CHAPTER 1

INTRODUCTION

1.1 Background

The term pipeline refers to a long line of connected segments of pipe, with pumps, valves, control devices, and other equipment or facilities needed for operating the system. It is intended for transportation of a fluid (liquid or gas), mixture of fluids, solids or fluid-solid mixture [1]. The term pipeline also implies a relatively large pipe spanning a long distance.

This project is focusing on the underwater / submarine pipeline which transports crude oil from the offshore platform to the onshore processing facilities. The submarine pipeline is laid or being trenched into the seabed during the construction phase. After certain time period, the sand that covers or act as a foundation of the pipeline might loose as the waves propagates.

For the transport of large quantities of fluid (liquid or gas), a pipeline is undisputedly the most favored mode of transportation. According to Liu [2], the advantages of pipelines in this case compare to the tanker and barge are:-

- Economical in many circumstances: Factors that favor pipelines include large throughput, rugged terrain, and hostile environments. For reservoir field with large reserve and located near the land, pipelines are chosen since it can accommodate the delivery capacity for a period of time.
- High reliability: Pipelines operation of pipeline is continuous, automatic, and unaffected by the weather. Furthermore, they are least affected by labor strikes, holidays, delivery schedules, etc. The system operates continuously around the clock without stop even during maintenance.
- Unaffected by the weather because most of the pipelines are buried / trenched into the soil.

1.2 Problem Statement

Wave-induced lateral instability of entrenched submarine pipeline is a wave–pipe–seabed coupling problem. Under wave loading, to limit the lateral movement of entrenched pipeline, a balance exists between wave loading, the submerged weight of pipeline and soil resistance are required. Without sufficient resistance from the soil, breaking of pipeline will occur as a result of pipeline instability. [2]

Conventionally, to avoid the occurrence of such instability, the methods used are:-

- The pipeline has to be given a heavy weight coating.
- The pipeline is alternatively being anchored / trenched into the soil of seabed.

Since both methodologies are considered expensive and complicated from the aspects of design and construction. Furthermore, the lateral movement of underwater pipeline due to wave current will cause several problems such as:

- Pipeline may experience crack or break due to high force exerted due to the wave current. Thus, less efficiency in crude oil transportation due to pressure drops.
- High vibration because of pipeline span / overhanging on top of the sand foundation.
- Deposition of wax, slug and other contaminants due to pipeline bending.

The term instability of pipeline in this paper refers to the condition where the pipeline experience losing stability under the wave loading. This might due to the sand that act as a foundation around the pipeline are washed-out by the water wave current. Plus, the term of pipeline breakout used in this paper signifies that the pipe has been displaced larger than its diameter.

Therefore, the study on wave-pipe–soil interaction problem regarding the stability of pipelines is particularly important for coastal engineers involved in the design of pipeline. Thus, further intervention could be implemented in order to reduce the risk of pipeline damage.

1.2 Objectives

To provide a better understanding of the physics of lateral stability or breakout of entrenched offshore pipelines under wave loading through laboratory experiment.

1.3 Scope of Study

- Experiment will be conducted based on the deep water condition in the laboratory by using principles of similarity between prototype and pipeline model.
- The study on the wave-induced stability of pipeline will be conducted based on:-
    i. Freely laid pipelines.
    ii. Anti-rolling pipelines.
    iii. Vary wave frequency.

CHAPTER 2

LITERATURE REVIEW

2.1 Loadings on an Underwater Pipeline

Hydrodynamic forces, gravity forces, the pipeline weight, external pressure, internal pressure, and buoyancy forces are among the major forces that act on the submarine pipeline (Figure 2.1). Therefore, in order for the pipeline to be static, the summation of forces acted on the pipeline must be equal to zero. The problem occurs when the hydrodynamic or other external forces that acts on the submarine pipeline is large enough to move the pipeline from its original places.

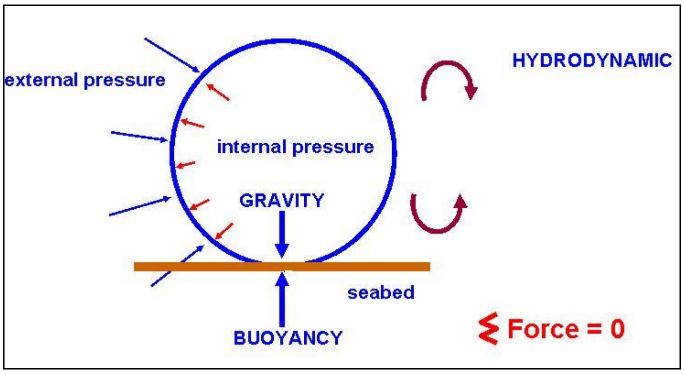

Figure 2.1: Loadings on pipeline [3]

The crude transfer pipeline has been coated with concrete and trenched into the seabed in order to avoid the lateral movement (Figure 2.2). Moreover, the heavy weight coated pipeline is designed in order to prevent it from floating due to the buoyancy forces.

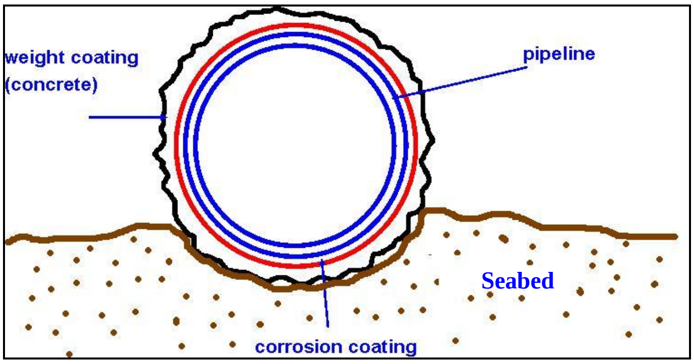

Figure 2.2: Pipeline is trenched into the seabed [3]

2.2 Principle of deep water condition

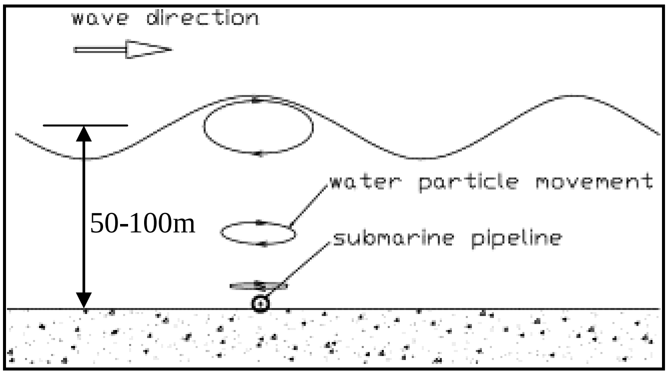

Figure 2.3: The hydrodynamic force induced by wave [2]

When gravitational ocean waves propagate over the shallow ocean zone, the water particles oscillate elliptically at upper water level with certain frequency, but mainly horizontally near the sea bottom due to the boundary effect (Figure 2.3)

The wave movement from the sea level will generate elliptical oscillatory water particle. The elliptical oscillatory water particle will be smaller in shape as it moves down to the seabed.

Thus, in deep water condition, the water particle mainly moving horizontally near the seabed as a result of boundary effect as mentioned earlier. The oscillatory flow induces drag, inertia and lift forces upon the pipeline, which will affect the pipeline lateral stability.

