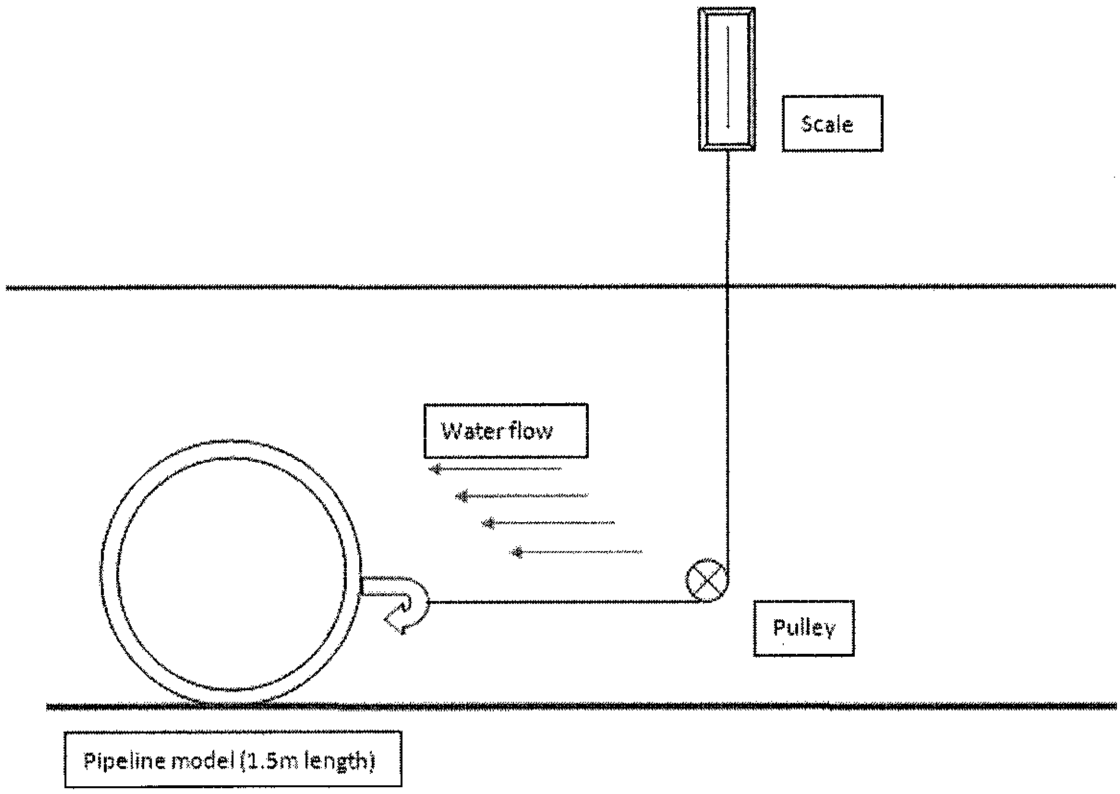

Figure 8: Pipeline on wave tank bed

To ensure that the pipe stays at the bottom of wave tank, a calculation to determine its buoyancy is calculated.

$$B = \rho V g$$

$$B = 1000(V)(9.807)$$

3" pipe:

$$V = \frac{\pi(0.076^2)}{4}(1.5)$$

$$B_{3in} = 67.1N = 6.8kg$$

4" pipe:

$$V = \frac{\pi(0.102^2)}{4}(1.5)$$

$$B_{4in} = 120.2N = 12.26kg$$

Therefore minimum weight for pipe is ~7kg and ~13kg for 3" and 4" pipe, respectively. However, during trial run, it is observed that 10kg and 15kg are not sufficient for 3" and 4" pipe weight, respectively. This may be caused by extra buoyancy from the cap of the pipe, which is quite significant. So the next value of weight is used in the experiments.

3.3 Hazard Identification

Hazard identification is necessary to avoid implications later on when doing the experiments. Identifying hazards before it occurs often can save time, money and even life. There are a few vital areas that had been identified as hazardous, and a few steps had been taken as a cautionary measure. They are:

3.3.1 Noise

These experiments will require the usage of a powerful pump that generates a lot of noise. To counter the side effect of noise, ear mufflers will be used, and the pump had been isolated during the installation of the flume.

3.3.2 Vibration

There will be a lot of vibration by the pumps that generate currents for our flume. Therefore precautionary steps have been taken by padding the pump area (done during pump installation).

3.3.3 Electrical

As the experiments will mainly use high electricity power to operate the pump, some cautionary steps have been taken:

1. Isolate the plug from water tank/pump.
2. Use rubber insulator to cover the switchbox in case of overflowing of water tank.
3. Only operate the pump when proven necessary.

3.3.4 Dust

No dust hazard identified in the lab experiments.

3.3.5 Fire and Explosion

Although most of the equipments use water, fire and explosions hazard do exist as the pump uses high electricity energy. Since the nature of fire hazards in my experiments are water-electricity related, conventional water-based fire extinguishing plan is unsuitable. Instead, dry-chemical and foam-based fire extinguisher are prepared as a contingency plan.

Chapter 4: Results and Discussion

4.1 Results

There are three results in this project:

1. Experiment results
2. Manual calculations
3. Spreadsheet results (DNV standard)

The results will be discussed one by one.

