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MASTER'S THESIS

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ABSTRACT

Subsea pipelines are increasingly being required to operate at high temperature and pressure HT/HP. The pipeline installed on the seabed and left exposed have a potential to buckle, walk and change configuration under high temperature and pressure (HT/HP). This could lead to failure of the Pipeline if buckling and walking is not properly controlled or mitigated.

The objective of the thesis work is to study and understand the influence of pipeline-soil interaction on the design of surface laid subsea pipeline susceptible to lateral buckling and pipeline walking.

The main focus of the thesis work is on the use of snake-lay configuration as a mitigating measure under controlled buckling design and rock dumping if needed to limit feed-in into buckle and end expansions; the effect of thermal gradient on axial walking and the use of direct electric heating (DEH) to reduce rate of walking.

The snake-lay configuration is achieved by installing deliberate horizontal lay imperfection to trigger a sufficient number of thermal buckles at a pre-determined location along the pipeline. The desire is to limit pipeline expansion at the connecting ends by using snake-lay design with intermittent rock dumping.

The work includes performing non-linear finite element analysis (FEA) and modeling the soil-pipeline interaction of as-laid pipeline using general finite (FE) element software ANSYS. The results are discussed against the relevant design criteria based on design codes DNV-OS-F101, DNV-RP-F110 and Subsea 7 Lateral Buckling Analysis Design Guideline.

FE analyses were performed to study the lateral buckling of a 2km VAS model with an initial out-of-straightness (OOS) under operating temperature and pressure.

Consequently, the effect of thermal gradient of an asymmetric heating process in pipeline walking phenomenon is investigated. Based on FE analyses findings, the use of direct electric heating (DEH) system to reduce the rate of axial walking is proposed and explained.

Keywords: Initial imperfection, Lay radius, walking, lateral buckling, Out-of-straightness (OOS), pipe-soil interaction, end expansion, effective axial force, Feed-in, Virtual anchor, snake-lay, thermal gradient, pipeline, direct electric heating (DEH).

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Obele Ifenna Isaac

Stavanger, June 10, 2013.

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Nomenclature

Abbreviations

BE Best Estimate

LB Lower Bound

UB Upper Bound

DNV Det Norske Veritas

FEA Finite Element Analysis

OOS Out-of-Straightness

OD Outside Diameter

OS Offshore Standard

RP Recommended Practice

SMYS Specified Minimum Yield Strength

MSL Mean sea level

SNCF Strain Concentration factor

DEH Direct electric heating

VAS Virtual Anchor Spacing

HP/HT High Pressure / High temperature

PLET Pipeline End Terminal

SCR Steel Catenary Riser

KP Kilometer point on pipeline

ANSYS Analysis System

PLET Pipeline End terminal

APDL ANSYS parametric design language

SMTS Specified Minimum Tensile Strength

WD Water Depth

PIP Pipe in Pipe

Symbols

E Young's modulus of the steel pipe

H Residual lay tension

I Second moment of area

M_b Bending moment

N_a Axial force

P_e External pressure

P_i Internal pressure

$N_{eff}(x)$ Effective axial force

R Ray radius

F_{cr} Critical Buckling Force

$W_{submerged}$ Weight submerged

N_{OOS} Force due to out-of-straightness (OOS)

$U_{feed-in}$ Design feed-in length

X65 Steel grade of 65000psi

T_{amb} Ambient temperature

N_{Hobbs} Force Hobbs

σ_H Hoop stress

σ_L Longitudinal stress

σ_{LE} Longitudinal stress due to End cap

σ_{LT} Longitudinal stress due to temperature

$\varepsilon_{poisson}$ $Strain\ due\ to\ Poisson\ effect$

N $True\ wall\ Force$

1. Introduction

1.1 General

As oil and gas industry moves farther into deep and ultra-deep waters, HP/HT envelope continually being pushed outward and fields with wellhead pressures and temperatures of order of 600bars (8700 psi) and 170^{o}C are being developed.

Hence, the need for improved technology in handling the delivery of well fluid has become a challenge to pipeline industries.

Environmental and operational conditions in deep waters make it almost impracticable to operate pipeline system (as shown in Figure 1-1) and hence will require appropriate design guidelines in regulating the pipeline-soil behavior in order to counter the large uncertainties developed in the design of such system. These uncertainties from pipe-soil force-displacement response are as a result of differences in seabed-pipeline temperatures, pressures and higher hydrostatic pressures.

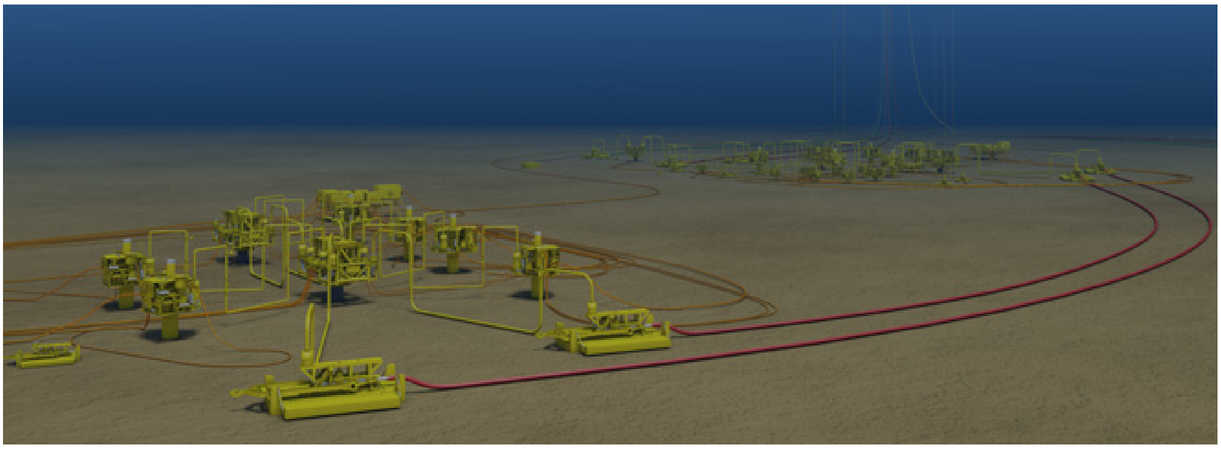


Figure 1-1: Example of Deep Water Subsea Field Layout (2b1stconsulting, 11 September, 2012)

Pipeline left exposed on seabed under operational conditions have a potential to buckle, walk and change configuration due to high temperature and pressure (HT/HP) operational conditions. If the pipeline is restrained, a compressive axial force will be induced in the pipeline. According to (Palmer and King, 2004), this could lead to buckling of the pipeline if the compressive axial force induced reaches the critical buckling force. As a result of the induced force, the pipeline will tend to move upward or sideways to release the excessive axial force induced.

The direction of the movement depends on the pipeline restrictions. As shown in Figure 1-2, large induced axial compressive force for trenched or buried pipeline will therefore lead to upheaval buckling (Upward) while exposed surface laid-pipeline leads to lateral buckling (sideways). This will endanger the integrity of the pipeline if not controlled.

The phenomenon above is termed **Global buckling**. This is not a failure mode in itself, but a load response and could lead to several failure modes such as local buckling, fracture and fatigue (DNV-RP-F110, 2007).

Figure 1-2: Upheaval and Lateral Buckling (Floriano et al., 2011)

Local buckling is normally the governing failure mode resulting from excessive material utilization (Almeida, 2001). It appears as wrinkling or as a local buckle on the compressive side of the cross section as shown in Figure 1-3. This failure mode could result in excessive material Ovalisation and reduced cross-section area which reduces production efficiency or even cause full production stop in any event of pig getting stuck during pigging/inspection. A locally buckled pipeline cannot stand an increased bending moment in the pipeline. This also could lead to pipeline collapse or production lost time.

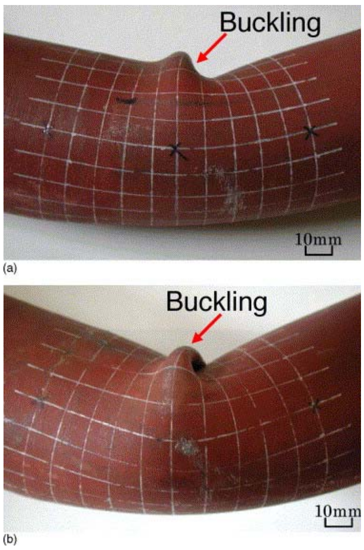


Figure 1-3: Example of a local buckled Pipe (Takahashi et al., 2007)

Fracture is another failure mode; it is the failure on the tensile side of the cross section which is due to excessive material utilization through cyclic loading of the pipeline system.

Fractured pipeline could cause leakage or full bore rupture leading to reduced production, or even full production stop (Almeida, 2001).

Figure 1-4: Example for Ovalisation Failure Mode (Kyriakides and Corona, 2007)

Low cycle fatigue which often occurs for limited load cycles gives strains in the plastic region. This resulting strain could possibly cause pipe leakage or rupture (see figure 1-5), resulting to production reduction, or full production stop. Pipeline exposed to seawater and stresses from buckle could also lead to leakage through hydrogen induced stress cracking.

Figure 1-5: Example for Rupture Failure Mode (Ahmed and & Gareth, 2012)

There has been buckling cases in several fields in the world for example, as recorded “In January 2000, a 17km 16-Inch pipeline in Guanabara Bay, Brazil, suddenly buckled 4m laterally and ruptured, leading to a damaging release of about 10,000 barrels of oil and a great loss to the operator.

Field observation showed that as a result of temperature increase, the pipeline displaced laterally, when failure took place. Operating pressure and temperature of the pipeline were 400bar (5800psi) and 95°C, respectively. The soil beneath the pipeline was very soft clay with about 2kPa undrained shear strength at seabed” (Almeida, 2001).

In this thesis concerning the lateral buckling problem stated above, the tendency for pipeline to buckle will be investigated. A non-linear finite element analysis will be conducted on the area of the pipeline which is found to be susceptible to lateral buckling.

If buckling cannot be avoided, the most economical mitigating measure (for example, snake-lay configuration) will be utilized.

Moreover, under repeated start-ups and short-downs and corresponding heating and cooling during subsea operations, cumulative axial displacement of short pipelines could occur. This un-wanted mechanism is termed **pipeline walking**.

This walking mechanism as written by SAFEBUCK JIP (Carr et al., 2006) could lead to excessive pipeline end movement and ultimately the failure of tie-in jumper/spool connection, loss of tension in a steel catenary riser (SCR) and increased loading within buckled area.

The driving mechanism of axial walking is the expansion and contraction of the pipeline and also on the possibility of no movement in case of an anchor point constraint. As a result of pipeline walking, the expansion at one end of the pipeline would be more than the expected value calculated during design stage and may cause failure of expansion spool or riser (Almeida, 2001).

The rate of axial walking depends strongly on temperature profiles, the magnitude of axial resistance, the mobilization distance and the degradation to residual conditions (Carr et al., 2006).

According to (Almeida, 2001), in year 2000, there were six incident reported in North sea as a result of excessive expansion of pipeline and at least one loss of containment failure due to pipeline walking.