2.3 Principle of Similarity (Dimensionless Analysis)

In the field, the storm wave events are unpredictable and the field conditions are often characterized with significant uncertainty. Thus, development and testing of offshore pipeline model in laboratory is essential, for it is difficult to accurately obtain data from prototypes. However, care must be taken to make sure that the model simulates the behavior of the prototype as accurately as possible. [2]

The similarity method proposed by Chakrabarti can be utilized for modeling wave-induced breakout of entrenched submarine pipelines, which is a ‘wave–pipeline–soil’ coupling problem, and thereby, the properties of wave, pipeline and soil are involved. The critical submerged weight of pipeline per meter to keep it stable, W_s, is mainly related to the following parameters: - [2]

$$\boldsymbol{W_s = f\,(D, k, T, U_m, \upsilon, t, \acute{\mathring{A}}_o, \rho_{sat}, \rho_w, g, d_s, D_r)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(2.1)}$$

- D, pipe diameter;
- K, roughness coefficient of pipe surface;
- T, wave period;
- U_m, maximum value of the velocity of water particles at seabed;
- ν, kinematics viscosity of water
- t, total loading time;
- $Å_0$, the velocity of the increase of oscillatory flow amplitude;
- ρ_{sat}, the density of saturated sand;
- ρ_w, the density of water;
- g, gravitational acceleration;
- d_s, the sand diameter;
- D_r, the relative density of sand.

Based on **Vaschy–Buckingham’s theorem [4],** ten independent dimensionless parameters can be obtained from Eq. (2.1). A functional relationship that represents the phenomenon of pipeline instability may be expressed as

$$\boldsymbol{G = \frac{W_s}{\gamma' D^2} = F\left(Fr, KC, Re, \frac{t}{T}, \frac{Å_0}{U_m}, \frac{\rho_{sat}}{\rho_w}, \frac{D}{d_s}, D_r, k\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(2.2)}$$

Where the dimensionless submerged weight of the pipeline, G, is defined as $\boldsymbol{G=W_s/(\gamma' D^2)}$ (in which $\boldsymbol{\gamma'=(\rho_{sat} - \rho_w)g}$ is the buoyant unit weight of soil). **Froude number, *Fr*,** is defined as dimensionless number comparing inertial and gravitational forces, $\boldsymbol{Fr = \frac{U_m}{\sqrt{gD}}}$ [2] & [5] while **Reynolds number, *Re***, is a ratio of inertia forces to viscous forces, $\boldsymbol{U_m D/\nu}$ [2] & [6]. It is also used to predict the characteristic of flow regime whether fluid flow is laminar, transition, or turbulent.

In Eq. (2.2), the **Keulegan–Carpenter number, KC**, is defined as **KC=$\boldsymbol{U_m T/D}$**. In general, KC number controls the generation and development of vortex around pipeline under oscillatory flow loading [2] & [7]. Also, it is related to the hydrodynamic force on the pipe under wave action.

Based on above similarity analysis, the dimensionless parameters in Eq. (2.2) can be deduced to three important parameters, Froude number (*Fr*), Keulegan–Carpenter number (KC) and Reynolds number (*Re*), which are relevant to flow characteristics.

According to principle of similarity, we can obtain the following relationship from Froude number:

- Froude Number, Fr

Known that, $Fr = \frac{U_m}{g.D^{\frac{1}{2}}}$ ………………………………………………………………. **(2.3)**

$$\left(\frac{U_m}{g.D^{\frac{1}{2}}}\right)_{model} = \left(\frac{U_m}{g.D^{\frac{1}{2}}}\right)_{prototype}$$

$$\frac{(U_m)_{model}}{(U_m)_{prototype}} = \frac{\left(g.D^{\frac{1}{2}}\right)_{model}}{\left(g.D^{\frac{1}{2}}\right)_{prototype}}$$

Since, $g_{model} = g_{prototype}$,

$$\frac{(U_m)_{model}}{(U_m)_{prototype}} = \sqrt{\frac{(D)_{model}}{(D)_{prototype}}}$$

$\lambda_{U_m} = (\lambda_D)^{1/2}$ ………………………………………………………………… **(2.4)**

- Keulegan Carpenter, KC

From Keulegan Carpenter number, $Kc = \frac{U_m T}{D}$ **…………………………………. (2.5)**

$$\left(\frac{U_m T}{D}\right)_{\mathrm{model}} = \left(\frac{U_m T}{D}\right)_{prototype}$$

$$\frac{(U_m)_{\mathrm{model}}}{(U_m)_{prototype}} = \frac{(T)_{prototype}}{(T)_{\mathrm{model}}} \times \frac{(D)_{\mathrm{model}}}{(D)_{prototype}}$$

$$\lambda_T = \frac{\lambda_D}{\lambda_{U_m}}$$

Since, $\lambda_{U_m} = (\lambda_D)^{1/2}$; we left with $\lambda_T = (\lambda_D)^{1/2}$

From Keulegan Carpenter number, $Kc = \frac{U_m T}{D}$

$$\lambda_{Kc} = \frac{\lambda_{U_m} \lambda_T}{\lambda_D}$$ **……………………………………………………………….…. (2.6)**

Since $\lambda_{U_m} = (\lambda_D)^{1/2}$ and $\lambda_T = (\lambda_D)^{1/2}$, simplifying equation above led to;

$$\lambda_{Kc} = 1$$

This indicates that *Fr* and KC numbers can be satisfied concurrently in the model tests. However, if the quantities strongly depend on Reynolds number, direct scaling is not possible. In the case of water wave with a free surface, the gravitational effect predominates, and pipeline on-bottom stability is related to the submerged weight of the pipeline. The effect of other factors, such as viscosity, surface tension, etc., is generally small and negligible. Since both *Fr* and *Re* cannot be satisfied concurrently for model tests, it is convenient to employ the Froude scaling process and allowance are made for variation in Reynolds number. For example, the values of *Fr* and KC numbers of coastal sediments in South China Sea vary between 0–0.5 and 0–20 [2], respectively, which is the range we used in the laboratory experiments. However, the *Re* number is smaller than the actual value by about two orders. [2]