4.1.1 Measured Experiment

For 3" pipe

W = 12kg

F_{net} = 2.74N per 1.5m length = 1.8N per m length

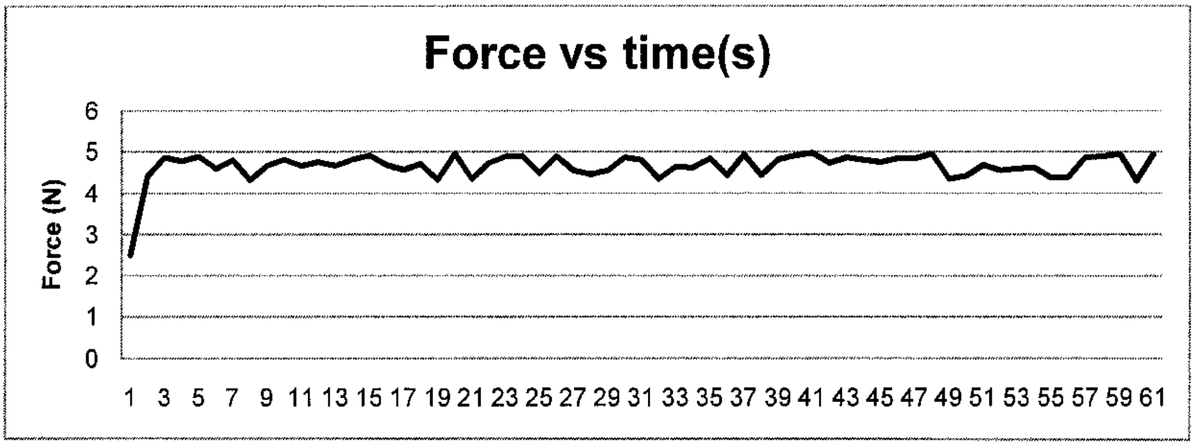

Figure 9: Force vs Time, 3" pipe, W=12kg

W = 14kg

F_{net} = 2.53N per 1.5m length = 1.68N per m length

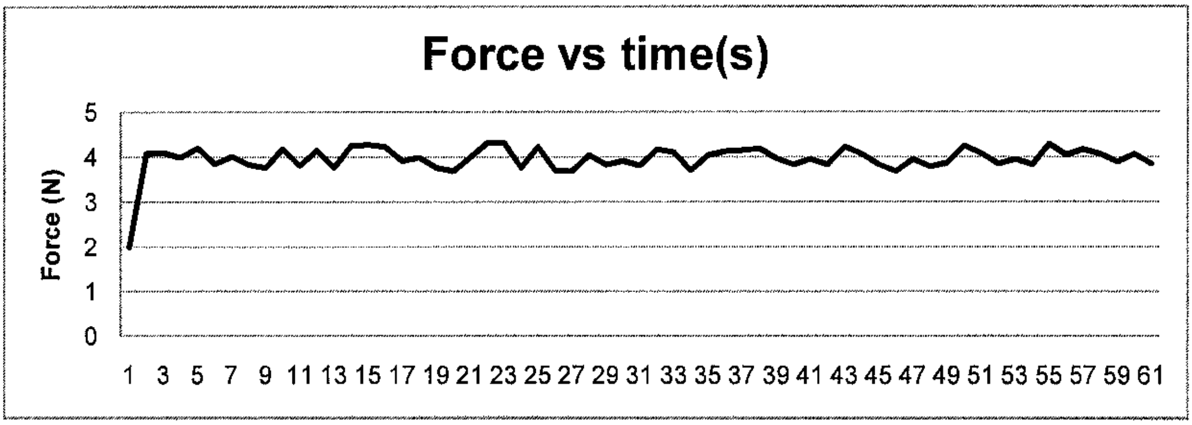

Figure 10: Force vs Time, 3" pipe, W=14kg

W = 16kg

F_{net} = 2.50N per 1.5m length = 1.67N per m length

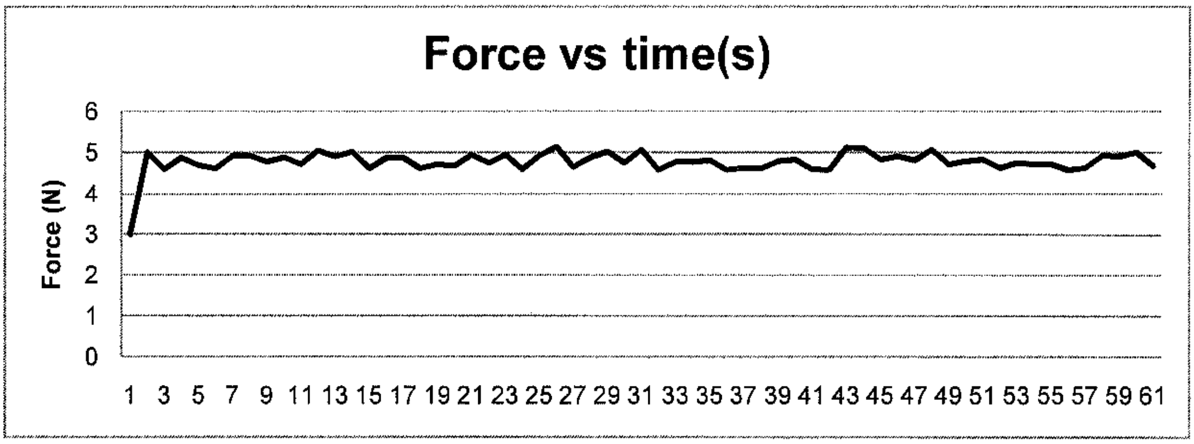

Figure 11: Force vs Time, 3" pipe, W=16kg

Summary:

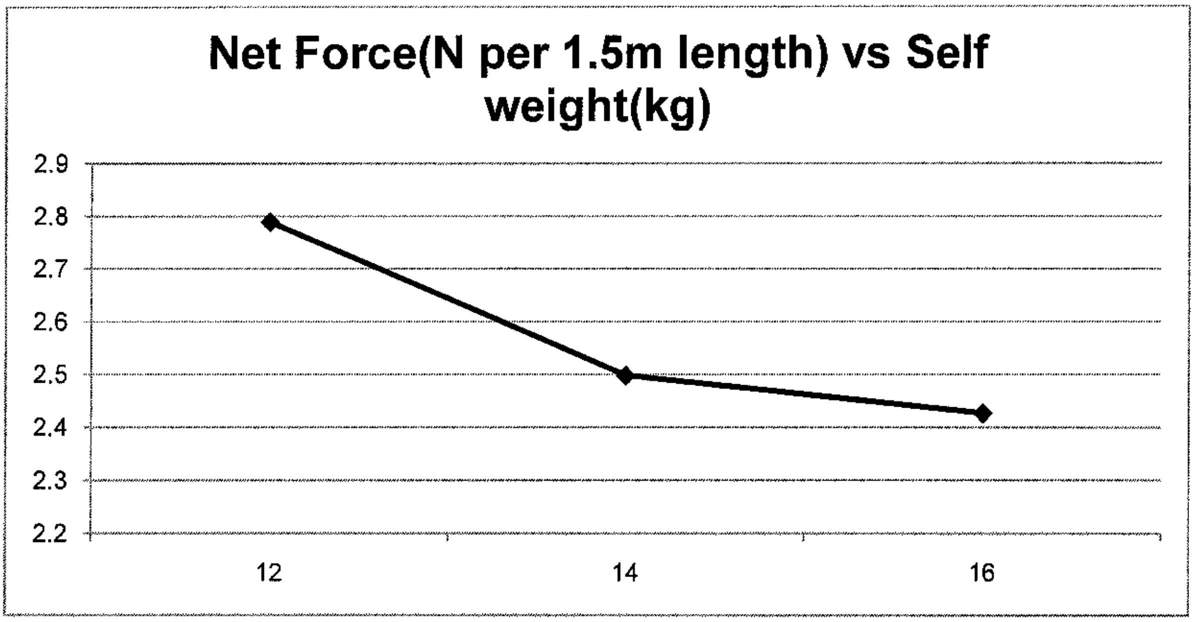

Figure 12: Net Force (N per 1.5m length) vs Weight, 3" pipe

For 4" pipe

W = 20kg

F_{net} = 3.86N per 1.5m length = 2.57N per m length

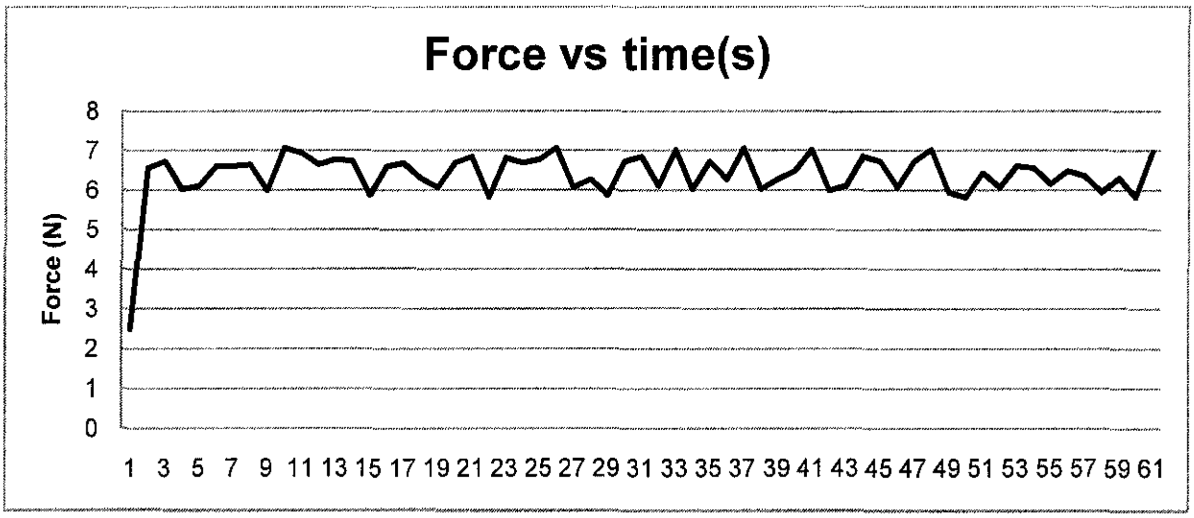

Figure 13: Force vs Time, 4" pipe, W=20kg

W = 22.5kg

F_{net} = 2.79N per 1.5m length = 1.86N per m length

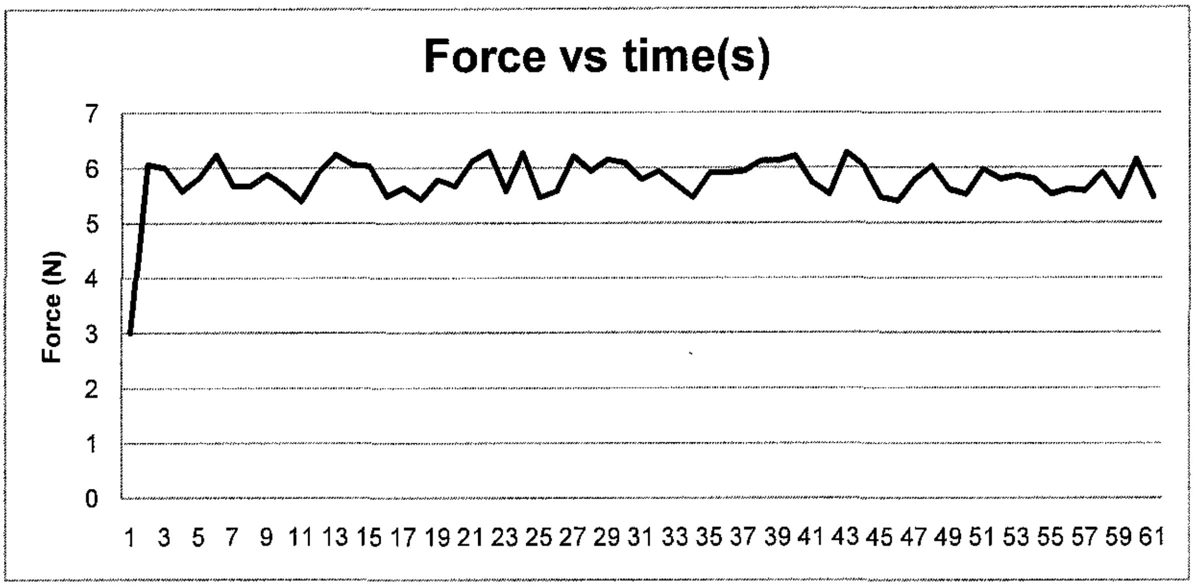

Figure 14: Force vs Time, 4" pipe, W=22.5kg

W = 25kg

F_{net} = 2.37N per 1.5m length = 1.58N per m length

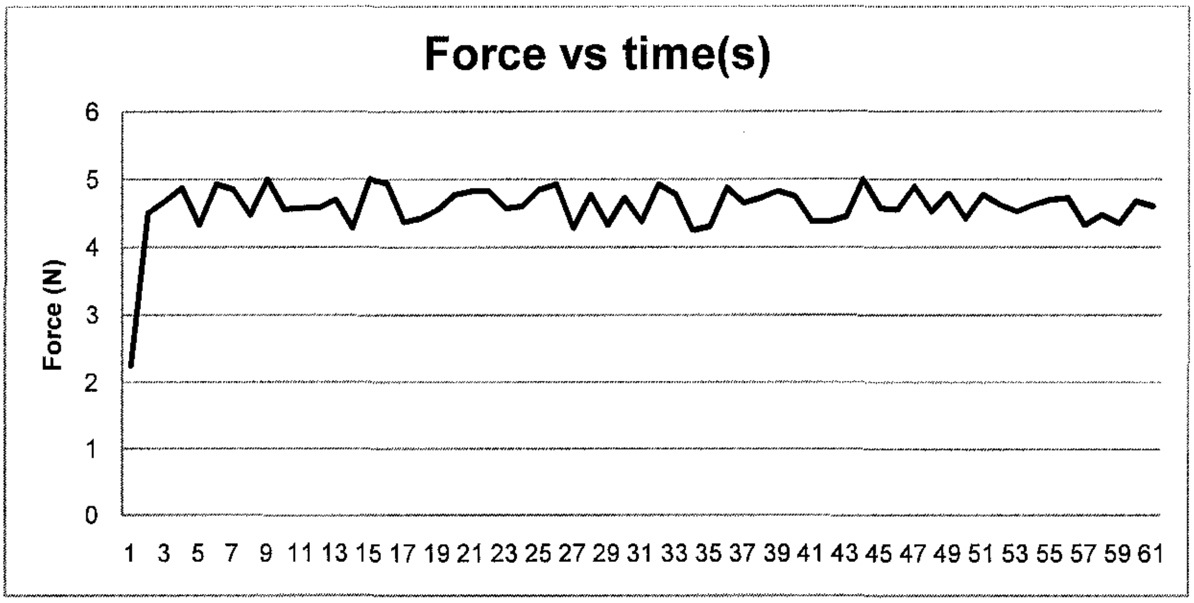

Figure 15: Force vs Time, 4" pipe, W=25kg

Summary:

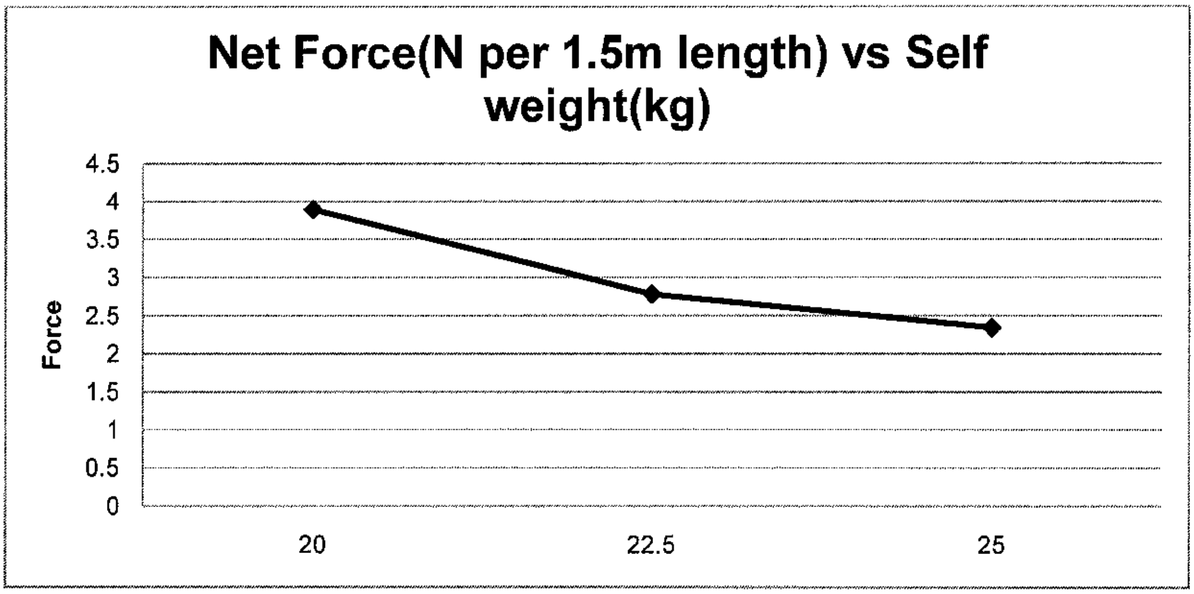

Figure 16: Net Force (N per 1.5m length) vs Self weight (kg), 4" pipe

4.1.2 Manual Calculation

Calculation for the model pipe (4"):

If a current of 0.142m/s is applied;

L = 1.50m

C_D = 0.7

C_L = 0.9

μ = 0.8 (Taken from Coastal Structures)