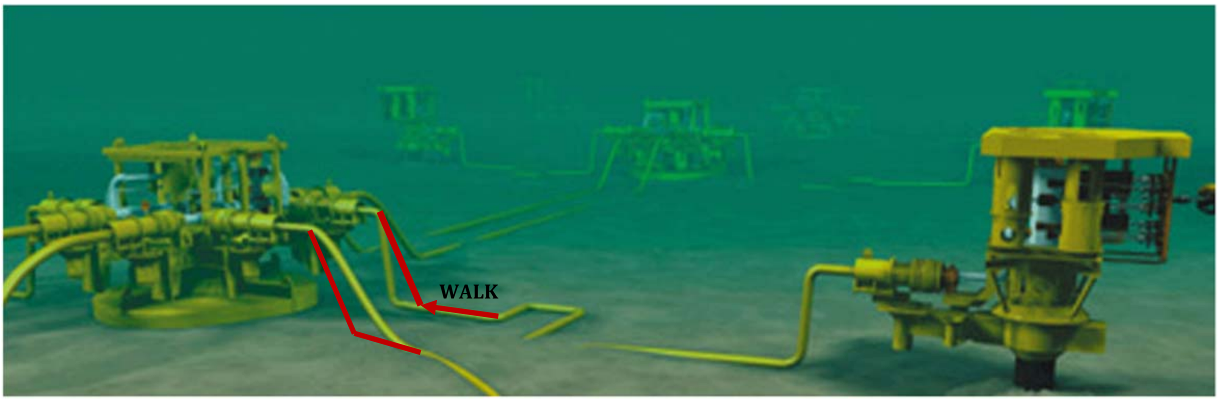


Figure 1-6: Illustration of Pipeline walking (creep) that could lead to excessive end movement and ultimately the failure of tie-in jumper/spool connection (EcoPrasinos, 2012)

1.2 State of the Art

1.2.1 Pipeline-Soil Interaction

Pipe – soil interaction influences both mobilization load (breakout resistance) and pipeline post-buckling configuration from the moment installation commences (DNV-RP-F110, 2007) . This behavior and responses are subject to global buckling in HP/HT conditions. The interaction between the pipeline touchdown loads, combined with the dynamic of the pipe catenary and the seabed surface soil defines the initial pipeline embedment (Bruton et al., 2007). During installation, the remolding of the soil influences the axial resistance affecting the condition at which the pipeline becomes restrained. In the same way, lateral resistance affects the tightness of the installation curves that can be achieved during pipe-laying.

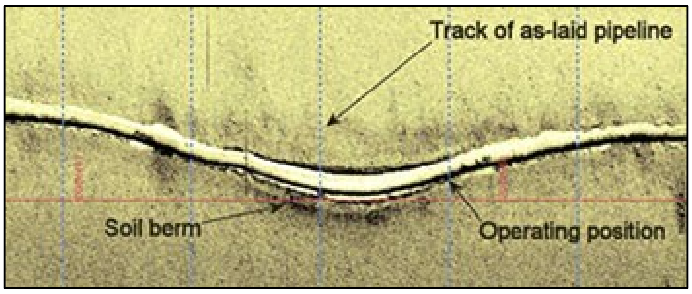


Figure 1-7: Example of Pipeline Response during Pipe-soil Interaction (Bruton et al., 2007)

Pipeline-soil interaction is the largest uncertainty in the design of pipelines both due to variation and uncertainty in characterization (DNV-RP-F110, 2007). The corresponding force-response models have been developed during phase 1 of the SAFEBUCK JIP. The SAFEBUCK JIP was initiated to address this challenge and aims to raise confidence in the lateral buckling design approach and to improve understanding of the related phenomenon of pipeline walking (Bruton et al., 2007).

Consequently, SAFEBUCK JIP performed analysis about pipeline structural response which detailed the responses during installation, expansion during first loading, response in a buckle (first load), response in a buckle (Cyclic behavior - influence of berms) and buckle initiation.

It was shown in their work that pipelines have a total different behavior at lower bound axial friction and upper bound axial friction. The lower bound friction (for example$\mu_a = 0.10$), means that the pipeline experiences greater end expansion and is susceptible to **Pipeline walking**. The Upper bound friction (for example, $\mu_a = 0.58$) means that the pipeline is fully constrained over some of its length so that the section in contact will not move axially, thus preventing walking, but the effective axial compressive force will hence increase significantly making it susceptible to **lateral buckling.**

In summary, it was deduced that the low axial friction will increase the end expansion and axial feed-in into a buckle site while high axial friction will tend to reduce end expansion and feed-in as can be seen from the Figure 1-8 below:

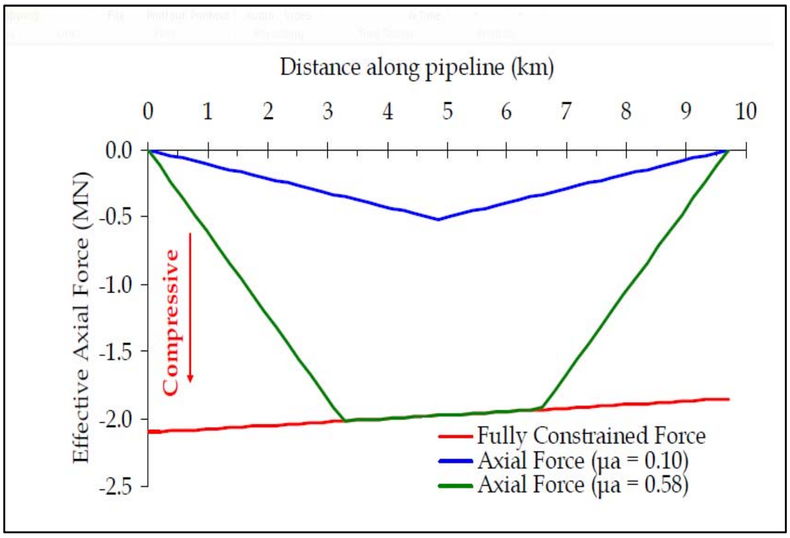


Figure 1-8: Illustration of Pipe-soil interaction for Effective axial force for a range of friction in a straight Pipe (White and Bruton, 2008)

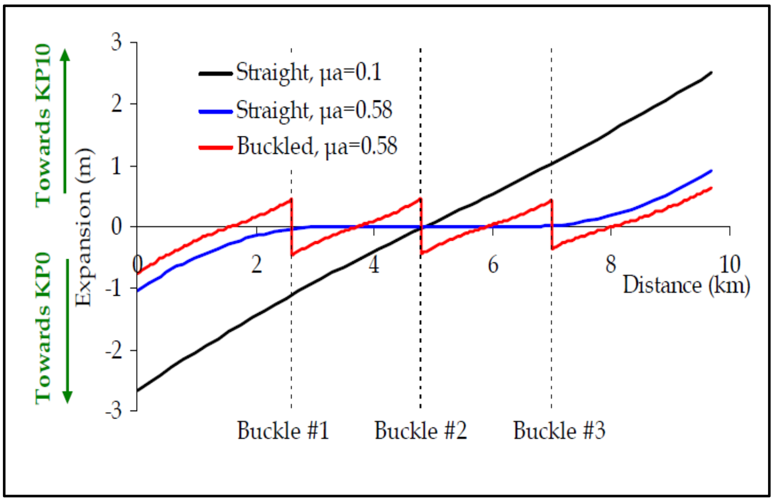


Figure 1-9: Illustration of Pipe-soil interaction for displacement along short pipeline with lateral imperfections (White and Bruton, 2008)

From Figure 1-9, it is seen that the compressive axial force in a pipeline depends on the temperature condition of the pipeline and the axial friction. The paper (White and Bruton, 2008) re-stated that if the compressive force is large enough, then the pipeline may be susceptible to lateral buckling but this will only occur when the compressive force exceeds the critical buckling force as stated previously above (Palmer, 2004).

Also, as the temperature and pressure fluctuates, it creates a cyclic soil-pipeline interaction which influences berms formation. Subsequent consolidation increases its strength and will result in axial feed-in and out of the buckles with each cycle. This is an unwanted scenario in subsea pipeline operation and should be controlled.

1.2.2 Engineered Buckle initiators and Mitigating Measures

Buckles are deliberately initiated by introducing initiation sites (triggers) along the pipeline route to ensure that the pipeline laterally buckles in a planned scenario in order to avoid the induced axial compressive forces concentrating in a particular site.

Buckle is initiated by either one of the following parameters; effective compressive force in the pipeline, out-of-straightness (OOS) features and lateral breakout resistance. Lateral Buckling breakout having the highest uncertainty (Bruton et al., 2007).

Potential localization which is related to inhomogeneity in pipeline as-laid configuration, pipe-soil interaction and temperature leads to longer feed-in length to the largest buckles and increases the susceptibility to buckling and fracture.

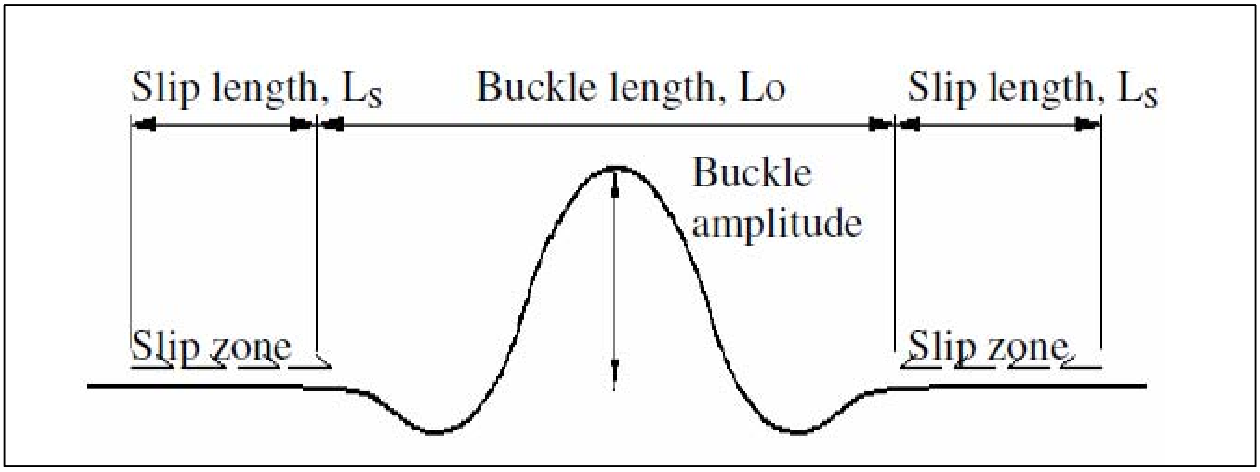


Figure 1-10: Different Regions in a buckle (Kein et al.)

As the temperature in the pipeline increases the slip length will therefore continue to feed-into the buckle after the buckle has been developed (Kein et al.). The length of the slip zone depends on the available frictional resistance to oppose the feed-in. A virtual anchor is developed where there is sufficient frictional force to constrain the slip completely.

The post effective force will therefore change to take into effect the compressive forces into the buckle. This scenario for the post effective force for an isolated single buckle is showed in Figure 1-11 according to the analysis conducted by JP Kenny group.

According to the paper (Bruton et al., 2007), if lateral buckles are initiated at regular intervals along the pipelines, the loads are effectively shared between the buckle sites.