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

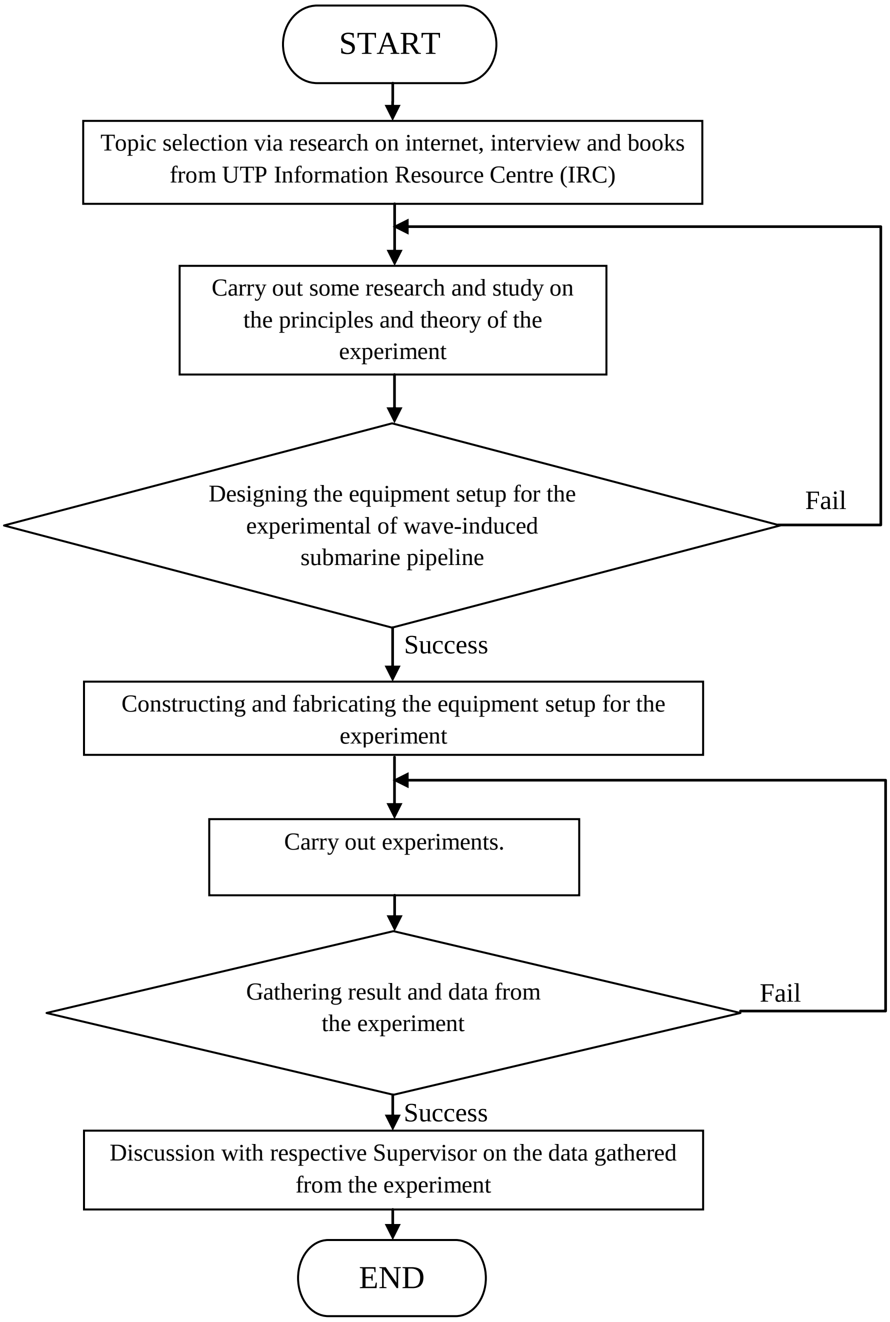

Figure 3.1: Methodology Process of the experiment

3.2 Project Activities

3.2.1 Topic selection via research on internet, interview and books from UTP Information Resource Centre (IRC)

The author had done some research on the pipeline problem in order to get a FYP title for the semester July 2007 and January 2008.

3.2.2 Designing the equipment setup for the experimental of wave-induced submarine pipeline

For this methodology phases, the author had to do some research and principle regarding the wave mechanics and deep water condition since this project involve the force around the pipeline at the seabed. Plus, this section requires the most period of time since it involves the designing of the equipment setup. Initially, the author came out with different design of equipment setup. However, most of the designs are not suitable for simulating the deep water investigation. Thus, the author had finalized the design (refer APPENDIX A-1) but the unavailability of certain equipment such as butterfly valve and control valve restrict the experiment to be done. Finally, the availability of water wave flume from civil department has helped the author to finish the experiment. Initially, the wave flume was unavailable since it must be removed. Therefore, the author only managed to do the experiment at the middle period of FYP II.

3.2.3 Outlining and estimating the price of the equipment to be used in the project

This phase require the author to list out some equipments to be used in the experiment. Initially, the author faced difficulties in buying the equipment since there is no allocation or budget from UTP for final year student in completing the FYP. Students have to buy the equipment and claim afterwards but the procedure in getting the claims consumes a lot of time. However, in this project, the author managed to outline and estimate the price of equipments to be purchased.

3.2.4 Constructing and fabricating the equipment setup for the experiment

The construction and fabrication parts begun in the middle semester of FYPII since the designing phase consumes a lot of time. The author managed to fabricate the test section box (Figure 3.4) which consists of a Perspex, nut, screw and washer. Firstly, the author had to determine the dimension of water wave flume in order for the author to insert the test section into the wave flume.

3.2.5 Gathering result and data from the experiment

After the fabrication phase was completed, the experiment is carried out. The author had to liaise with Civil Department technologist as the wave flume is under the Civil Department. The author had consulted Mr. Idris who is responsible for the wave flume. After getting permission from him, the author managed to conduct experiment and obtained the data from the experiment.

3.2.6 Discussion with respective Supervisor on the data gathered from the experiment

The final phase of the project is the discussion on the data gathered from the experiment. This experiment yield qualitative and quantitative result. For the qualitative result, the video camera is used to record the movement of the pipeline model. The qualitative result is obtained by recording the pipeline displacement.

3.3 Project Phase for FYP I and FYP II

As mentioned before in the relevancy of this project, the first half of the Final Year Project involves researching, designing, and constructing the equipment setup for the experiment. The author has completed some researches on the basic wave mechanics, similarity analysis between prototype pipeline and pipeline model, the equipment specifications, and experimental setup. On the designing part, the author had consulted respective supervisor, Mr. Rahmat and lab technician, Mr. Zailan in order to get some fundamentals on the equipment design and setup. As a result, the author came out with some designs. However, only one design had been chosen by the author as the proposed equipment setup for the experiment (Figure 3.2 – 3.6).

On the second half of the project, the author found some difficulties in the designing and construction phase. The designing phase took a quite time due to ensure the reliability and accuracy of the data gathered from the experiment. Basically, the author had designed the U-Shaped oscillatory flow tunnel (see Appendix A-1) but was unable to construct the original design setup for this experiment due to the unavailability of certain equipment such as butterfly valve, control valve and suitable air compressor to induce the water. Plus, the equipment setup for the U-shaped oscillatory flow tunnel must be constructed with no leakage in order for the flow to be steady. The main predominance of the U-tube experiment is its ability of modeling the horizontal movement of water particles, which is one of the main factors that cause scouring and pipe instability. The dynamic pressure induced by waves could not be modeled in U-tube. However, the scale of the wave dynamic pressure is much smaller than static pressure in the small scale model test. Thus, we use the horizontal movement of the water particle to represent the horizontal wave loading on the whole wave–soil–pipe interaction problem.