D = 0.142m

B = 127.49N

$$Total\ Force_{hor} = F_D - \mu(W - D - F_L)$$

$$Total\ Force_{hor} = C_D\rho\, Du^2/_2 - 0.8\left(W - D - C_L\rho\, Du^2/_2\right)$$

$$= \frac{0.7 \times 1.50 \times 0.102 \times 0.142^2 \times 9807}{2} - 0.8\left(W - B - \frac{0.9 \times 1.50 \times 0.102 \times 0.142^2 \times 9807}{2}\right)$$

$$= 10.59N - 0.8(W - 127.50 - 13.62)$$

$$= 10.59 - 0.8(W - 141.12)$$

W = 196.14N, 220.66N, 245.175N

F_{hor} = -33.43N, -53.04N, -72.65N

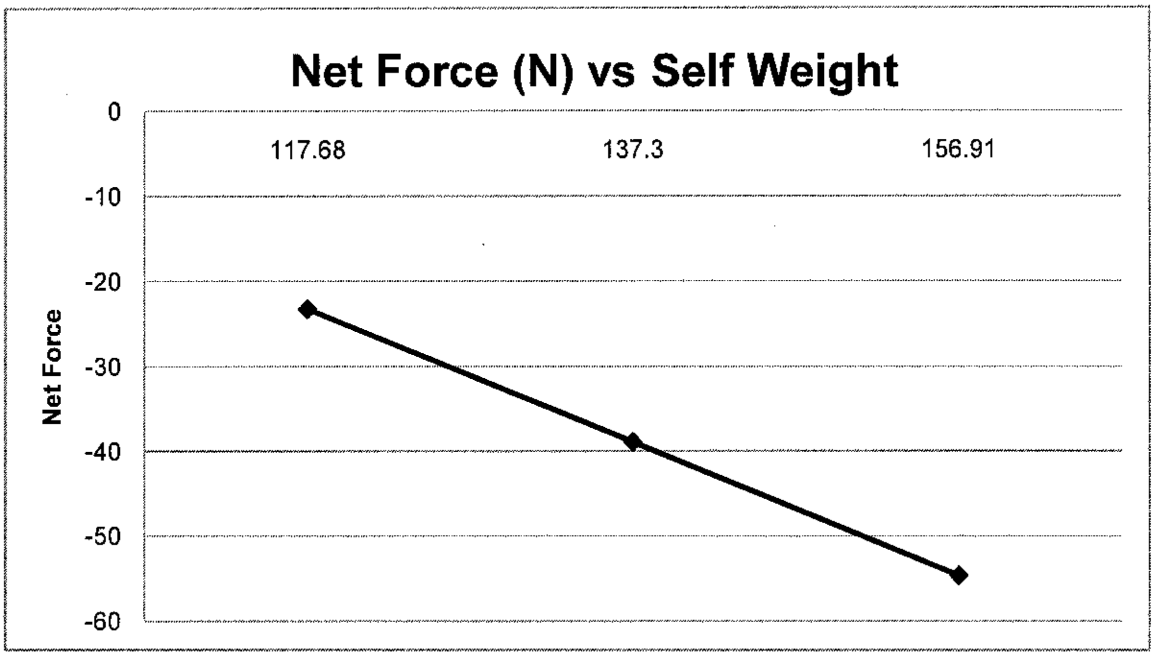

Figure 17: Net Force vs Self Weight (Calculation, 4")

Calculation for model pipe (3"):

If a current of 0.142m/s is applied;

L = 1.50m

$C_D = 0.7$

$C_L = 0.9$

μ = 0.8 (Taken from Coastal Structures)

D = 0.076m

B = 68.65N

$$Total\ Force_{hor} = C_D\rho\, Du^2/_2 - 0.8\left(W - D - C_L\rho\, Du^2/_2\right)$$

$$= \frac{0.7 \times 1.50 \times 0.076 \times 0.142^2 \times 9807}{2} - 0.8\left(W - B - \frac{0.9 \times 1.50 \times 0.076 \times 0.142^2 \times 9807}{2}\right)$$

$$= 7.89 - 0.8(W - 68.65 - 10.15) = 7.89 - 0.8(W - 78.8)$$

W = 117.68, 137.30N, 156.91N

F_{hor} = -23.21N, -38.91N, -54.60N

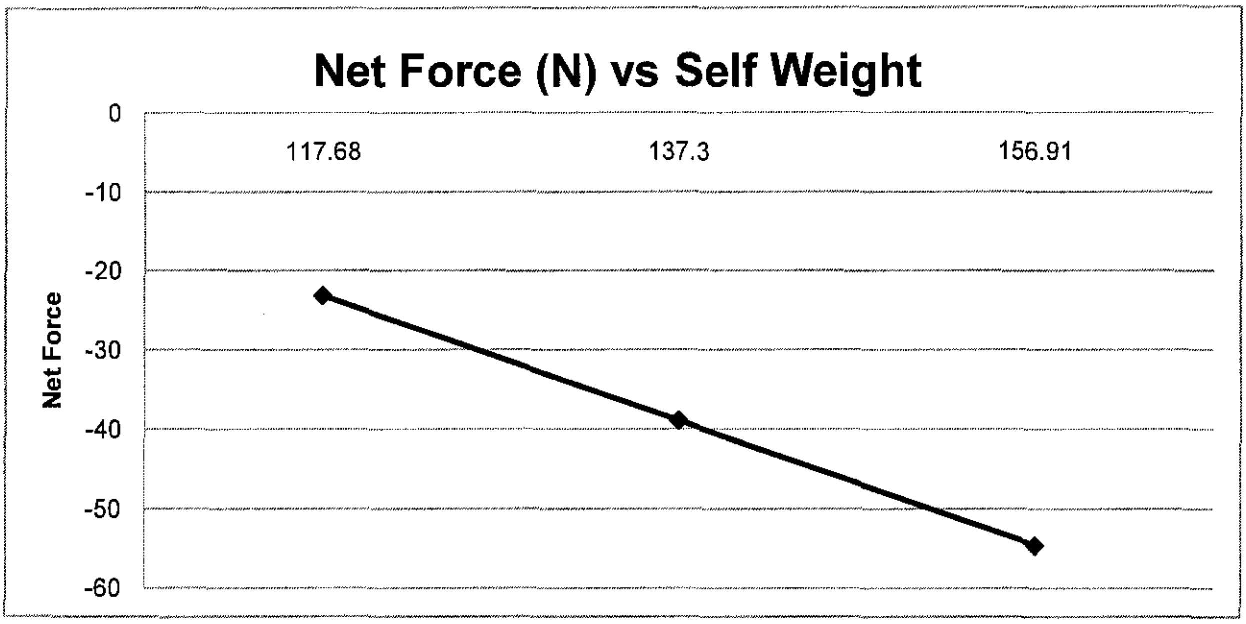

Figure 18: Net Force vs Self Weight (Calculation, 3")

4.1.3 Spreadsheet (DNV Standards)

This spreadsheet supplied by a consultant is based on DNV standards. Based on Betty Revisit-4 project, the spreadsheet results can be seen in Appendix III.

4" pipe: Lift, Drag, Inertia = 0.642, 0.856, 0.382

3" pipe: Lift, Drag, Inertia = 1.151, 1.535, 0.217

Total forces expected from 18" pipeline (prototype) are 11.602, 15.469, 3.736 (Lift, Drag Inertia).

4.2 Discussion

There are two parts of theories present in this research, the force theory and the modeling theory.

4.2.1 Force

The force theory explains about how forces acting on a pipeline. There are two major forces, waves and current forces. For current, a simple force equation 3 and equation 4 are used. In explaining forces caused by waves, an equation called Morison equation (equation 5) is used. Both current and waves will cause drag and lift while waves will create an inertia effect on the pipeline as we can see in equation 5.

4.2.2 Modeling

There are a few methods of pipeline modeling that can be adopted in this project. Two (2) closely related modeling theories are:

1. Reynolds modeling
2. Froude modeling

Froude modeling is selected because to obtain similar Reynolds number in the lab is practically impossible (Chakrabarthi, 1994).

The results obtained from experiments and calculations differ slightly. However, both yield similar graphs.

This is because the coefficients used are taken from literature reviews, and might need some adjustments to suit the test condition.

From the tests and calculations, we can see that weight have a great impact on the net forces acting on a subsea pipeline. Heavier pipe will lead to lesser net forces.

Chapter 5: Conclusion and Recommendation

5.1 Conclusion

1. Two major forces acting on a subsea pipeline are:
    a. Wave forces
    b. Current forces
2. In current, there are lift and drag forces acting on a pipeline
3. Wave forces use Morison equation, which includes accelerating effect of fluid.
4. In this project, only current is accounted for, as it is located in deepwater site.
5. During this preliminary stage of project, a few methods of modeling have been identified. The Froude scaling is selected for the experimental works.
6. Direct measurement of forces is going to be applied in the experiments by using the method described in the methodology chapter.
7. The heavier the pipe, the lesser the net force acting on it.