Moreover, the shorter the spacing between buckle initiators, the lower is the probability of buckle forming at t each site as desired. Therefore, selecting appropriate and suitable spacing is the key but a challenging task in design.

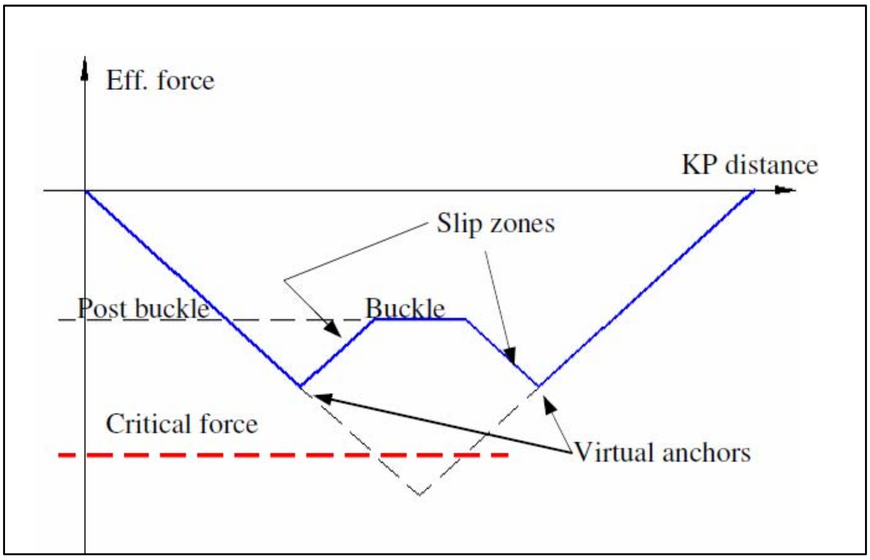


Figure 1-11: Post Effective force of a single isolated buckle (Kein et al.).

If the temperature is further increased after the post buckling, more pipe length will feed into the buckle and will increase the moment of the buckle (Kein et al.). This could lead to formation of more buckles along the pipeline.

If the buckles are spaced such that the distance between successive buckles is less than the total buckle length (Lo + 2Ls) of an isolated buckle, the feed-in is shared between the two buckles as shown in Figure 1-12 (Kein et al.). This is known as expansion sharing (DNV-RP-F110, 2007).

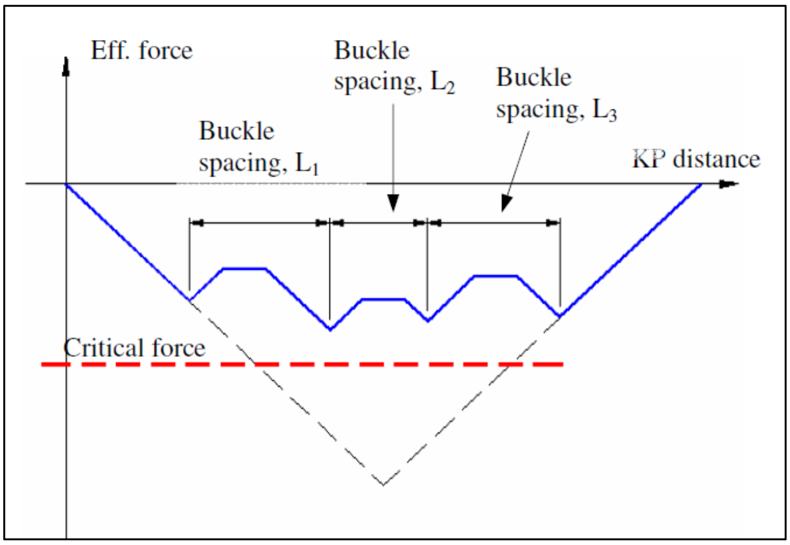


Figure 1-12: Illustration of expansion sharing with multiple buckles (Kein et al.).

The conventional techniques to avoid buckling have been to restrain the pipeline by trenching, burying and rock dumping. Alternatively, the thermally induced stress in the pipeline can as well be relieved with the use of inline expansion spools or mid-line expansion spools (Cheuk, 2007).

In spite of this, these methods are becoming less cost-effective as the operating temperatures and pressures are being required to increase further as the exploration moves into deeper waters where trenching and burying are not viable. Hence, the pipeline is left exposed on the seabed and allowed to buckle laterally.

In accordance with the recommended practice, DNV-RP-F110 (2007) if the response from the applied loads exceeds the pipe cross-sectional capacity, mitigating measures have to be introduced.

Apart from the conventional ways of preventing buckling there are number of improved mitigating measures that have been utilized in the industry during the past years.

The lateral buckling concept has been a design concept that aims to work with the induced expansion phenomenon rather than working against the induced stresses on the pipeline and some of the measures that have been used are as follows:

a) **Sharing of expansion into adjacent buckles**:
This can be achieved by the use of rock dumping at intermittent sections, with the aim to increase the restraint to axial movement in order to reduce the feed-in into isolated buckles that may be triggered by imperfection or trawl gear (DNV-RP-F110, 2007).

b) **Mid-line Expansion spool**:
This utilizes the mid-line spool to absorb the pipe expansion under operational temperature and pressure. Figure 1-13 shows a mid-line expansion spool which was modeled in U configuration and imposed to thermal expansion at both ends. (Kein et al.).

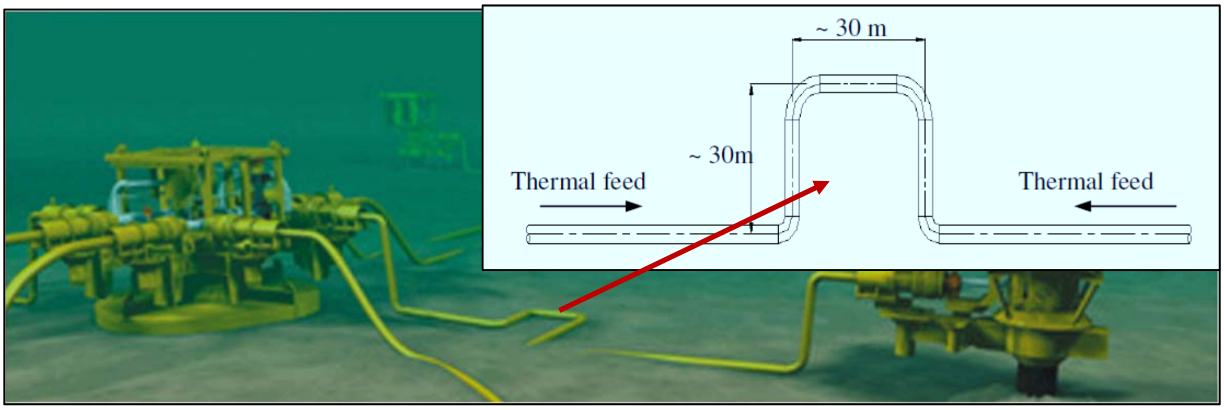


Figure 1-13: Example of Mid-line expansion spool (Kein et al.)

c) **Vertical Triggers/Sleepers**:
This is a method that utilizes initial vertical imperfection (Out-of-straightness - OOS) to initiate a lateral buckle. Pipe sleepers pre-laid across the seabed is used to raise the pipeline off the seabed. This will create a vertical imperfection, OOS, which will initiate a buckle at this section. Figure 1-14 illustrates buckles initiated by trigger. The buckle crown elevates the pipe above the seabed and causes a reduction in lateral friction resistance, and hence reduces uncertainties concerning lateral pipe-soil interactions.

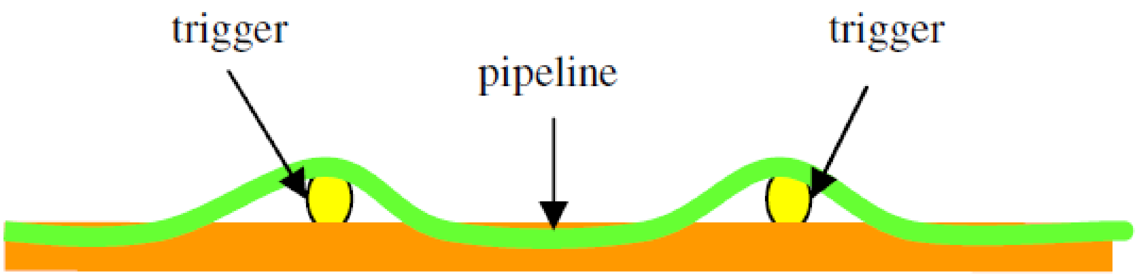


Figure 1-14: Buckle initiating using Vertical sleepers (Kein et al.)

Trigger/Sleeper lowers the critical buckling force as a result of reduction in lateral friction resistance. This allows for higher thermal feed-in into the buckle site, therefore increasing the buckle spacing and as a result reducing the number of buckle initiator required (Kein et al.).

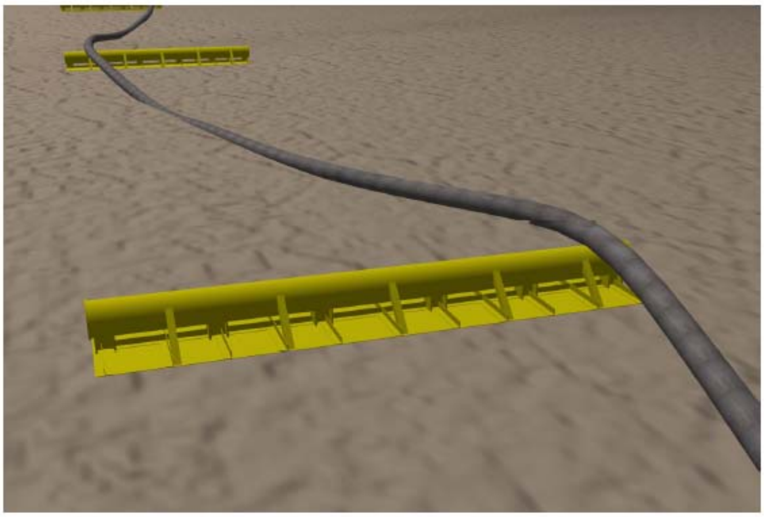


Figure 1-15: 3D view of Buckle initiation using Vertical trigger (Kein et al.)

d) **Buckle Initiation using distributed Buoyancy or additional insulation coating**:
Figure 1-16 illustrates buckle initiation using distributed buoyancy. The distributed buoyancy is added to reduce the weight at the intermittent sections. As the critical buckling force is a function of pipeline weight, the added distributed buoyancy leads to buckle initiations as the weight reduces.