3.4 Experimental Setup

Figure 3.2: Water Flume / wave tank for the experiment

Figure 3.3: Test Section of the water wave flume

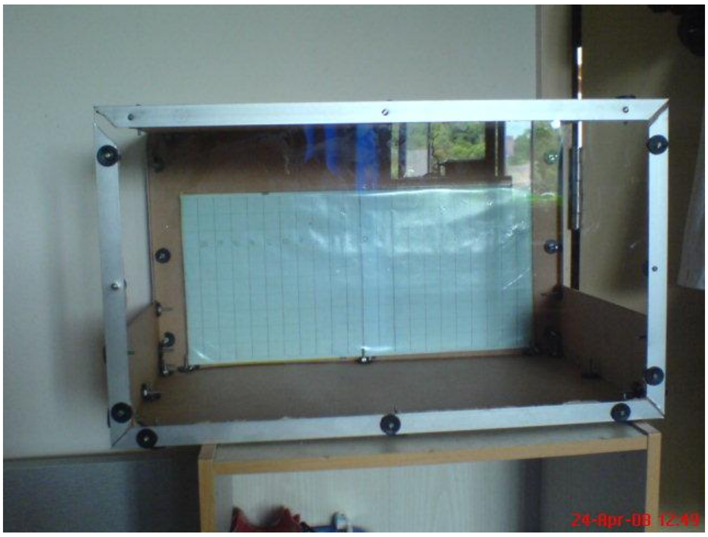

Figure 3.4: Test Section Box inserted into the water flume

Dimension: - Length : 0.55m
Width : 0.30m
Height : 0.30m

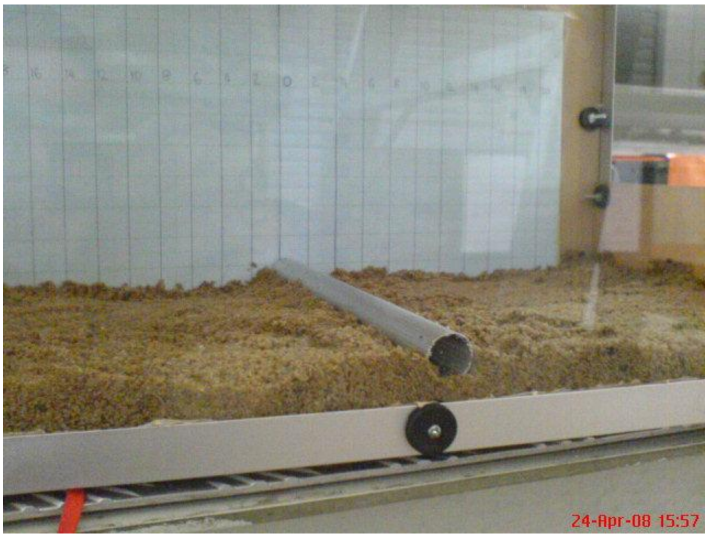

Figure 3.5: Pipeline Model is trenched in the sand / seabed

Dimension: - Diameter : 0.01m
Length : 0.28m

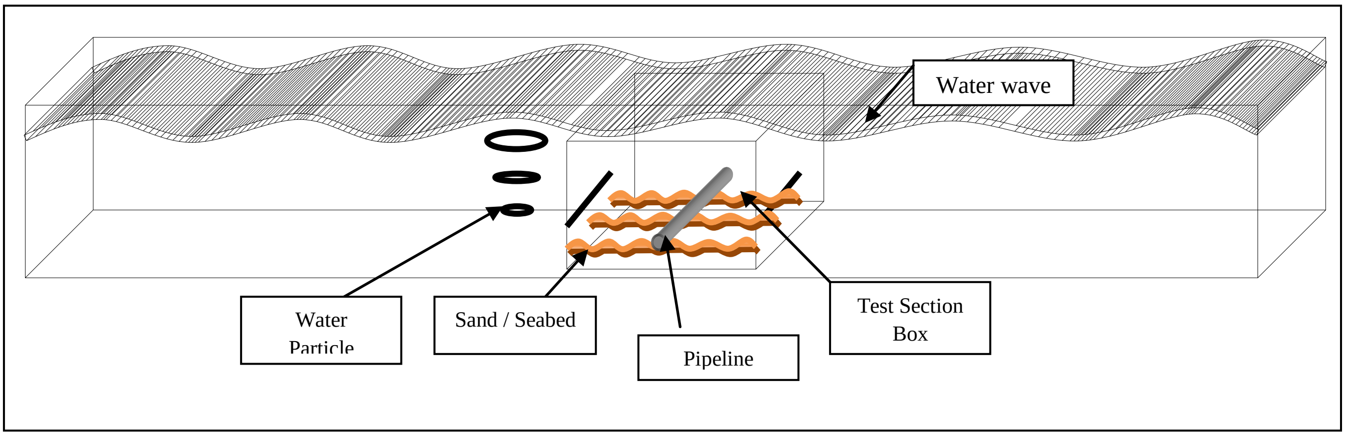

Figure 3.6: The arrangement of the experimental setup

Principle of the experiment

- Based on the Figure 3.6 above, the Test Section Box is inserted into the wave flume tank.
- The water particles oscillate elliptically as it travels downward from the surface.
- As it moves downwards towards the seabed, the elliptical oscillation of water particle became smaller.
- At seabed, the water particle moves mainly in horizontal movement.
- Thus, this wave water flume is suitable to demonstrate the real condition of underwater pipeline.

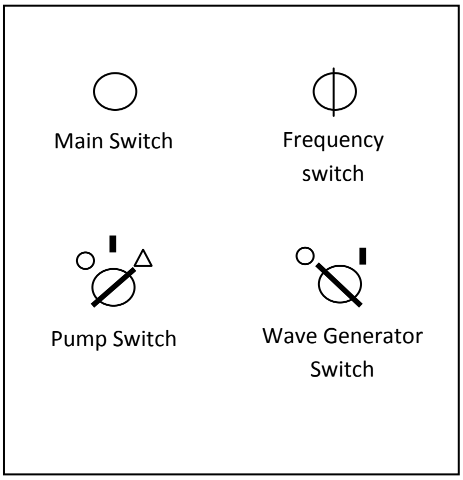

Figure 3.7: Switch Panel for Water Wave Flume

3.5 Experiment Procedure

1) Switch on the main switch of the water wave flume tank. (Figure 3.7)
2) Wait until the panel indicates system ok.
3) Switch on the pump until the delta sign.
4) Open and Control the valve slowly to allow the water flow into the tank.
5) Close the valve until desired water level is reached. In this case 30cm.
6) When the water level is reached, insert the test section box (Figure 3.4) into the wave flume tank.
7) Set and trench the pipeline model into the sand / seabed model. (Figure 3.5)
8) Set frequency of the wave generator at 2 Hz*.
9) Switch on the video camera and start recording.
10) Switch on the wave generator switch on the control panel.
11) Observe the sand scour around the pipeline and the trench foundation.
12) Record the displacement and time of the pipeline model to break out from its original place. (note: measure the oscillatory amplitude when the pipeline breakout)
13) When the pipeline is breakout from its original place, stop the video camera recording.
14) Repeat step 7-13 using different frequency (4Hz, 6Hz, 8Hz and 10Hz)*.
15) For anti-rolling pipeline model, the procedures is the same except that the pipeline is restricted to roll and only horizontal and vertical movement is allowed.

*Note: The frequency being applied here is only to demonstrate the variation of wave motion under different condition in sea wave. The value of this frequency is not being studied in a real life situation. However, under certain condition of sea wave (rough sea wave or normal sea wave), the frequency may vary. Thus, the applied frequency of 2-10Hz is just to show that the variation of wave frequency may affect the time for pipeline to breakout from its initial place.

3.6 Water Wave Flume

Wave energy tank is a tank that used wave generator to create waves of various types. This accessory unit is used to help obtain information on the behavior of waves in the offshore area as well as in coastal protection.

The rotational speed of the drive motor can be varied, corresponding to wave frequency.