5.2 Recommendation

1. Expand the experiment to other parameters: wave, soil, pressure.
2. Try to obtain coefficients for the experimental setup.
3. Use digital scale to record force, rather than analog scale which requires tedious work.

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Appendices

Appendix I: Storm surge, wave and current criteria, seawater properties, splash zone, hydrodynamic coefficients

4.0 ENVIRONMENTAL DATA

This section presents the design environmental, meteorological and geotechnical data for the pipeline system based on [Ref 1]. For design purposes, an environmental return period of 10-year is considered for installation, 1-year for hydrostatic testing condition and 100-year for operating condition.

4.1 Water Depths

The Betty and Baronia field water depths range from minimum 72.3m at KP 1.25 to a maximum of 77.8 at KP 17.815 as per the Pipeline Route Survey Report, Ref [2]. The water depths at the relevant platforms are assumed to be as per Table 4.1.

Table 4.1: Facilities Water Depths

Facilities	Water Depths (ft)	Water Depths (m)
BEP-A	239	72.85
BNG-B	250	77.45

Note:
1. Water depths at the platforms were as per the As-Built BEP-A structural jacket drawings, Ref [6]

4.2 Tidal Characteristics

Tidal characteristics are summarized in Table 4.2.

Table 4.2: Tidal Characteristics

Tides	Height (m)
HAT	2.1
MSL	1.2
LAT	0.0

4.3 Storm Surges

Storm Surges for the Betty field are as summarized in Table 4.3.

Table 4.3: Storm Surges

Return Periods	Storm Surge (m)
1 year	0.3
10 year	0.4
100 year	0.6

4.4 Wind Criteria

The wind criteria at Betty Development are as summarized in Table 4.4.

Table 4.4: Wind Criteria

Wind	Unit	Return Periods		
		1 year	10 year	100 year
Hourly mean wind	m/s	15	19	24
10 min wind	m/s	16	20	32
1 minute mean wind	m/s	17	22	36
3 sec gust	m/s	19	25	40

4.5 Wave Criteria

The wave criteria at Betty Development are as summarized in Tables 4.5 – 4.7.

Table 4.5: Omni-Directional Wave Criteria

Wave Parameters	Unit	Return Periods for Omni-Directional Wave		
		1 Year	10 Year	100 Year
Hs	m	3.7	4.4	5.1
Tz	s	6.7	7.3	7.9
Tp	s	9.5	10.4	11.1
Hmax	m	7.4	8.8	10.2
Tass	s	8.8	9.6	10.4

Table 4.6: 1 Year Return Directional Wave Criteria

Wave Parameters	Unit	Waves from the following direction Sectors (Bearing Clockwise from True North)		
		270 to 360 to 060 degree	061 to 221 degree	221 to 269 degree
Hs	m	3.7	2.2	3.0
Tz	s	6.7	5.2	6.1
Tp	s	9.5	7.3	8.5
Hmax	m	7.4	4.4	6.0
Tass	s	8.8	6.8	7.9

Table 4.7: 100 Year Return Directional Wave Criteria

Wave Parameters	Unit	Waves from the following direction Sectors (Bearing Clockwise from True North)		
		270 to 360 to 060 degree	061 to 221 degree	221 to 269 degree
Hs	m	5.1	3.1	4.1
Tz	s	7.9	6.2	7.1
Tp	s	11.1	8.7	10.0
Hmax	m	10.2	6.2	8.2
Tass	s	10.4	8.1	9.3

Where,

Hs	Significant wave height (m)
Tz	Zero crossing wave period (s)
Tp	Peak wave period (s)
Hmax	Individual maximum wave height (m)
Tass	Wave period associated with Hmax (s)

4.6 Current Criteria

Table 4.8: Omni-Directional Ocean Current at Betty

Layer	Depth (below surface)	Return Periods for Current Speed (m/s)		
		1 Year	10 Year	100 Year
Surface	1.0*d	1.4	1.55	1.75
Near Surface	0.9*d	1.35	1.5	1.69
Mid-Depth	0.5*d	1.07	1.19	1.34
Near Bottom	0.1*d	0.50	0.55	0.62
Bottom	0.01*d	0.18	0.21	0.23

Notes:
1. d= total water depth
2. A power profile of 1/3 is applied to derive current speed at water levels below sea surface.
3. The Metocean data can be found in Appendix A.

Table 4.9: 1 Year Return Directional Current Speed

Layer	Depth (below surface)	Current Speed (m/s) (Towards the following sectors)			
		North to Northeast	West; East	Northwest	South to Southeast to Southwest
Surface	1.0*d	1.40	1.12	0.84	0.56
Near Surface	0.9*d	1.35	1.08	0.81	0.54
Mid-Depth	0.5*d	1.07	0.86	0.64	0.43
Near Bottom	0.1*d	0.50	0.40	0.30	0.20
Bottom	0.01*d	0.18	0.15	0.11	0.07

Table 4.10: 100 Year Return Directional Current Speed

Layer	Depth (below surface)	Current Speed (m/s) (Towards the following sectors)			
		North to Northeast	West; East	Northwest	South to South East to Southwest
Surface	1.0*d	1.75	1.40	1.05	0.70
Near Surface	0.9*d	1.69	1.35	1.01	0.68
Mid-Depth	0.5*d	1.34	1.07	0.80	0.54
Near Bottom	0.1*d	0.62	0.50	0.37	0.25
Bottom	0.01*d	0.23	0.18	0.14	0.09

4.7 Seawater Properties

The seawater properties used are as per Table 4.11.

Table 4.11: Seawater Properties

Seawater Properties	Unit	Data	Ref
Mass Density	Kg/m^3	1025	7
Seabed Temperature	°C	20	-

Note:
1. The seabed temperature is assumed based on previous project data in that region.

4.8 Splash Zone

The splash zone is defined as follows:

- As per the PTS 20.196 [Ref.8], the splash zone coated joint shall be placed approximately from EL (-) 4 m to EL (+) 8 m with respect to Mean Sea Level (MSL).

- As per PTS 31.40.10.10, [Ref 13], the splash zone range is defined as the astronomical tidal range plus the wave height having a probability of exceedance of 0.01. The upper limit of the splash zone is determined by assuming 65% of this wave height above HAT and lower limit by assuming 35% below LAT.

The governing criteria will be considered in the design. Neoprene or an alternative acceptable coating system shall be applied at the Splash Zone coating pipe joint.

4.9 Hydrodynamic Coefficients

The hydrodynamic force coefficients presented herein are for use in the calculation of quasi-static forces on pipelines resulting from fluid motion.

Table 4.12: Hydrodynamic Coefficients

Coefficient	For Pipeline Section (Note 1)	For Riser Section
Drag, Cd	0.7(Note 2)	0.7 (no marine growth) 1.0 (with marine growth) (Note 3)
Lift, CL	0.9	0.0
Inertia, CI	3.29	2.0

Notes:

1. Data has been extracted from DNV RP E305 [Ref. 16].
2. For sub-critical and critical flow regime Re < 3×10^5 and M ≥ 0.8, realistic CD value should be calculated. (where M = current velocity/wave velocity = Uc / Us)
3. Data has been extracted from DNV 1981 [Ref. 15]

4.10 Seabed Features and Soil Data

4.10.1 Seabed Features

Based on the Pipeline Route Survey, Ref. [2], the seabed generally consists of very gentle slope. No significant bathymetry gradient were observed along the proposed route. The surficial sediments were interpreted as comprising very soft to soft silty CLAY with varied proportion of silt.

The seabed was extensively pitted, which was probably the result of bioturbation (disturbance of sediment by organisms, particularly burrowing organisms) and/or the result of slow deposition by flocculation or differences in the magnitude of different process. The pits were typically 1m in diameter and 0.4m deep.

The major seabed features found within the surveyed corridor are individual pockmarks, pockmark clusters and scars. A total of 4 individual sonar contacts were recorded within the surveyed corridor.