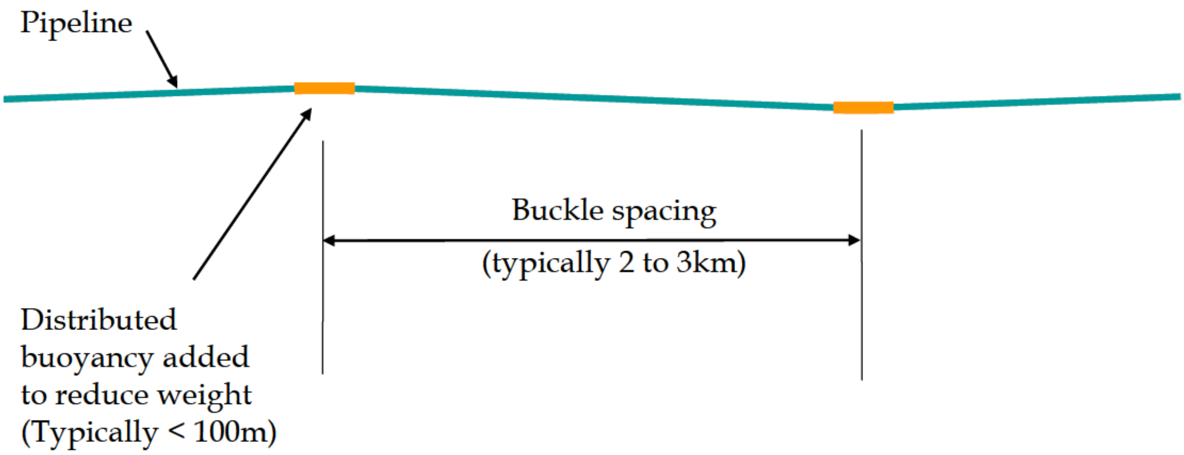


Figure 1-16: Buckle initiation using distributed Buoyancy (Bruton et al., 2005)

e) **Snake –Lay Configuration**:
Figure 1-17 present typical snake lay configuration. The concept of snake lay is to deliberately install horizontal lay imperfections to trigger a sufficient number of buckles at pre-determined locations along the pipeline so that the thermal expansion is distributed among a number of buckles rather than being concentrated at a few buckle sites (Rundsag et al., 2008).

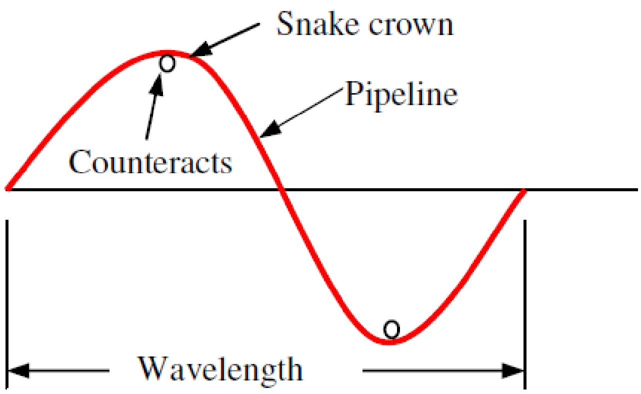


Figure 1-17: Snake Lay Configuration (Kein et al.)

1.2.3 Axial Walking Control Measures

Axial walking cases can as well be controlled by the above mentioned measures where it is less economical to be carried out. Axial walking will not result in pipeline failure if the pipeline itself is not susceptible to lateral buckling (Rong et al., 2009). But, due to accumulated displacement over several cycles, it may lead to failure of tie-in jumpers/spools connected to pipeline. It could also lead to increased loading in buckle section and cause a potential localization in the buckled area.

Many mitigating measures have been utilized in the industry to counter the effect of end expansion resulting from repeated shut-downs and cool down during subsea operations. The measures could be one of the following:

a) **Use of Anchors**: Walking is mostly mitigated by attaching the pipeline or its end structures to anchors. As shown below in Figure 1-18, the connection of the suction anchor to the pipe can be done with a friction clamp. The details of this system can be found in (Subsea7, 2012) and (Bruton et al., 2010)

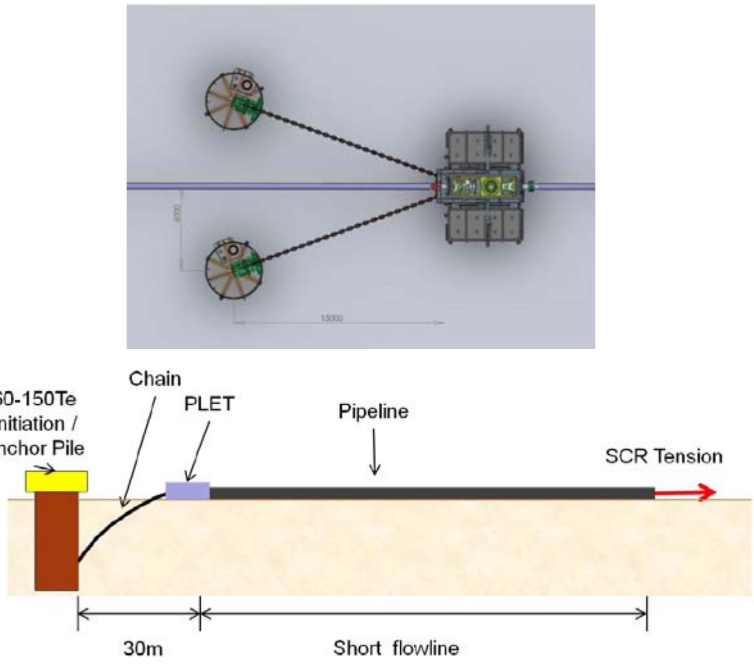


Figure 1-18: Schematic View of Suction anchor, flowline and Riser System (Subsea7, 2012)

b) **Increased Jumper/Spool Expansion Capacity**: The end expansion buckling capacity can be increased at additional cost to withstand against the cyclic loading from axial displacement and hence there is a curtail effect of pipeline walking (Rong et al., 2009). The end expansion capacity can be achieved by using longer spool/Jumpers. The Effective axial force during start-up and shut-down will have to be used to design and accommodate the increased jumper and spool expansion capacity.

c) **Increased Axial Friction**: As previously mentioned in this report, pipeline interacted with lower bound friction (for e.g. $\mu_a = 0.10$) will experience greater end expansion and will be susceptible to Pipeline walking (Bruton et al., 2005). One of the controlling measures for such axial walking is to increase the axial friction. The requirement of increased axial friction at appropriate sections can be assessed by investigating through FE and pipe-soil interaction analysis. The increased axial friction can be achieved by using several techniques such as concrete weight coating, trenching and burying and the use of rock dumps or mattress at the appropriate sections (Rong et al., 2009).

d) **Use of Inline Expansion Loop**:

In order to accommodate the end expansion and contraction of the pipelines, inline expansion loops are installed at regular intervals along each pipeline (see Figure 1-19). This has been utilized in many short and long pipelines.

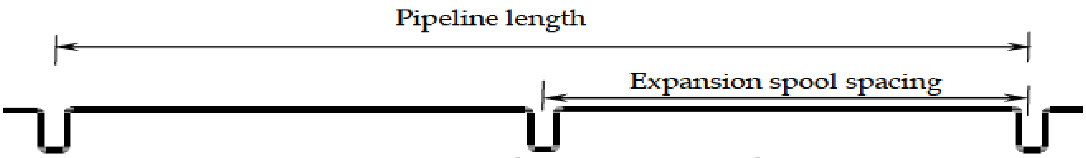


Figure 1-19: Inline Expansion Spool

f) **PLET with Sliding Foundation End Structure**

Figure 1-20 and Figure 1-21 show an arrangement of PLET with sliding foundation. This is a pipeline walking mitigating measure that utilizes the sliding foundation end structures (Carneiro and castelo, 2010). This measure is used where the expansion and contraction are large enough that the expansion spools cannot accommodate and the use of longer spools will be expensive to operate. Further, this measure will take greater expansion forces even deep water. Depending on the spool size attached to the PLET, the effect of end expansion will be reduced as axial friction factor seizes to be a driving force.

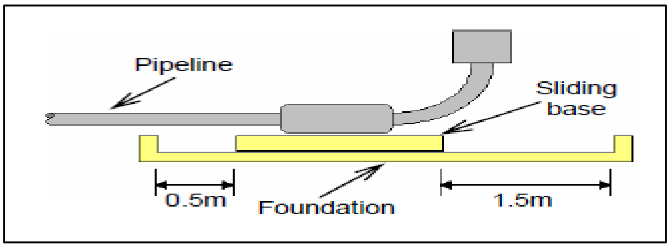


Figure 1-20: Sketch of the PLET with Sliding Mechanism (Carneiro and castelo, 2010)

Figure 1-21: PLET with Sliding Foundation (Carneiro and castelo, 2010)

1.3 Thesis Objectives

The objective of the present thesis work is to study and understand the influence of pipeline-soil interaction on the design of surface laid subsea pipeline susceptible to **lateral buckling** and **pipeline walking**.

The main focus of the thesis work is on:

- The use of snake-lay configuration as a mitigating measure under controlled buckling design and rock dumping if needed to limit feed-in into buckle and end expansions.

- The effect of thermal gradient on axial walking and the use of direct electric heating (DEH) to reduce rate of walking.

The snake-lay configuration is achieved by installing deliberate horizontal lay imperfection to trigger a sufficient number of thermal buckles at a pre-determined location along the pipeline. The aim is to limit pipeline end expansion at the connecting ends and feed-in into the buckle using snake-lay design with intermittent rock dumping.

The acceptability of snakes as engineered buckles will be verified based on lateral buckling criteria by performing a design check according to DNV RP F110:

- Local buckling check (displacement control criteria) which is the main criteria to obtain the allowable virtual anchor spacing.

The work includes performing analytical investigations of pipeline expansion and lateral buckling and verifying the results against the predictions from a non-linear finite element analyses (FEA). The non-linear FE analyses are performed by modeling the soil-pipeline interaction of as-laid pipeline and using general finite element software ANSYS.

The work further analyzes the lateral buckling of the pipeline with an initial out-of-straightness (OOS) while applying internal pressure and temperature over a 2km VAS model.

Also, the work include FE based analyses to investigate the effects of thermal gradient in pipeline walking phenomenon is investigated and assess the use of direct electric heating (DEH) system to reduce axial walking. This is done by considering two thermal gradients of asymmetric heating profile having same heating steps.

The effect of axial friction factor in axial walking phenomenon is analyzed using FE software ANSYS while comparing the results with analytical results obtained using SAFEBUCK guideline.

1.4 Outline of Thesis

The thesis is organised in 9 chapters based on the problem and solution considering the objectives presented in the previous page. The details of the chapters are briefly outlined below.

Chapter 2: (Theoretical background – Pipe Behaviour) this chapter presents the behaviour of pipe material under the influence of compressive axial force and the operating stresses that could affect the pipe to move in different directions.

Chaptere3: (Theoretical background – End expansions) this chapter summarizes expansion that occur at the end connection due the movement of pipe end as a result of induced effective axial forces. Detailed analyses of the driving factors like temperature and pressure loading, strain and end-cap effect are discussed.

Chapter 4: (Theoretical background – Lateral Buckling) the chapter details some of the governing theory's behind pipeline lateral buckling behaviour like Hobbs critical force analysis, effective axial force, anchor force, initiation control mechanism (expansion sharing formula) and allowable feed-in based on recommended practice or standard.

Chapter 5: (Theoretical background – Pipeline walking) presents the theory behind pipeline axial walking, relevant equations, driving mechanism and previous work done by SAFEBUCK JIP.

Chapter 6: Design Methodology – The chapter describes the relevant steps and procedures which are to be followed in designing for lateral buckling and pipeline walking on even seabed. The design requirement, the assumption, the reason for the use of ANSYS software in the work and the snake Lay configuration principle shall be discussed within this module.