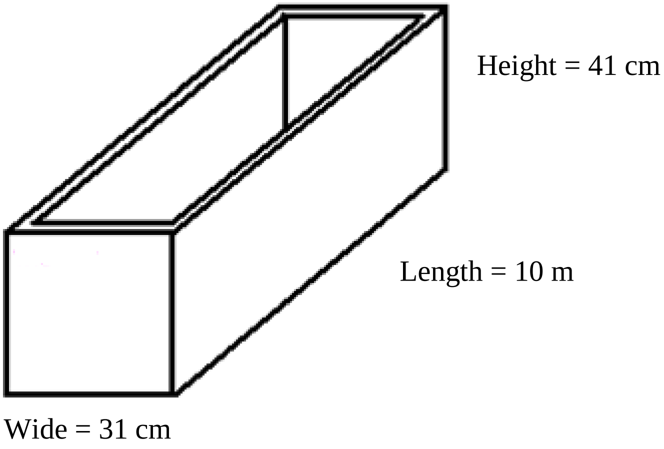

Figure 3.8: Dimension of the Wave Flume Tank

Figure 3.9: Motor and the flap to generate water waves

3.6.1 Flume Principle

The modular flow channel 5m working section is a basic unit with a modular construction, which allows the study of the flow behavior in a large number of experiments. The extensive accessories give researchers and instructors the opportunity to carry out experiments of all areas of hydromechanics.

The measurement section of the basic unit is 5m long. It can be extended by adding 2.5m intermediate sections to reach a maximum length of 15m.

Important components of the basic unit are the specially designed inlet area which creates a homogenous flow, a centrifugal pump for creating the water circuit, regulative flaps for adjusting the throughput quantity, a magnetic-inductive flow meter and a hand-operated slope adjustment which is used to compensate the flow losses or to simulate a natural slope.

Because the unit can be setup anywhere, its adaptability to specific local conditions is guaranteed.

3.7 Pipeline Model

Pipeline model is composed of aluminum and have the length of **0.28m** with **0.01 m** diameter. The author uses the direct scaling of the pipeline model to the prototype in a real condition. The diameter of actual underwater pipeline used in oil transportation in South China Sea is 1m [8]. The depth of the sea is considered 50-100m in a real condition. In laboratory, the author uses the depth of 30cm due to the limitation of the height of the wave flume. Below is the summary of the direct scaling of the pipeline and the sea depth:-

Scale: - 1 m: 1 cm

Actual pipeline diameter: **1m**, thus, pipeline model = **1cm**.
Water/sea depth: **40-80m**, depth of available water wave in laboratory = **30-32cm**, Due to the limitation of water depth in water wave flume, the author choose to use water depth of **30 cm**.

3.7.1 Two Constraint condition

Case I: Pipeline is free at its ends (Figure 3.10). The pipeline is allowed to move rotationally, vertically or horizontally. The real condition of underwater pipeline may not be allowed to rotate, but this experiment is conducted just to show the sand scour around the pipeline and to compare with the anti-rolling pipeline. Theoretically and hypothetically, the anti-rolling pipeline might behave like the real underwater pipeline and thus requires more time to be displaced. This condition is approved in the result and discussion section.

Figure 3.10: Pipeline is free at its end

Case II: The rolling of the pipeline is restricted, but pipeline can move freely in horizontal and vertical directions. A method for anti-rolling of pipeline was designed, as shown in Figure 3.11. The anti-rolling method is mainly using cellophone tape paper which is attached to the end of pipeline model to restrict the pipeline rolling and the density is nearly same as that of water, therefore, it does not lay additional resistance on pipe section but only provides anti-rolling torsion while pipe moving. The device includes two parts, which are installed at the two ends of the pipeline separately.

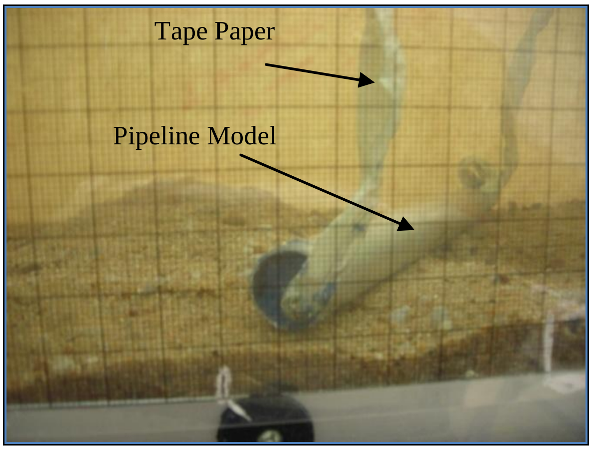

Figure 3.11: Method of restricting the rolling of pipeline

3.7.2 Submerged Weight of Pipeline

The submerged weight of pipeline is the main concern for the on-bottom stability design. The effects of submerged weight of pipelines with different outer diameters on pipeline instability are studied in the paper.

According to the similarity parameter *G* in Eq. (3.1), the submerged weight of test pipes can be adjusted to model the typical submerged weight of actual pipelines. The parameter *G* for the model and prototype pipes can also be expressed as:

$$G = \frac{(W_s)_p}{\gamma'_p D_p^2} = \frac{(W_s)_m}{\gamma'_m D_m^2} \quad \text{………………………... (3.1)}$$

where the subscripts ‘p’ and ‘m’ represent the parameters for the prototype and model, respectively. Referring to the typical $(W_s)_p$ of actual pipes with diameter of 1.0 m, which is from about 1.0–3.0 kN/m, leading to the values of *G* varying between 0.1 and 0.3.

The submarine pipeline generally has a large span so that the wave-induced breakout of pipeline may be treated as a two-dimension problem. Real life condition of underwater pipeline is laid on the seabed for few kilometers and sometimes up to larger than 100 km. In order to demonstrate the lateral movement of this pipeline due to wave current, a segment of this pipeline is investigated and is treated in two-dimension view. The model pipe spans the soil box vertically to the direction of oscillatory flow. In the experiments, to minimize the ending effects, the test pipes composed of aluminum have the length of 0.28m, thus the gaps between pipe ends and the test section box side walls are about 1 cm. Therefore, local scouring at the end of the pipe model is not considered as a problem, which has been proved in the experiments.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Qualitative Data

For this qualitative data gathering, video camera is used in order to record the phenomenon of pipeline model breaks out from its' original place.

4.1.1 Free End Pipeline Model

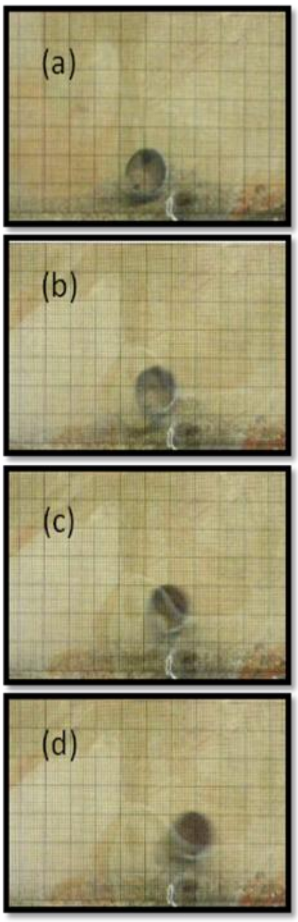

Figure 4.1: Three characteristic states of pipe instability for free-end pipeline model (a) Onset of sand scour, (b) pipeline rocks, and (c) & (d) pipeline breakouts.