4.10.2 Soil Friction Factors

The friction factors taken from PTS 20.196, [Ref 8] and DNV RP E305, [Ref 16] are as listed below.

Table 4.13: Friction Factors

Description	Installation/ Hydrotest	Operation
Pipeline Lateral Stability (clay) (Note 1)	Figure 5.11 of DNV RP E305	
Axial Movement (expansion analysis) (Note 2)	0.4 (Note 2)	

Notes:
1. As per Chart in Figure 5.11 of DNV RP E305 [Ref 16].
2. The mean range of 0.3 – 0.5 suggested in PTS 20.196 [Ref 8].

4.10.3 Soil Data

Soil data, based on the Final Factual Report, Ref [3] is as tabulated below.

Table 4.14: Soil Data

Sample	Rec Depth (m)	Soil Description	Bulk Density kg/m^3	Undrained Shear Strength, Cu (kPa)
GC01	0.0	Very soft light grey silty CLAY	-	-
	0.2	Very soft light grey silty CLAY with traces of sand	-	-
	0.5	Very soft light grey slightly sandy silty CLAY	-	-
	1.0	~ditto~	1540-1580	3
GC02	0.0	Very soft light grey silty CLAY with traces of sand	-	-
	0.2	Very soft light grey sandy silty CLAY	-	-
	0.5	Very soft light grey slightly sandy silty CLAY	-	-
	1.0	Very soft light grey silty CLAY	-	11
	1.2	~ditto~	1640	-
GC03	0.0	Very soft dark grey slightly sandy silty CLAY	-	-
	0.2	~ditto~	-	-
	0.5	~ditto~	-	-
	1.0	Very soft dark grey silty CLAY	1560	8

Table 4.14: Soil Data (con't)

Sample	Rec Depth (m)	Soil Description	Bulk Density kg/m^3	Undrained Shear Strength, Cu (kPa)
GC04	0.0	Very soft dark brown slightly sandy silty CLAY	-	-
	0.2	~ditto~	-	-
	0.5	~ditto~	-	-
	1.0	Very soft dark brown silty CLAY with decayed wood and organic matter	1330	3
	1.2	~ditto~	1190	-
GC05	0.0	Very soft dark grey sandy silty CLAY		-
	0.2	~ditto~		-
	0.5	Very soft dark grey slightly sandy silty CLAY		-
	1.0	~ditto~	1850	12
GC06	0.0	Very soft dark grey slightly sandy silty CLAY with shell fragments	-	-
	0.2	Very soft dark grey sandy silty CLAY with shell fragments	-	-
	0.5	~ditto~	-	-
	1.0	~ditto~	1860	11

4.10.4 Soil Resistivity

Soil resistivity, based on the Final Factual Report, Ref [3] is as tabulated below.

Table 4.15: Soil Resistivity

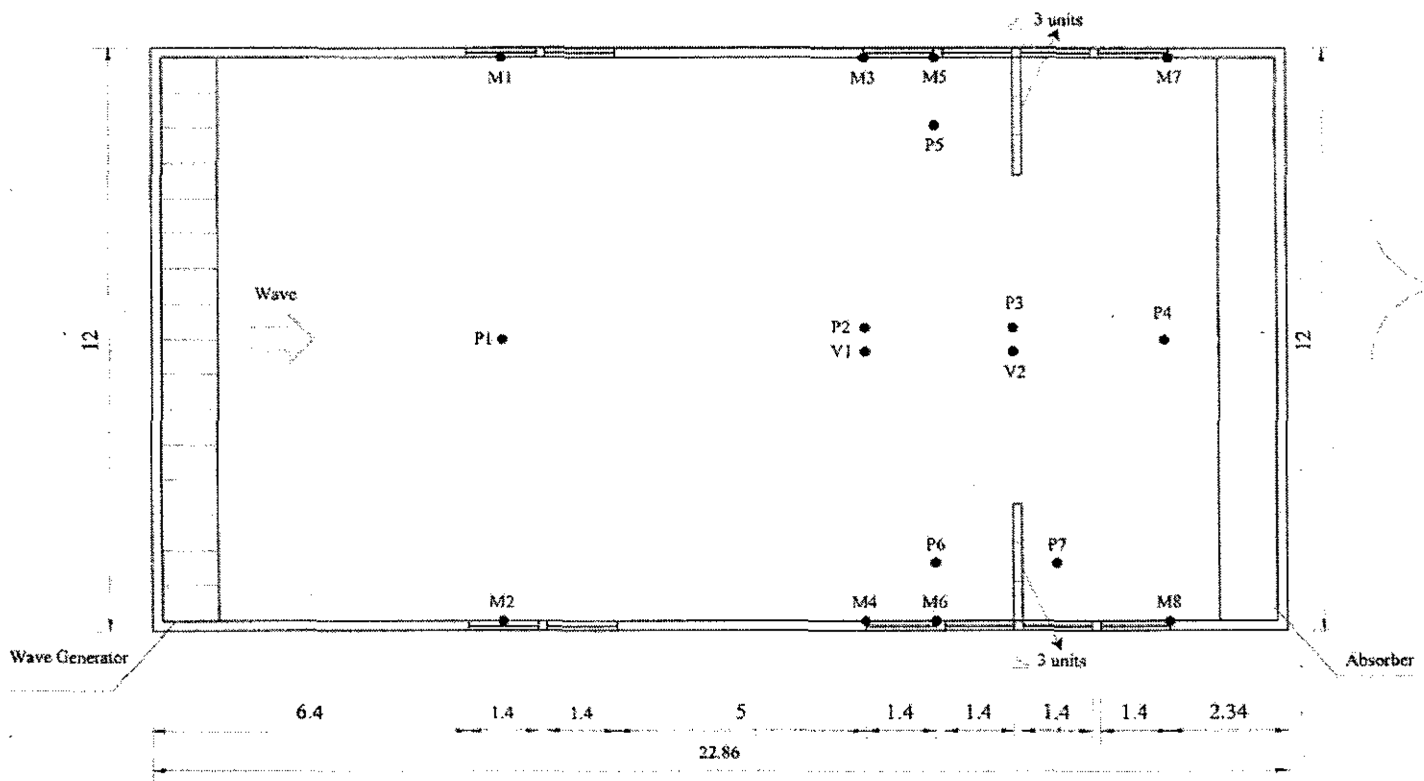
Soil Sample	Depth (m)	Resistivity (ohm.m)
GC01	1.0	0.66
GC02	1.0	0.73
GC03	1.0	0.76
GC04	1.0	0.61
GC05	1.0	0.98
GC06	1.0	0.93
GC07	1.0	0.92

4.11 Marine Growth

The marine growth thickness for the riser shall be assumed to be 90mm at MSL. No marine growth is considered for the pipeline. This thickness shall be assumed to decrease by 1mm for every further 2 metres of water depth. The marine growth density should be the same as seawater

4.12 Jacket Displacement

The jacket displacement for Betty and Baronia platforms are given by the structural department. The data is then used for the riser stress analysis. Please refer to Appendix B for details.