Chapter 7: Description of the study – The chapter presents, the thesis problem and the necessary data. An in-place design of 10km pipeline for lateral buckling and 2km flowline for axial walking is presented.

Chapter 8: Results and Discussion – The chapter presents the results obtained from the analytical calculations and FE analysis. Furthermore, the results with respect to lateral and pipeline working mechanism are discussed. Also, the results from snake lay configuration results are presented and discussed.

Chapter 9: Conclusions and Further work – The chapter summarizes the results of the analysis and presents the conclusions of the thesis and recommendations for any future work.

2. Theoretical Background

2.1 Pipe Behaviour

The present section discusses the theoretical background and basic scientific principle relating to pipe-soil interaction with respect to end expansion, lateral buckling and axial walking. This will vary from the driving factors of high temperature and pressures, breakout resistance to thermal buckling.

The basics of the study were generated by the principle of buckling phenomenon in a simple bar element. The same principle is applied for a subsea pipeline installed on a seabed.

2.2 Buckling

"Buckling occurs physically when a structure becomes unstable under a loading configuration and mathematically when a bifurcation occurs in the solution to equation of equilibrium" (Ondrej, 2012). Buckling could either be a:

- **Bifurcation Buckling** – This is a situation where the elastic stiffness of the structure is cancelled by the effects of compressive stress within the structure. If the effect of this causes the structure to suddenly displace a large in a direction normal to the loading direction, then it is a classical bifurcation buckling. Figure 2-1 and Figure 2-2 illustrate the bifurcation buckling and the load response in the bucking

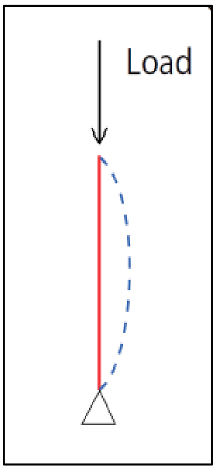


Figure 2-2: Bifurcation Buckling (Ahmed and & Gareth, 2012)

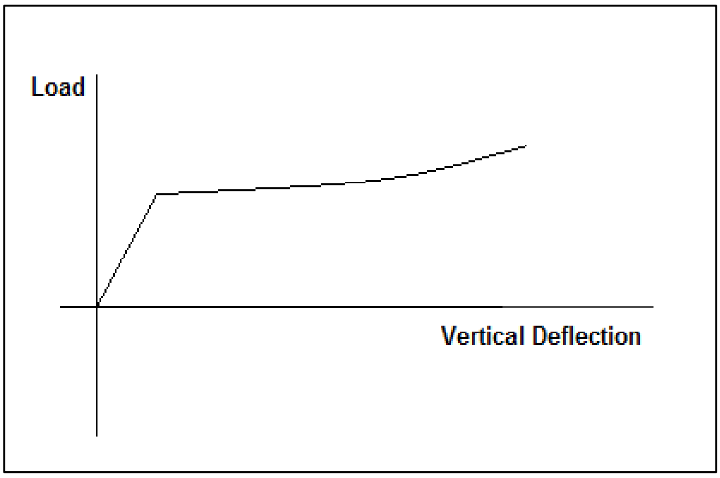


Figure 2-1: Load Response in Buckling (Robert)

- **Snap-through Buckling** – If there is a sudden large movement in the direction of the loading it is called a snap-through buckling. According to Robert "This occurs in structures experiencing limit point instability, when the load is increased infinitesimally beyond the critical load, the structure undergoes a large deformation into a different stable configuration which is not adjacent to the original configuration" (Robert).

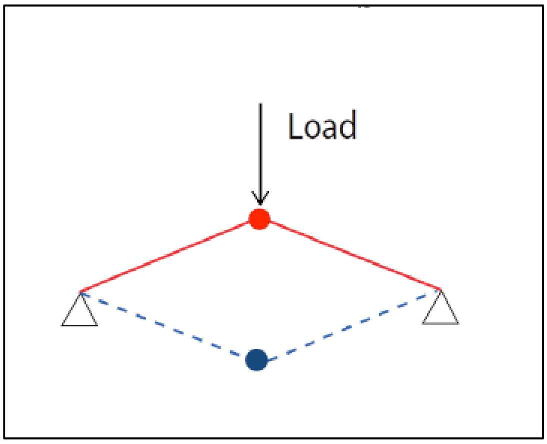


Figure 2-3: Snap-Through Buckling (Ahmed and & Gareth, 2012)

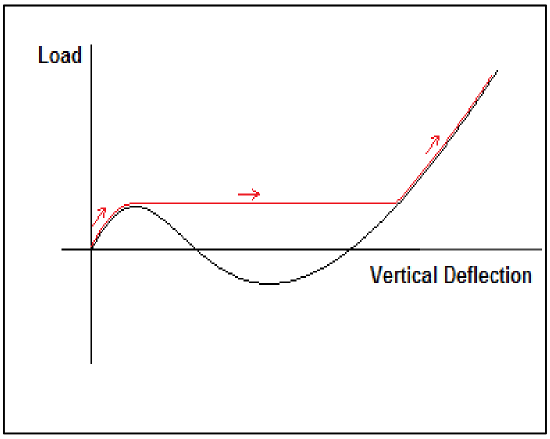


Figure 2-4: Load Response in buckling (Robert)

For pipeline with small initial imperfection, the buckling is expected to occur as a snap through buckling jumping from a particular equilibrium of smaller displacement to another equilibrium position of higher displacement while for those with large initial imperfection, it will undergo a gradual displacement (Ahmed and & Gareth, 2012). Figure 2-3 and Figure 2-4 illustrates the snap through buckling and its load response.

In reality, pipelines lateral imperfection will arise mostly from vessel's motion during pipe laying. Hence, the pipeline will buckle laterally once the effective force reaches the critical Buckling Force. The term initial imperfection will be discussed later in this report accordingly.

Consider a beam section of length, L and Flexural rigidity, EI and compressive axial force, P.

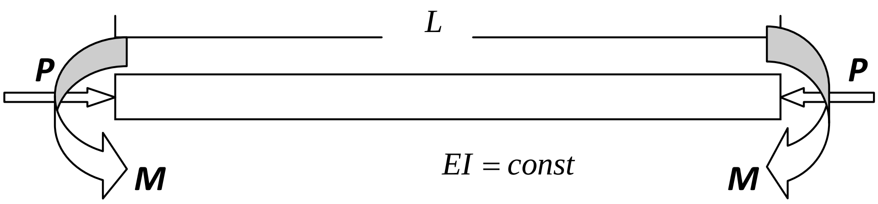


Figure 2-5: Beam Section under Loading

Buckling is said to occur if the combined bending and compressive stresses reaches the **Critical Buckling Load**, $\boldsymbol{P_{cr}}$. By considering the equilibrium of lateral forces and bending moments acting on the beam section.
The dynamic equation of motion for the beam section exposed to an axial compressive force, P is given as:

$$EI\frac{d^4w}{dx^4} + P\frac{d^2w}{dx^2} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (1)$$

From the homogeneous equation above, taking $\boldsymbol{w = e^{\lambda x}}$

Substituting the function $\boldsymbol{w = e^{\lambda x}}$ in equation (1), we have

$$\lambda^4 + \frac{P}{EI}\lambda^2 = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (2)$$

From equation, 2, the solution for λ becomes a complex number

$$\lambda = \pm\sqrt{\frac{P}{EI}i}$$

Hence, the general homogenous solution becomes:

$$\boldsymbol{w = Asin}\sqrt{\frac{P}{EI}}\,x + Bcos\sqrt{\frac{P}{EI}}\,x + C + Dx$$

Considering a case of simply supported beam and, invoking the boundary condition we have:

$$w(x = 0\,) = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{no defection at the support}$$

$$M(x = 0) = EI\frac{d^2w}{dx^2} = 0 \ldots\ldots\ldots . \textit{no bending at the support}$$

$$w(x = L) = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{no defection at the support}$$

$$M(x = L) = EI\frac{d^2w}{dx^2} = 0 \ldots\ldots\ldots . \textit{no bending at the support}$$

From the above, we can deduce that

$$B = C = D = 0$$

Therefore, we have:

$$\boldsymbol{APsin}\sqrt{\frac{P}{EI}}\,L = 0$$

Here A and P cannot be zero, so we conclude that ………………………… $\boldsymbol{sin}\sqrt{\frac{P}{EI}}\,L = 0$

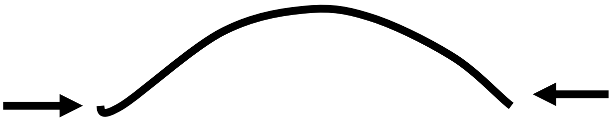
$$Therefore, \sqrt{\frac{P}{EI}}\,L = \boldsymbol{\pi n}$$

The Critical Buckling that must be exceeded for buckling to occur becomes:

$$\boldsymbol{P_{cr}} = \frac{n^2\pi^2EI}{L^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (3)$$

For $\boldsymbol{n} = 1$,

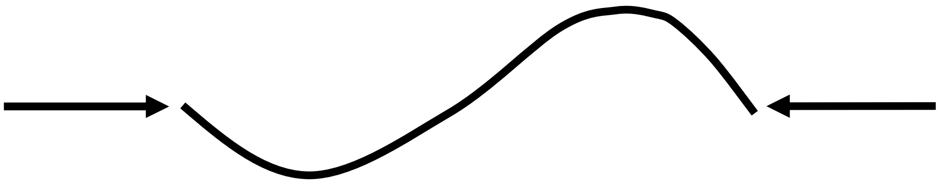
$$\boldsymbol{P_{cr}} = \frac{\pi^2EI}{L^2}$$



$\boldsymbol{mode}\ \mathbf{1}$

For $\boldsymbol{n} = 2$,

$$\boldsymbol{P_{cr}} = \frac{4\pi^2EI}{L^2} = 4P_{@\ n=1}$$



$\boldsymbol{mode}\ \mathbf{2}$

2.3 Operating Stresses

Operating stresses are stresses which result from a combination of internal pressure and thermal stresses that occur during operation (Guo et al., 2005). During Operations, pressure and temperature build up and cause the pipeline to expand both radially and longitudinally due to the differences created between the pipeline and the surroundings. The stresses vary in magnitude depending on the forces opposing them, for example, the forces from axial soil friction, end constraints and end cap.

(Karunakaran, 2012) stated that “when a pipeline is subjected to internal pressure, three mutually perpendicular principal stresses will be set up in the cylinder materials (see Figure 2-6)”, namely

a. Circumferential or hoop stress
b. The radial stress
c. Longitudinal stress

Taking into account that the *radial stresses* which acts normal to the curved plane of the isolated element are negligibly small as compared to other two stresses especially in the case of relatively thin-pipe when $(D/t > 20)$.