4.1.2 Anti-Rolling Pipeline Model

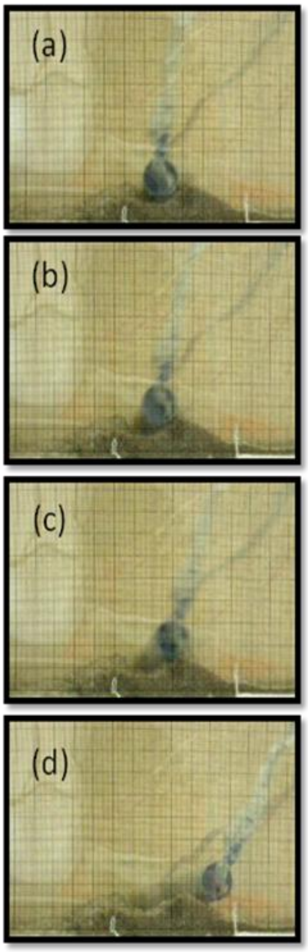

Figure 4.2: Three characteristic states of pipe instability for anti-rolling pipeline model (a) Onset of sand scour, (b) pipeline rocks, and (c) & (d) pipeline breakouts.

4.2 Quantitative Data

4.2.1 Free-End Pipeline Model

Time (s)	Displacement (cm)
2	0
4	0
6	0.1
8	0.1
10	0.2
12	0.25
14	0.8
16	1
18	3

Table 4.0: Time and Displacement for the Free-End Pipeline Model (Frequency 2Hz)

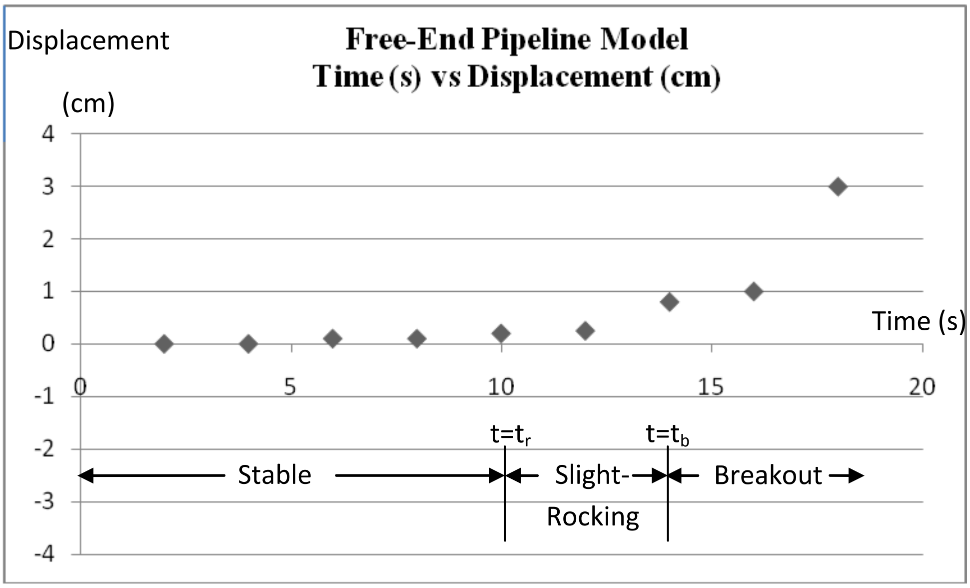

Figure 4.3: Graph Time (s) versus Displacement (cm) for Free-End Pipeline Model

4.2.2 Anti-Rolling Pipeline Model

Time (s)	Displacement (cm)
2	0
4	0
6	0
8	0.1
10	0.1
12	0.2
14	0.4
16	0.5
18	1.2
20	2
22	3

Table 4.1: Time and Displacement for the Anti-Rolling Pipeline Model (Frequency 2Hz)

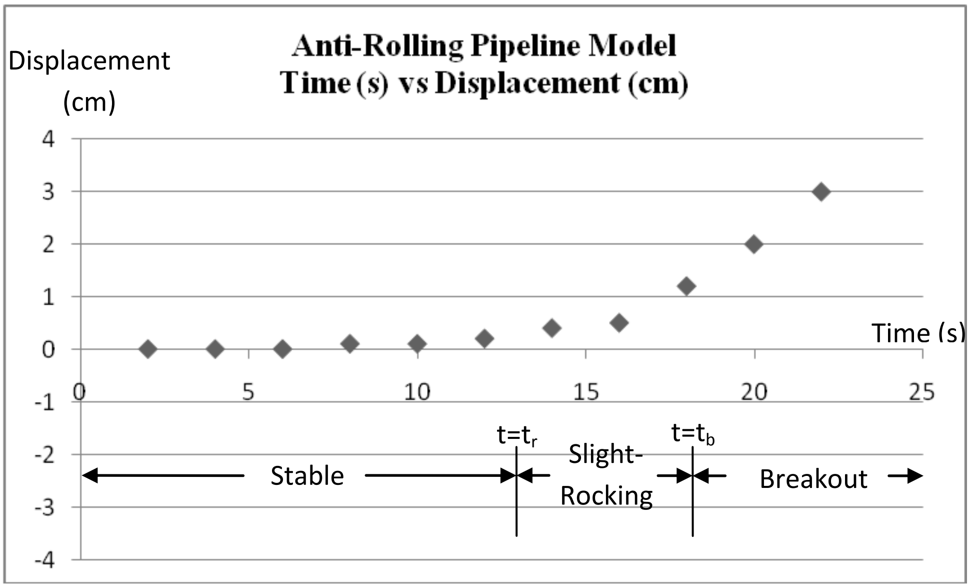

Figure 4.4: Graph Time (s) versus Displacement (cm) for Anti-Rolling Pipeline Model.

4.2.3 Breakout time for variance frequency

For this section, the author measure time for pipeline model for both cases to breakout from its original place with variation of frequency.

4.2.3.1 Free-End Pipeline Model

Frequency of the water wave, Hz	**Time for Pipeline to breakout, s**
2	14
4	17
6	19
8	20
10	22

Table 4.2: Frequency and the Time for the pipeline model to breakout

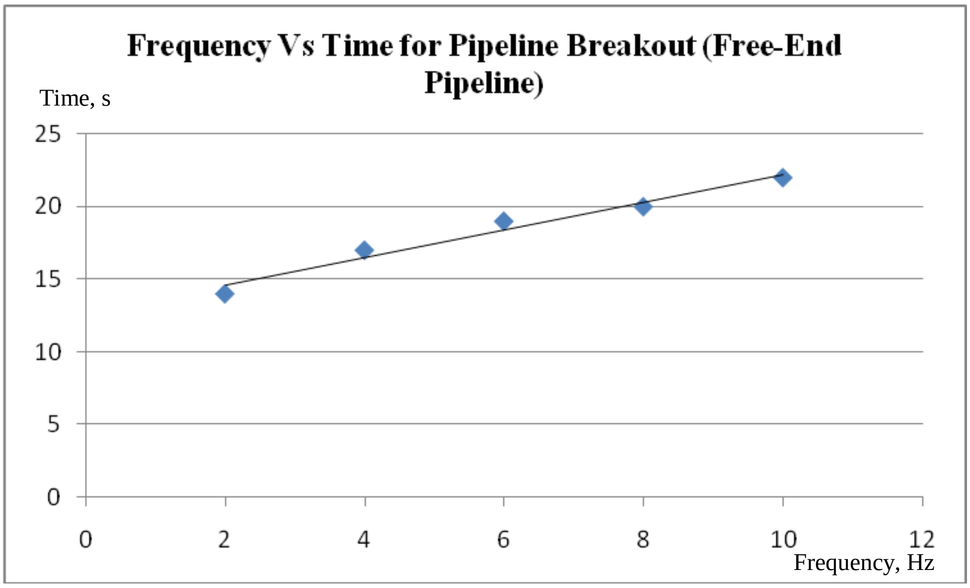

Figure 4.5: Graph Frequency (Hz) versus Time (s) for Free-End Pipeline Model.