PLAN VIEW OF THE WAVE TANK

M = Measurement points for manual/visual/photographic methods
P = Wave Probes/gauges
V = Velocitimeters

Appendix III: Pipeline On-Bottom Stability Analysis (Spreadsheet)

PIPELINE ON-BOTTOM STABILITY ANALYSIS

PETRONAS CARIGALI

Betty Revisit-4

DFE/5

2-Dec-08

00-year storm condition -Operating Phase

e Diameter	457.000	mm	
ickness	9.144	mm	
ecific Gravity relative to Water	1.200		
Coating Density	3044.000	kg/m^3	
Coating Cutback	350.000	mm	
ion Coating Thk	5.500	mm	
ion Coating Density	1280.000	kg/m^3	
ion Coating Cutback	1280.000	mm	
Density	2000.000	kg/m^3	

ENTAL DATA

Wave Height	(Hs)	5.100	m	
d	(Tp)	11.100	sec	
th	(d)	77.450	m	
locity	(Ur)	0.230	m/s	(90 deg. to pipe at Zr)
Exponent (INPUT "N" = 999999, 8, 4 or 2)	(N)	999999		
e wrt pipeline		90.000	deg	
erence Point	(Zr)	0.50000	m	(Above seabed)

n Size	(d50)	0.110	mm	
trength	(Su)	3.000	kpa	(For clays) (INPUT "0" For sand)

CRETE COATING THICKNESS:

Coating Thk	30.000	mm	(INPUT)

LIDITY OF METHOD FOR BOUNDARY LAYER REDUCTION OF COMBINED WAVE AND CURRENT FLOW

ness	(Zo)	9.17E-06	m		
(b)^-0.25		0.002	m	Valid, Zr > 0.2Ao,	0.00
		86		Valid, Ao/Kb >=30	
		0.06		Not Valid, Us/Ur<1	
		1.818			
		1.00	(Input Zoa/Zo=1, if reduction due to combined wave and current is not considered Otherwise Input Zoa/Zo from Figures A.1 to A.7)		

ED BOTTOM HYDRODYNAMICS:

Factor due to Wave Spreading & Direction	(R)	1.000		(From Figure 2.3)
Wave Velocity	(Us)	0.013	m/s	PIERSON MOSKOVITZ (PM) spectrum is used
ossing Period	(Tu)	13.031	sec	
nt Velocity	(Uc)	0.210	m/s	

SULTS:

Outside Diameter	(D)	528.000	mm	
/ D		0.329		
s		15.775		
ngth Parameter	(1/S)	0.771		
1 Factor		1.300		(From Figure 5.11)
e Submerged Weight		2054.140	N/m	(No water absorption is considered)
fic Gravity		1.933		
Wave Acceleration	(As)	0.006	m/s^2	
Number		9.83E+04	(Default for kinematic viscosity of seawater is 1.2E-6m^2/s)	
nertia Coeffs		0.900	1.200	3.290
nertia Forces	(N/m)	11.602	15.469	3.736
HASE ANGLE OF HYDRODYNAMIC FORCES	(THETA)	52.00	deg	
ON FACTOR	(Fw)	1.000		(From Figure 5.12)
IPE SUBMERGED WEIGHT	(Ws)	26.375	N/m	(ok Less than actual pipe submerged weight)

ON:

ACTUAL PIPE SUB. WEIGHT,N/m	REQUIRED PIPE SUB. WEIGHT,N/m	ACTUAL SAFETY FACTOR	REQUIRED SAFETY FACTOR	CONCRETE COATING THICKNESS ACCEPTABLE
2054.14	26.38	77.88	1.00	YES

PIPELINE ON-BOTTOM STABILITY ANALYSIS (4" Diameter)

PETRONAS CARIGALI

Betty Revisit-4

DFE/5

2-Dec-08

100-year storm condition -Operating Phase

te Diameter		101.600	mm	
hickness		9.144	mm	
ecific Gravity relative to Water		1.200		
Coating Density		3044.000	kg/m^3	
Coating Cutback		350.000	mm	
ion Coating Thk		5.500	mm	
ion Coating Density		1280.000	kg/m^3	
ion Coating Cutback		1280.000	mm	
Density		2000.000	kg/m^3	

ENTAL DATA				
Wave Height	(Hs)	5.100	m	
d	(Tp)	11.100	sec	
th	(d)	77.450	m	
locity	(Ur)	0.100	m/s	(90 deg. to pipe at Zr)
Exponent (INPUT "N" = 999999, 8, 4 or 2)	(N)	999999		
le wrt pipeline		90.000	deg	
ference Point	(Zr)	0.50000	m	(Above seabed)

n Size	(d50)	0.110	mm	
trength	(Su)	3.000	kpa	(For clays) (INPUT "0" For sand)

CRETE COATING THICKNESS:				
Coating Thk		30.000	mm	(INPUT)

LIDITY OF METHOD FOR BOUNDARY LAYER REDUCTION OF COMBINED WAVE AND CURRENT FLOW

ness	(Zo)	9.17E-06	m		
(b)^-0.25		0.002	m	Valid, Zr > 0.2Ao,	0.00
		86		Valid, Ao/Kb >=30	
		0.13		Not Valid, Us/Ur<1	
		1,818			
		1.00	(Input Zoa/Zo=1, if reduction due to combined wave and current is not considered Otherwise Input Zoa/Zo from Figures A.1 to A.7)		

ED BOTTOM HYDRODYNAMICS:				
Factor due to Wave Spreading & Direction	(R)	1.000		(From Figure 2.3)
Wave Velocity	(Us)	0.013	m/s	PIERSON MOSKOVITZ (PM) spectrum is used
ossing Period	(Tu)	13.031	sec	
nt Velocity	(Uc)	0.081	m/s	

SULTS:					
Outside Diameter	(D)	172.600	mm		
/ D		1.005			
s		6.089			
ngth Parameter	(1/S)	1.144			
i Factor		0.986		(From Figure 5.11)	
e Submerged Weight		452.712	N/m	(No water absorption is considered)	
fic Gravity		2.925			
Wave Acceleration	(As)	0.006	m/s^2		
Number		1.36E+04	(Default for kinematic viscosity of seawater is 1.2E-6m^2/s)		
nertia Coeffs		0.900	1.200	3.290	
nertia Forces	(N/m)	0.642	0.856	0.382	
PHASE ANGLE OF HYDRODYNAMIC FORCES	(THETA)	49.00	deg		
ON FACTOR	(Fw)	1.000		(From Figure 5.12)	
PE SUBMERGED WEIGHT	(Ws)	1.898	N/m	(ok Less than actual pipe submerged weight)	

ON:

ACTUAL PIPE SUB. WEIGHT,N/m	REQUIRED PIPE SUB. WEIGHT,N/m	ACTUAL SAFETY FACTOR	REQUIRED SAFETY FACTOR	CONCRETE COATING THICKNESS ACCEPTABLE
452.71	1.90	238.46	1.00	YES

PIPELINE ON-BOTTOM STABILITY ANALYSIS (3" Diameter)

PETRONAS CARIGALI

Betty Revisit-4

DFE/5

2-Dec-08

00-year storm condition -Operating Phase

e Diameter		76.200	mm
ickness		9.144	mm
ecific Gravity relative to Water		1.200	
Coating Density		3044.000	kg/m^3
Coating Cutback		350.000	mm
on Coating Thk		5.500	mm
on Coating Density		1280.000	kg/m^3
on Coating Cutback		1280.000	mm
Density		2000.000	kg/m^3

ENTAL DATA

Wave Height	(Hs)	5.100	m	
d	(Tp)	11.100	sec	
th	(d)	77.450	m	
ocity	(Ur)	0.150	m/s	(90 deg. to pipe at Zr)
Exponent (INPUT "N" = 999999, 8, 4 or 2)	(N)	999999		
e wrt pipeline		90.000	deg	
erence Point	(Zr)	0.50000	m	(Above seabed)

n Size	(d50)	0.110	mm	
trength	(Su)	3.000	kpa	(For clays) (INPUT "0" For sand)

CRETE COATING THICKNESS:

Coating Thk	30.000	mm	(INPUT)

IDITY OF METHOD FOR BOUNDARY LAYER REDUCTION OF COMBINED WAVE AND CURRENT FLOW

ess	(Zo)	9.17E-06	m	
(b)^-0.25		0.002	m	Valid, Zr > 0.2Ao, 0.00
		86		Valid, Ao/Kb >=30
		0.09		Not Valid, Us/Ur<1
		1,818		
		1.00		(Input Zoa/Zo=1, if reduction due to combined wave and current is not considered Otherwise input Zoa/Zo from Figures A.1 to A.7)

ED BOTTOM HYDRODYNAMICS:

Factor due to Wave Spreading & Direction	(R)	1.000		(From Figure 2.3)
Wave Velocity	(Us)	0.013	m/s	PIERSON MOSKOVITZ (PM) spectrum is used
ossing Period	(Tu)	13.031	sec	
nt Velocity	(Uc)	0.119	m/s	