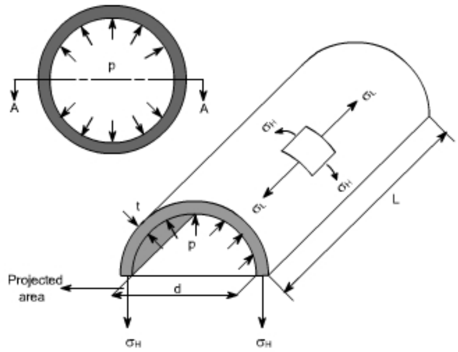


Figure 2-6: Stress Induced by Internal Pressure Loading (Karunakaran, 2012)

2.3.1 Hoop Stress (σ_H)

For a thin-wall pipeline$(D/t > 20)$, subjected to internal pressure, P, the effect of the radial force distributed around the circumference will produce a stress called circumferential or Hoop Stress σ_H (Karunakaran, 2012).

$$\sigma_H = \frac{PD}{2t}$$

Where: $\sigma_H = Hoop\ stress$

$P = Internal\ Pressure$

$D = net\ internal\ Diameter$

$t = nominal\ wall\ thickness$

As operations gets to the deeper waters, the mitigating effect of external pressure should be included as follows:

$$\sigma_H = \frac{(P_{local} - P_e)D}{2t}$$

Where: $P_{local} = Local\ design\ presure$

$P_e = External\ Pressure$

$D = external\ diameter$

2.3.2 Longitudinal Stress (σ_L)

Longitudinal stress is referred as the axial stress experienced by the pipe wall. As seen below from Figure 2-7, it comprises the stresses due to the end cap effect, temperature (thermal stress), bending, axial and Poisson's effect (hoop stress).

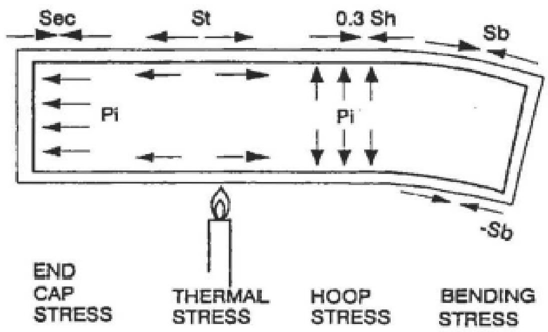


Figure 2-7: Longitudinal Stress component (Prof. Sharma)

2.3.2.1 End Cap Effect (σ_{LE})

The longitudinal stress due to the end cap effect can be calculated by dividing the total pressure against the end of the pipe (end cap effect) by the cross-section area of the pipe.

Figure 2-8: Pressure induced by End Cap Effect (Karunakaran, 2012)

$$\sigma_{LE} = \frac{Force}{X - section\ area} = \frac{P.(\frac{\pi D^2}{4})}{\pi Dt} = \frac{PD}{4t}$$

2.3.2.2 Thermal Stress

In restrained condition, either by soil friction, anchor, buried or trenched, the restriction of the expansion generated by temperature differences between the installation and operating temperature induces a compressive stress on the pipeline. As a result of this restriction, the longitudinal strain is zero and the induced compressive thermal stress generated is given as:

$$\sigma_{LT} = -\alpha E \Delta T$$

For the unrestrained condition, the longitudinal thermal stress is zero but the thermal strain is given as: $\sigma_{LT} = \alpha E \Delta T$

2.3.2.3 Hoop Stress (Poisson's effect)

The longitudinal stress induced due to Poisson's effect can be calculated according to the equation below:

$$\sigma_{LH} = v\sigma_H$$

Where: $v = poisson's\ ratio$; $0.3\ for\ steel\ pipe$

Figure 2-9 explains pipeline expansion due to poison's effect. According to (Guo et al., 2005), "When a two-dimensional element is heated but subjected to a restraint in the y-direction, the strain in the x-direction is increased due to the Poisson ratio v".

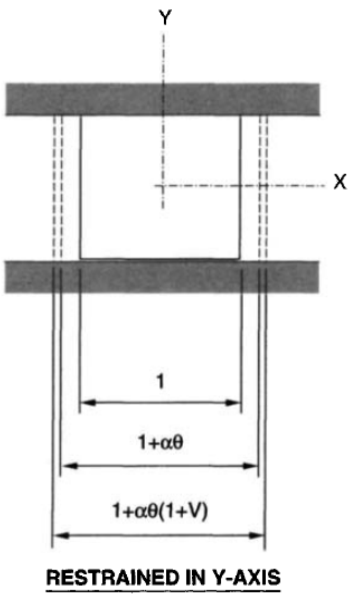


Figure 2-9: Pipeline expansion due to Poisson's effect (Guo et al., 2005)

2.3.2.4 Bending Stress

The Bending stress (σ_{LB}) associated with the longitudinal stress according to (Yong and Qiang, 2005), can be calculated as follows:

$$\sigma_{LB} = \frac{M_b}{Z_s}$$

$$M_b = Bending\ moment$$

$$Z_s = \frac{I_z}{(D/2)} = \frac{\frac{\pi}{64}(D^4 - {D_i}^4)}{(D/2)} = Sectional\ modulus\ of\ rigidity\ of\ the\ pipe$$

2.3.2.5 Axial Stress ($\boldsymbol{\sigma_{LA}}$)

The Longitudinal stress generated due to the axial stress can be computed as stated in (Yong and Qiang, 2005) by the equation:

$$\sigma_{LA} = \frac{N_a}{A_s}$$

Where: $N_a = Axial\ force$

$$A_s = Cross - sectional\ Area = \frac{\pi(D^2 - {D_i}^2)}{4}$$

2.3.3 Combined Stresses

Provided that the sign convention foe compressive and tensile effect are employed properly, the total longitudinal stress can be determined according to the relation given in (Guo et al., 2005) as:

$$\sigma_L = \sigma_{LE} + \sigma_{LT} + \sigma_{LH} + \sigma_{LB} + \sigma_{LA}$$

Therefore, the combined stress depending on the approved codes and standard for the project shall meet the requirement below:

$$\sigma_{combined} = \sqrt{{\sigma_H}^2 + {\sigma_L}^2 - \sigma_H\sigma_L} \ \leq \ F_{combined}.SMYS$$

3. Theoretical Background - End Expansions

3.1 Pipeline End Expansion

A Subsea pipelines with free end is considered laid on a flat seabed and free to expand. Under constant operating temperature and pressure, the pipeline expands and the soil friction forces are activated which oppose the expansion. The constraint created by the soil friction causes an effective compressive axial force to be induced in the pipeline which results in axial displacement (strain) of the pipeline. However, as a result of this restraint, the expansion will only manifest at the ends. This is referred to as End Expansion.

As shown below in Figure 3-1, expansion occurs within a transition region whose length depends on the limiting axial friction between the soil and pipeline. If the frictional resistance force is large, the corresponding transition region will be small and if the friction it is less, the transition length will be larger.

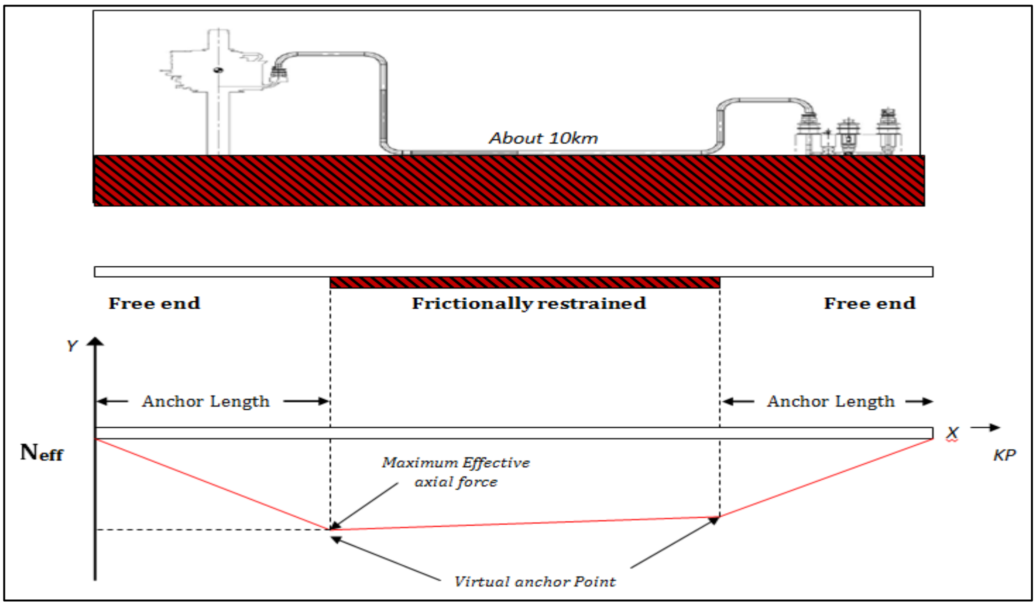


Figure 3-1: Example of Expansion Analysis

In pipeline design, expansion analysis will help to determine the maximum expansion at the ends and the associated axial strain loadings that the pipeline can carry without any failure. According to analyses performed by (Prof. Sharma), expansion analysis will provide information such as:

- The maximum axial loading that will buckle the pipeline
- The maximum expansion the spools/tie-in Jumpers can accommodate.

As shown in Figure 3-1, the degree of this expansion depends on the operational temperature, pressure, the pipe weight and the restraint on the pipeline. The pipeline will tend to expand until the anchor point where it is fully restrained by the soil friction. This distance from the pipeline end to the anchor point is called the **ANCHOR LENGTH**.

The lower the axial friction (the restraint), the greater the end expansion at the spool or tie-in end (the greater the anchor length).

3.1.1 Longitudinal Strain

The maximum pipeline end expansion is consequence of the net longitudinal strain and frictional force between the pipeline and the seabed (Offshorevn, 2010).

The pipeline expansion as stated above will occur at pipeline ends under unrestrained condition leading to longitudinal strain at the ends. The longitudinal strains are due to Temperature and pressure effect.

3.1.1.1 Thermal Strain (ε_T)

For an unrestrained pipeline, the temperature change created by the difference between the operating and installation temperature induces a thermal strain that is linearly proportional to the change in temperature in axial direction as shown in Figure 3-2:

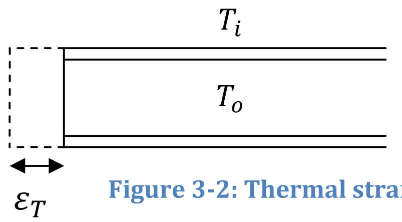


Figure 3-2: Thermal strain effect

Therefore, the thermal strain induced in the pipeline in an unrestrained condition is given as:

$$\varepsilon_T = \alpha \Delta T = \alpha (T_o - T_i)$$

3.1.1.2 Pressure Strain

The longitudinal strain created due to pressure loadings are as a result of end-cap effect and Poisons effect.

a. **End-Cap Effect:**
The pressure differential across the pipe wall induces an axial loading which give rise to a longitudinal strain in the pipeline as shown in Figure 3-3:

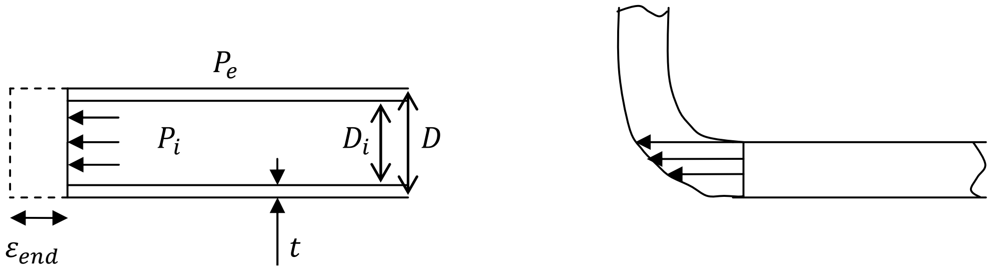


Figure 3-3: End Cap Effect

The effect can occur at closed end of a pipeline or at a bend. The strain due this can be calculated as stated below:

From the end-cap force which is given as

$$\boldsymbol{F_{end}} = P_i A_i - P_e A_e \quad = \frac{P_i \pi {D_1}^2}{4} - \frac{P_e \pi D^2}{4}$$

$$\boldsymbol{\varepsilon_{end}} = \frac{\boldsymbol{F_{end}}}{A_s E}$$

$Where\ the\ cross-sectional\ area, A_s\ is\ assumed\ to\ be,\qquad A_s = \pi D_i t$

Taking $D = D_i$, then the end-cap strain becomes:

$$\varepsilon_{end} = \frac{(P_i - P_e)D}{4tE}$$

b. Poisson Effect:

The internal pressure induces hoop stress and corresponding circumferential strain in the pipeline. The hoop expansion causes a longitudinal contraction of the pipe, i.e. the pipe expands in the hoop direction and the Poisson effect results in an axial contraction (opposite to end cap pressure effect) (Subsea7, 2011).The radial expansion created by this effect will cause a longitudinal contraction of the pipe as shown in Figure 3-4:

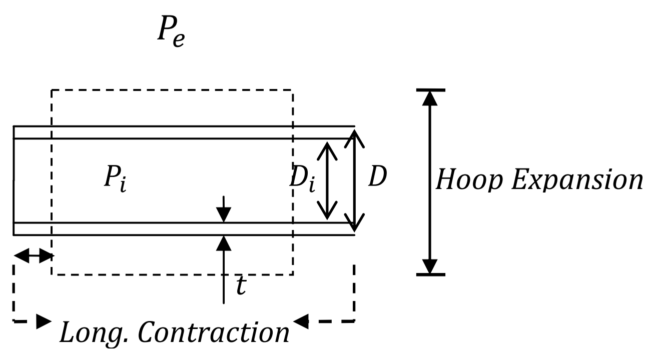


Figure 3-4: Poisson Effect

The strain due the Poisson effect can be calculated as given by (Yong and Qiang, 2005):

$$\varepsilon_{poisson} = -\frac{v\sigma_H}{E}$$

Assuming no effect of external pressure, the total longitudinal strain is given as:

$$\boldsymbol{\varepsilon_{longitudinal}} = \varepsilon_T + \varepsilon_{end} + \varepsilon_{poisson} = \alpha\Delta T + \frac{P_i D_i}{4tE} - \frac{v\sigma_H}{E} \quad = \quad \alpha\Delta T + \frac{\sigma_H}{\mathbf{2}}\frac{(1-2v)}{E}$$

3.1.2 Frictional Strain and Force

Pipeline resting on seabed experiences a frictional resistance between the soil and the pipeline outer surface, and the relationship between them is given by the Coulomb relationship. For a pipeline that do not penetrate the seabed, the Coulomb friction relation is applicable and appropriate (Prof. Sharma).

The frictional strain of a pipeline resting on seabed is given as:

$$\varepsilon_{friction} = \frac{\mu . W_{submerged} . L_{anchor}}{A_s E}$$

Where: $L_{anchor} = anchor\ length$

$W_{submerged} = Pipeline\ Submberged\ weight$

From the above expression, the frictional force that will be experienced between the soil and pipeline is given as:

$$\boldsymbol{N_{friction}} = \mu . W_{submerged} . L_{anchor} \dots\dots\dots\dots\dots\dots\dots\dots (4)$$

3.1.3 Effective Axial Force

During pipeline expansion, the combined driving axial force that must be counteracted in order to avoid end expansion is the effective axial force (Fyrileiv and Collberg, 2005). The effective axial force increases from pipeline end until it reaches its maximum at the point of full axial constraint.

According to (Fyrileiv and Collberg, 2005), "the effective axial force governs the structural response of the pipeline by influencing on lateral and upheaval buckling, anchor forces, end expansion and natural frequencies of free spans".

Considering the external and internal pressures, the effective axial force can be calculated by the following relation (Fyrileiv and Collberg, 2005):

$$N_{eff\ (x)} = N - P_i A_i + P_e A_e \dots\dots\dots\dots\dots\dots . (5)$$

$$N = True\ wall\ Force$$

$$But, \qquad P_i A_i - P_e A_e = N_{endcap} = End\ Cap\ Force$$

Therefore,

$$N_{eff\ (x)} = N - N_{endcap}$$

Taking installation barge tension into consideration, the barge tension, F_{lt} as shown in Figure 3-5 below is given as:

$$F_{lt} = N + P_e A_e = H \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (6)$$

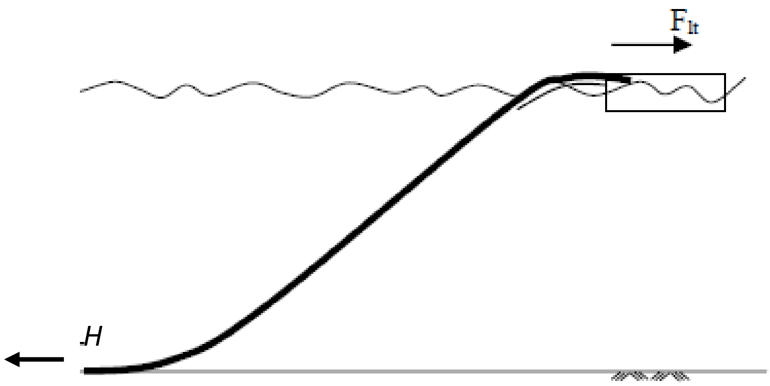


Figure 3-5: Illustration of Lay Tension induced during Pipe laying (Fyrileiv and Collberg, 2005)

During operation, the true axial force if fully constraint goes into compression as a result of the thermal expansion $(-EA_s\alpha\Delta T)$ and tension due to the hoop stress and Poisson's effect $(\upsilon\sigma_H A_s)$ (Fyrileiv and Collberg, 2005).

Therefore, from equation (5), the true axial force after installation becomes:

$$N = H - P_e A_e + \upsilon\sigma_H A_s - A_s E\alpha\Delta T$$

$$N = H - P_e A_e + vA_s \frac{P_i D_i}{2t} - A_s E\alpha\Delta T \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(7)$$

Equating (5) and (7), the effective axial force becomes:

$$N_{eff} = H - P_i A_i + vA_s \frac{P_i D_i}{2t} - A_s E\alpha\Delta T \ldots\ldots\ldots\ldots\ldots..(8)$$

In general, the effective axial **compressive** driving force of a pipeline under full axial constraint is given as:

$$N_{eff} = A_s E\alpha\Delta T - vA_s \frac{P_i D_i}{2t} + P_i A_i - H \ldots\ldots\ldots..(9)$$

Where: $P_i = Internal\ pressure\ difference\ relative\ to\ as\ laid,$ $\quad and\ A_s = \pi D_i t$

3.1.4 End Expansion

The amount of expansion induced at the ends can be calculated using the strain balanced method. This is done by integrating the strain between the free ends and the virtual anchor points. The longitudinal strain is the difference between the applied axial force and the frictional force induced by soil-pipeline interaction.

This combined driving axial force required to fully constrain the pipeline is as a result of the end-cap effect, Poisson's effect, thermal and residual lay tension. For design purposes, according to (Subsea7, 2011), the residual lay tension, may be assumed to be negligible. Therefore, the combined driving axial force (Effective Axial Force) that causes end expansion is given as:

$$\boldsymbol{N_{eff\,(x)} = H - \left[N_{end-cap\,(x)} + N_{poisson\,(x)} + N_{thermal\,(x)}\right]}$$

This force is also known as the **Anchor Force**.

Where:

$End\ cap\ Force$: $\boldsymbol{F_{end-cap\,(x)} = \Delta P.A_i}$……………………………(Subsea7, 2011)

$$\Delta P = P_{local\,(x)} - P_{external\,(x)}$$

$P_{local} = Local\ design\ prssure = P_{design} + \rho_{content}gh$

$\rho_{content} = density\ of\ the\ content$

$h = Vertical\ distance\ between\ design\ pressure\ reference\ location\ and$

$elevation\ of\ interest$

$Force\ due\ to\ poisson,$ $\boldsymbol{N_{poisson\,(x)} = -v\sigma_H A_s = -\Delta P.v.A_s}$

$$\boldsymbol{= -v\frac{\Delta P.D_i.A_s}{2t}}$$

$Force\ due\ to\ thermal,$ $\boldsymbol{N_{thermal\,(x)}} = EA_s\alpha\Delta T$

Neglecting the lay tension the combined driving axial Force that causes end expansion is given as:

$$N_{eff\,(x)} = N_{end-cap\,(x)} + N_{poisson\,(x)} + N_{thermal\,(x)}$$

$$N_{eff\,(x)} = EA_s\alpha\Delta T + \Delta P.A_i - v\frac{\Delta P.D_i.A_s}{2t}$$

$$A_s = \pi D_i t$$

$$A_i = \frac{\pi {D_i}^2}{4}$$

$$N_{eff\,(x)} = EA_s\alpha\Delta T + \frac{\Delta P.\pi {D_i}^2}{4}(1-2v) \ldots\ldots\ldots\ldots..(10)$$

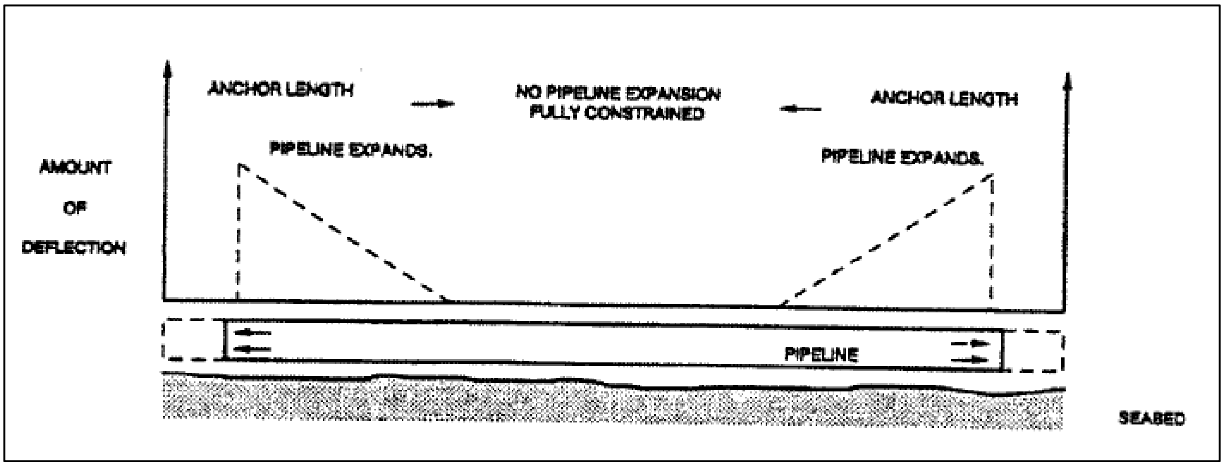


Figure 3-6: Pipeline End Expansion (Cheuk, 2007)

The maximum pipeline end expansion is consequence of the net longitudinal strain and frictional force between the pipeline and the seabed (Offshorevn, 2010).