4.2.3.2 Anti-Rolling Pipeline Model

Frequency of the water wave, Hz	**Time for Pipeline to breakout, s**
2	19
4	21
6	22
8	24
10	29

Table 4.3: Frequency and the Time for the pipeline model to breakout

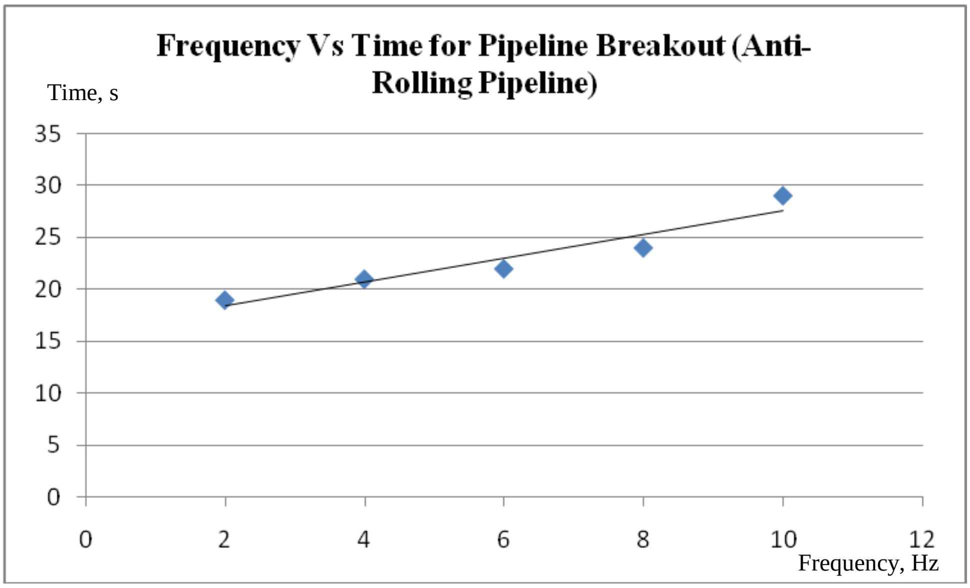

Figure 4.6: Graph Frequency (Hz) versus Time (s) for anti-rolling Pipeline Model.

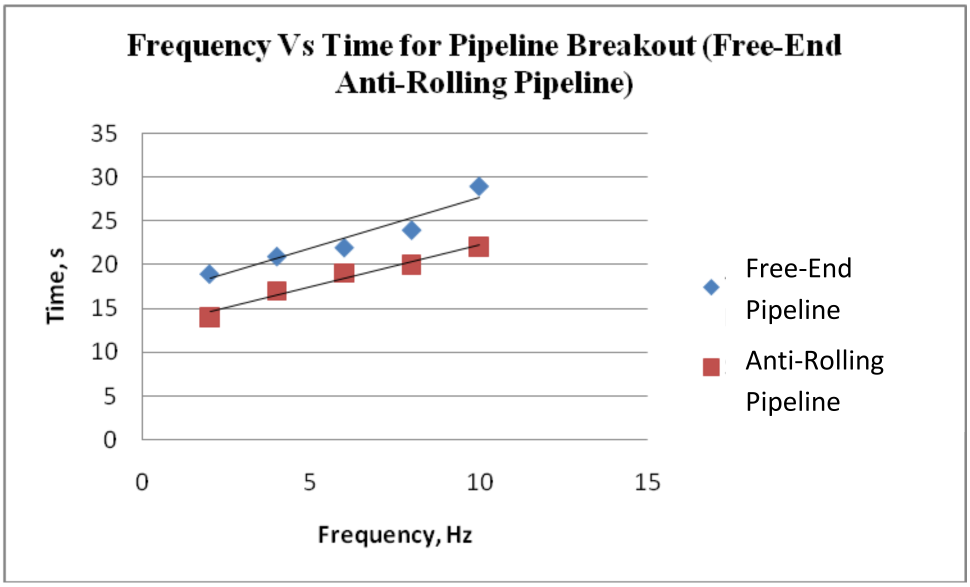

Figure 4.7: Graph Frequency (Hz) versus Time (s) for Free-End and Anti-Rolling Pipeline Model.

4.3 Discussion

4.3.1 Three characteristic times in pipeline instability process can be identified as:-

$t=t_s$: At a certain distance apart from the pipe, the sand grains at the bed surface start to move visibly. Onset of scour occurs (Figure 4.1 & 4.2 (a));

$t=t_r$: The pipe moves slightly (Figure 4.1 & 4.2 (b));

$t=t_b$: The pipe breakout from original site (Figure 4.1 & 4.2 (c)).

This experiment has been carried out earlier, thus, the author takes the initiative to implement this experiment since there are less experiment was carried out on the underwater pipeline in Malaysia. The author tries to get the image as shown in the Figure 4.8 which is the result from the experimental studies of lateral movement of underwater pipeline conducted by F. P. Gao et. Al [2]. Due to the limited sources of high tech equipments, the author unmanaged to obtained clear view of sand scour around the pipeline

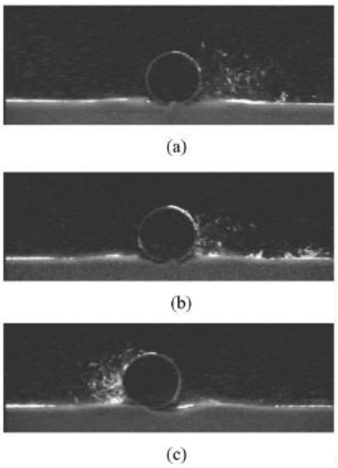

Figure 4.8: Three characteristic states of pipe instability (a) Onset of sand scour, (b) pipeline rocks, and (c) pipeline breakouts. [Figure is obtained from reference 2]

4.3.2 Phases of pipeline instability process

Correspondingly, the pipe and the surrounding sandy bed experience four typical phases:

Totally stable phase ($t<t_s$): the pipeline is stable completely. [2]

Metastable phase ($t_s \le t < t_r$): when the flow velocity is large enough to create considerable amount of sediment in suspension, it forms the main contribution to the sediment transport and piles up in the outer directions. Sand ripples are gradually formed in the vicinity of the pipe [Fig. 4.1& 4.2 (a)] [2]

Pre-failure phase ($t_r \le t < t_b$): at $t=t_r$, the pipe begins to move slightly in the horizontal and vertical directions [Fig. 4.1 & Fig 4.2 (b)]. [2]

Breakout phase ($t \ge t_b$): at $t=t_b$, the pipe suddenly moves away from its original site, or breakout takes place, after a period of slight moving [Fig 4.1 & Fig 4.2(c)]. [2]

4.3.3 Criterion for the on-bottom instability of pipeline

In the experiments, 0.01m pipe model diameter is used for medium sand. For 2Hz wave frequency, the oscillatory flow amplitudes at which pipe looses stability, A_b is recorded. From the observation, A_b = 3.42 cm.

$$\mathrm{KC_b} = 2\pi \mathrm{A_b} / \mathrm{D} \text{ (equation is referred to the reference 2)}$$

$$= 2\pi(3.42) / 1.2$$

$$= 17.9$$

The value of KC number signify that it obey the real condition in the values of KC numbers of coastal sediments in South China Sea which vary between 0–20 [2].