ULTS:

Outside Diameter	(D)	147.200	mm		
/ D		1.179			
;		8.970			
gth Parameter	(1/S)	1.257			
Factor		0.793			(From Figure 5.11)
e Submerged Weight		351.297	N/m		(No water absorption is considered)
fic Gravity		3.054			
Wave Acceleration	(As)	0.006	m/s^2		
Number		1.63E+04	(Default for kinematic viscosity of seawater is 1.2E-6m^2/s)		
nertia Coeffs		0.900	1.200	3.290	
nertia Forces	(N/m)	1.151	1.535	0.217	
HASE ANGLE OF HYDRODYNAMIC FORCES	(THETA)	36.00	deg		
ON FACTOR	(Fw)	1.000			(From Figure 5.12)
PE SUBMERGED WEIGHT	(Ws)	3.359	N/m		(ok Less than actual pipe submerged weight)

ON:

ACTUAL PIPE SUB. WEIGHT,N/m	REQUIRED PIPE SUB. WEIGHT,N/m	ACTUAL SAFETY FACTOR	REQUIRED SAFETY FACTOR	CONCRETE COATING THICKNESS ACCEPTABLE
351.30	3.36	104.57	1.00	YES

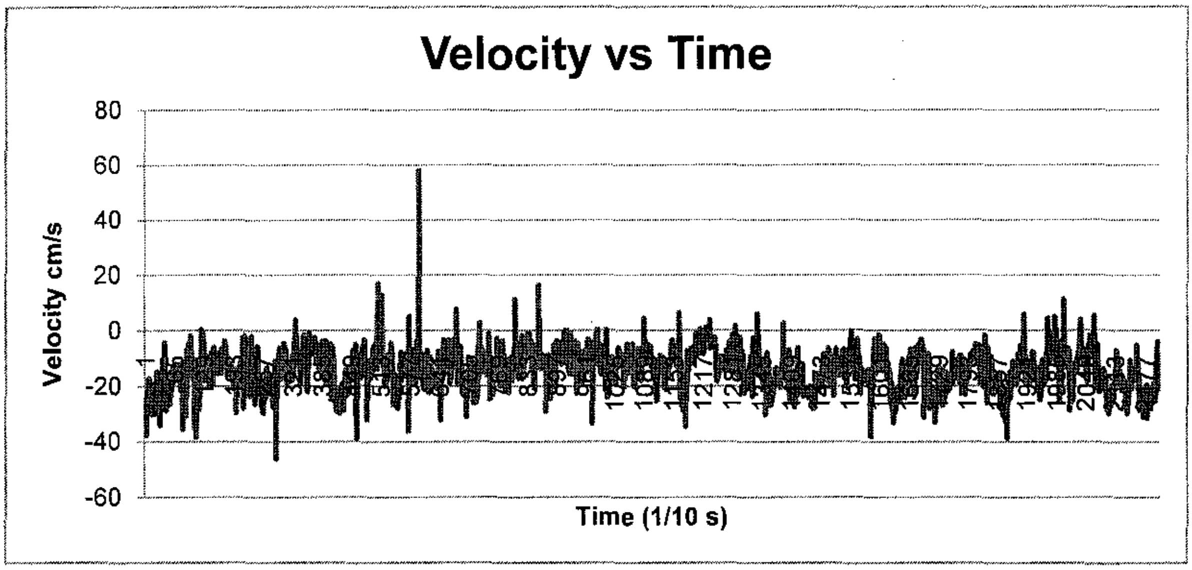


Figure 1: Surface Profile, v_{rms} = 15.5638 cm/s

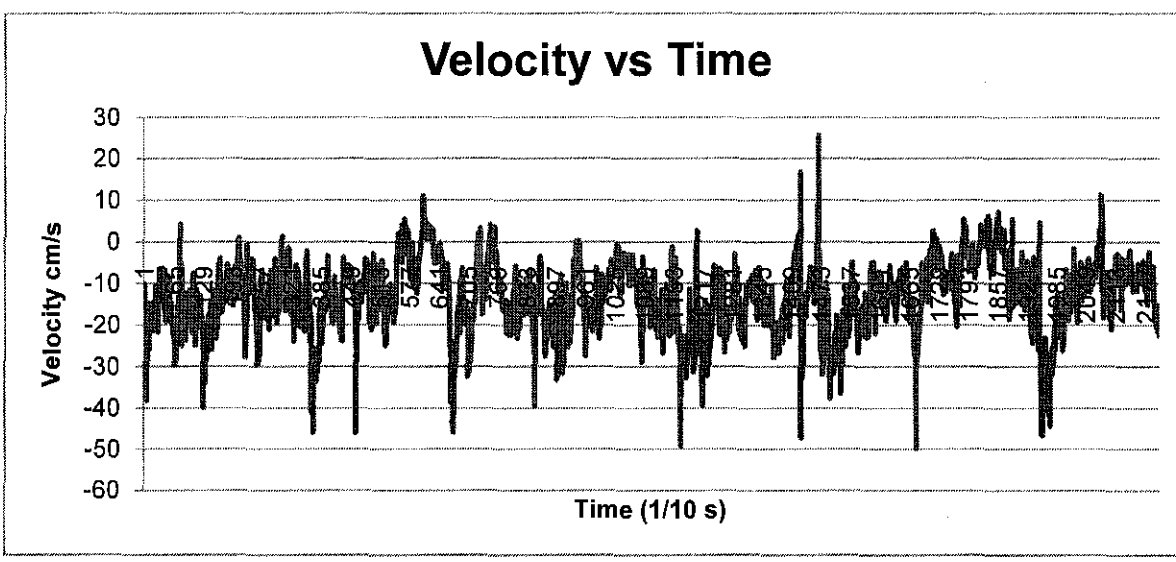


Figure 2: Middle profile, v_{rms} = 14.9055cm/s

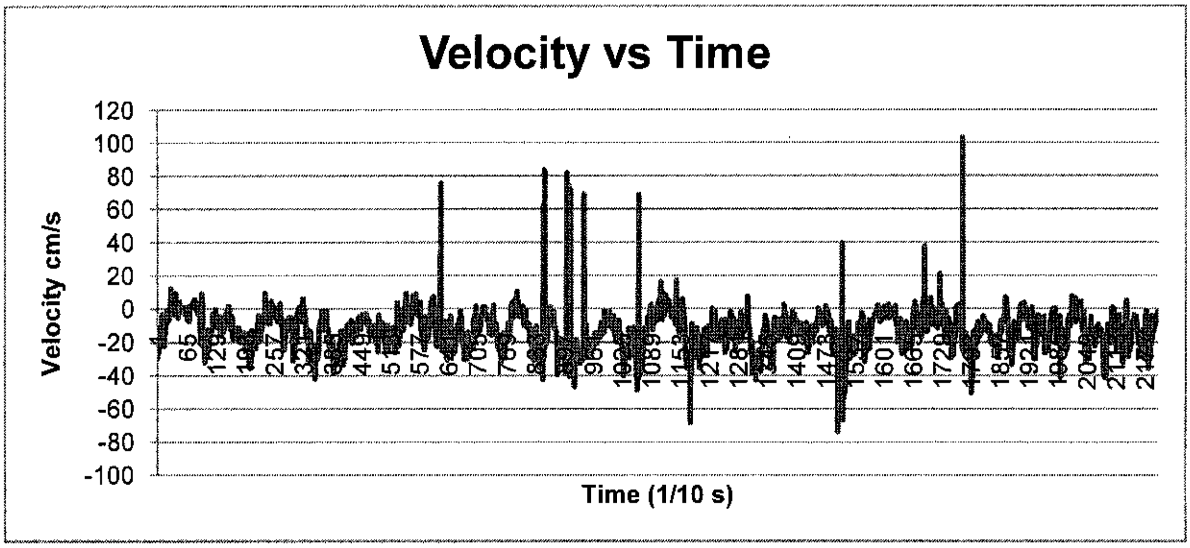


Figure 3: Bottom profile, v_{rms} = 14.3891cm/s