4.3.4 Effect of different frequency to the pipeline breakout

According to the Figure 4.5 & 4.6, the time for the pipeline to breakout from its original place is proportional to the frequency being applied. Wave frequency is the number of waves passing a point for a unit of time (1s) which is the inverse of period, 1/T. If the frequency is higher, it will take longer time for the pipeline to breakout from its original place. This has been proved by the experiment conducted by the author. This situation might be due to the characteristic of real life waves that tend to counter back the waves coming in from one side of the pipeline (Figure 4.9). Hyphothetically, the larger the frequency, more time it takes for the pipeline to be displaced from its initial place. Water waves generate eddy current/ vortex from right and left of the pipeline due to the characteristic of the real life wave current. This vortex / eddy current may result the sand scour around the pipeline and soon displace the pipeline. Although that the force from the eddy current from left and right of the pipeline might not be the same, but sooner, the pipeline will be displaced depending on which side has the larger forces. From the experiment, the pipeline was displaced in the opposite of the incoming waves and it shows that the forces of incoming waves have larger forces than the other side of the pipeline.

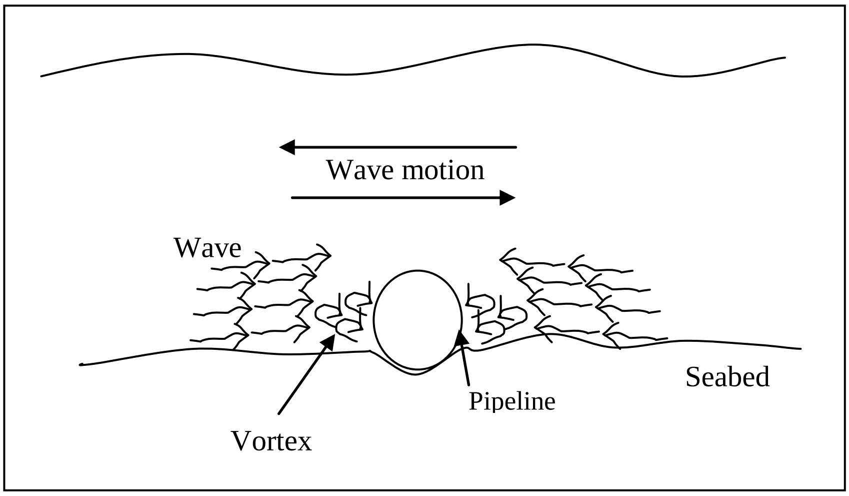

Figure 4.8: Characteristic of ocean waves and the formation of vortex

Plus, based on the Figure 4.7, Anti-Rolling Pipeline Model requires more time to breakout from its original place compared to the Free-End Pipeline Model. This is due to the additional resistance from the tape paper that resists the rotation of the pipeline model. As expected, the anti-rolling pipes are significantly more stable than freely laid pipes.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the analysis of a series of experiments conducted in an water wave flume tank, the following conclusions can be drawn:

Three characteristic times in process of pipe lateral instability, i.e. (a) onset of sand scour, (b) pipe rocking, (c) pipe breakout, are revealed from the pipe displacements records and experimental observation.

The calculated KC number for the experiment shows that the value signifies or corresponds to the value of KC numbers of coastal sediments in South China Sea.

The frequency of the water wave also may influence the breakout of the pipeline. From the experiment conducted earlier, it shows that the low frequency of water wave will result much faster the breakout of pipeline.

The effects of sand properties are also examined. It indicates that the sand particle has influence on soil permeability and sediment scour around pipes. This is observed when the waves had removed the sand foundation of the trench pipeline, which will eventually affect pipeline lateral instability.

Thus, the instability of underwater pipelines is a problem related to the wave-pipe-seabed coupling.

5.2 Recommendations

As a result, further studies on the wave-induced instability of pipeline could be implemented in order to solve the problems aroused because of the lateral movement of offshore pipeline. Moreover, the investigation / simulation of pipeline and the wave condition in laboratory could be improved to get better end results. The recommendations of the experiment are:-

1) Pipeline model should be coatings with concrete in order to demonstrate the real life underwater crude oil pipeline.
2) The method of recording the displacement of the pipe should be done using displacement sensor in order to get accurate data.
3) Using Hi-Tech Video camera to demonstrate the sand scour around the pipeline.
4) Demonstrate and proved that the wave particle movement at seabed whether it moves fully horizontal or elliptically.

Furthermore, the interaction between sand particle sizes also contributes to the lateral instability of pipelines. The different sand size will also be a factor of pipeline instability since it is important for the foundation of the pipeline and trench purposes.

As for further intervention, future work, and continuation, the author thinks that it is better to design an anti-wave-induced pipeline. This can be accomplished by considering the pipeline geometry, the damping theory, and etc. Among the interventions of the pipeline to counter the lateral movements are:-

1) Pipeline dampener – The method of attaching the pipeline with the fluid dampener around the pipeline. (Refer Appendix A-2)
2) Vortex breaker around the pipeline – The method of constructing the device that can decrease the amount of vortex generated around the pipeline.

As for now, the transportation of gas and oil via pipeline is very important and feasibly viable. The intervention in which it is economically practicable could change the perspective of method in transferring the gas / crude oil.

REFERENCES

1. *Henry Liu, Pipeline Engineering, Lewis Publishers, 2003*
2. *Journal of the instability of pipelines under wave current refers to, F. P. GAO, X. Y. GU, D. S. Jeng and H. T. Teo, http://www.sciencedirect.com/science, 9 October 2002.*
3. *AHMAD LUTPI B HARON (2007), a presentation Slide, "SKG-16 Upstream Operation Fundamental Program – Introduction to Surface Facilities"*
4. *Cengel & Cimbala, Fluid Mechanics – Fundamental and Applications, McGraw-Hill International Edition 2006, pg 281-288.*
5. *Cengel & Cimbala, Fluid Mechanics – Fundamental and Applications, McGraw-Hill International Edition 2006, pg 274.*
6. *Cengel & Cimbala, Fluid Mechanics – Fundamental and Applications, McGraw-Hill International Edition 2006, pg 324.*
7. *Peter Oshkai, Part of Free-surface Wave Interaction with a Horizontal Cylinder, an M.S. thesis, Appendix A: Definition of Keulegan-Carpenter Number and Related Issues, http://www.me.uvic.ca/~poshkai/research/ms/ap-a.html*
8. *Adli Budiman Zaidin, Pipeline Engineer, PETRONAS Carigali Sdn Bhd (PMO), Personal Interview, July 26, 2007.*

APPENDIX