The expansion can now be deduced as:

$$\delta = \int_0^{VAP} \varepsilon_{net}.\, dL$$

$$\delta = \int_0^{VAP} \left(\varepsilon_{\mathrm{endcap}} + \varepsilon_{poison} + \varepsilon_{thermal} - \varepsilon_{friction}\right).\, dL$$

$$\delta = \int_0^{VAP} \frac{\left(\mathrm{N}_{\mathrm{endcap}} + N_{poison} + N_{thermal} - N_{friction}\right)}{EA_s} dL$$

In general,

$$\delta = \int_0^{VAP} \frac{\left(N_{eff\,(x)} - N_{friction\,(x)}\right)}{EA_s} dL$$

As stated in (Subsea7, 2011), by taking an anchor point at the hot end and the cool end of the pipe, the expansion at the hot and cold end are given by the following expressions:

$$\delta_{HOT} = \int_{La\,(x1)}^{KP_0} \frac{\left(N_{eff\,(x)} - N_{friction\,(x)}\right)}{EA_s}.\, dx$$

$$\delta_{COLD} = \int_{KP_{n-1}}^{La\,(x2)} \frac{\left(N_{eff\,(x)} - N_{friction\,(x)}\right)}{EA_s} . dx$$

Where:

$\delta_{HOT} = hot\ end\ expansion$

$\delta_{COLD} = Codl\ end\ expansion$

$N_{eff\,(x)}$ = Resultant effective axial force

$N_{friction\,(x)}$ = Friction restraint along full beam

$La\ (x1) = hot\ end\ anchor\ point$

$La\ (x2) = cold\ end\ anchor\ point$

$KP_0 = Pipeline\ start\ Kilo\ Point$

$KP_{n-1} = End\ of\ Pipeline\ KP$

VAP= Virtual anchor point

4. Theoretical Background - Lateral Buckling

4.1 Lateral Buckling and its Mechanism

We have seen that compressive forces are induced in pipelines by the effect of temperature, pressure and other effects when the pipeline is restrained either by soil friction, rocks or anchors. Once these compressive forces exceed the critical buckling force of the pipeline, the pipeline will tend to buckle either upward, laterally or at an angle to release the excessive inbuilt forces.

(Sriskandarajah et al., 1999) defines lateral buckling as "*the theoretical buckling state that occurs under axial compressive loadings accompanied by gradual sideways movement as the pipeline breaks-out*".

The driving force for the lateral buckling behavior is due to effect of the effective axial compressive force generated by thermal expansion, end-cap effect, Poisson's effect of hoop expansion and the residual lay tension. At full axial constrain, the effective axial compressive force is given as:

$$N_{eff\,(x)} = EA_s\alpha\Delta T + \Delta P.A_i - v\frac{\Delta P.D_i.A_s}{2t} - H$$

Where:

$N_{eff\,(x)} = Effective\ axial\ compressive\ Force$

$E = Modulus\ of\ Rigidity$

$A_s = Cross\ sectional\ area\ of\ the\ pipe\ wall$

$\alpha = Coefficient\ of\ linear\ expansivity$

$\Delta T = Temperature\ change$

$\Delta P = Pressure\ differential$

$A_i = Area\ based\ on\ pipe\ \ internal\ diameter$

$v = Poissonæs\ ratio$

$D_i = Internal\ diamter$

$H = Residual\ lay\ tension$

4.2 Lateral Buckling Modes

Pipeline buckles when the effective force reaches the critical buckling load. According to (Kaye, 1996), these buckles can either be in symmetric or asymmetric mode. Axis of symmetry here refers to axis drawn through the center of the buckle and normal to the initial centerline of the pipeline (see Figure 4-1)

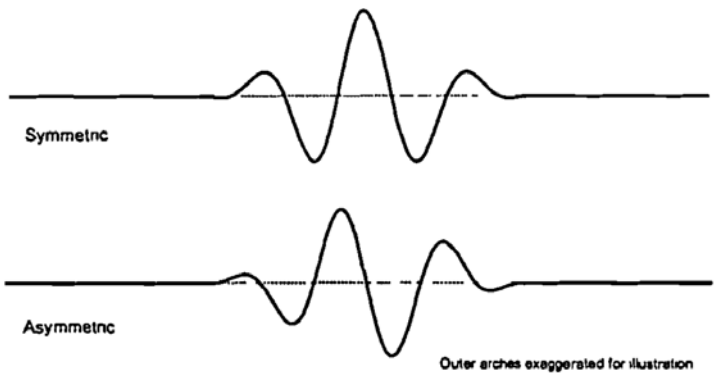


Figure 4-1: Symmetric and Asymmetric buckle modes (Kaye, 1996)

The actual buckle modes formed depend on the pipeline horizontal out-of-straightness and the seabed features.

(Hobbs, 1984) conducted some experimental work for investigating offshore pipeline buckling behavior by assuming that the pipeline remains elastic with no initial imperfection. It was concluded that pipeline can buckle into different lateral mode shapes as shown in Figure 4-2.

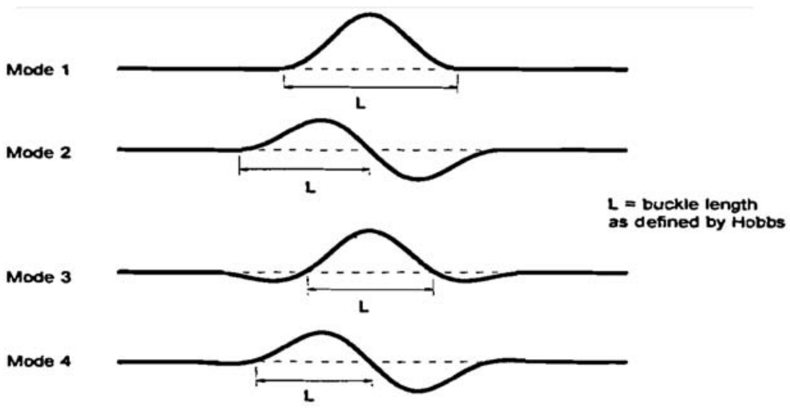


Figure 4-2: Lateral Buckling modes (Kaye, 1996)

The buckle is considered as sequence of half waves which arises due to inability of the soil friction to provide a concentrated lateral force required for equilibrium. The amplitude of the half wave decreases with increasing distance from the center of the buckle.

4.3 Feed-in- Zone

In order to release the excessive compressive force induced in a pipeline, a buckle is formed. Once the buckle is formed, the compressive forces in the buckle drops and the total length of pipe within the buckle region will be greater than the initial pipe length over the same section.

This means that there is movement of slip-length from the zone with higher compressive force to the zone with lower compressive force generated in the buckle section.

As the temperature in the pipeline increases the slip length will therefore continue to feed-into the buckle after the buckle has been developed (Kein et al.).

The length of the feed-in- zone depends on the available frictional resistance that resists the **feed-in**. If a buckle sections loses its ability to carry additional axial load, it is subjected to excessive lateral deformation and failure of the pipeline (Ahmed and & Gareth, 2012). This can be seen from the feed-in behavior of the most critical mode shape, which is mode 3 type of buckling shown in Figure 4-3 (also see Figure 4-2).

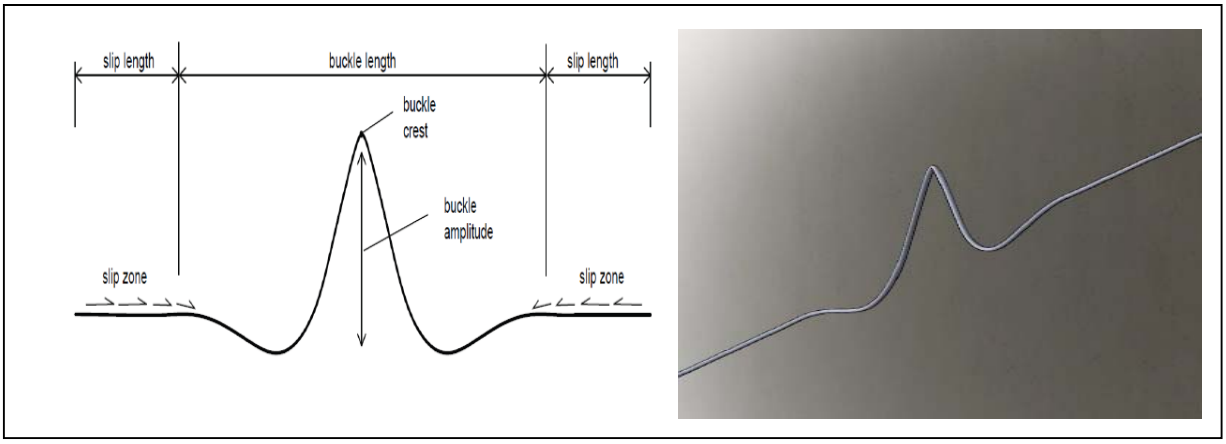


Figure 4-3: Feed-in-Zone for Mode-3 Buckling (Ahmed and & Gareth, 2012)

4.3.1 Feed-in-Length and Maximum Allowable Moment

Feed-in is the expansion into or the release of stored energy of the pipeline into a buckle formed as a result of thermal and pressure loading. The amount of pipeline length that is fed-in into the buckle can be deduced from the relation given below:

$$L_{feed-in} = \varepsilon_{effective\ axial\ strain} * L_{Buckle}$$

The maximum allowable feed-in length shall be established for displacement controlled condition on the basis of the relation given below

$$\varepsilon_{max} \leq \varepsilon_{ca}$$

Where

$\varepsilon_{max} = Maximum\ reported\ compressive\ axial\ strain\ in\ pipeline$

$\varepsilon_{ca} = Allowable\ compressive\ strain\ in\ pipeline$

The allowable compressive strain can be deduced from the criterion of displacement controlled condition (strain based) which is given in (DNV-OS-F101, 2012):

$$\varepsilon_{ca} = \frac{0.78}{\gamma_\varepsilon * SNCF}\left(\frac{t_{st}}{OD_{st}} - 0.01\right)\left(1 + 5.75\frac{P_{min} - P_e}{P_b}\right)\alpha_h{}^{-1.5} * \alpha_{gw} * \varepsilon R_c$$

Where:

$\varepsilon_{ca} = the\ allowable\ compressive\ strain\ in\ the\ pipe,$

$SNCF = Strain\ Concentration\ Factor,$

$\gamma_\varepsilon = resistance\ strain\ factor,$

$P_{min} = minimum\ internal\ design\ pressure,$

$P_e = external\ pressure\ due\ to\ maximum\ water\ deptH,$

$P_b = the\ burst\ pressure\ for\ uncorroded\ pipe\ section\ \ldots\ldots.see\ Equ.5.8\ DNV\ F101,$

$\alpha_h = \frac{R_{t0.5}}{R_m} \ldots\ldots\ldots yield/tensile\ strengt\ \ ratio\ ,$

$\alpha_{gw} = girth\ weld\ factor,$

$\varepsilon R_c = allowable\ compressive\ strain\ reduction\ factor,$

If the maximum feed-in exceeds the allowable feed-in, local buckling may occur and the pipeline integrity could be lost. During design for lateral buckling, it is recommended to do a check for the local buckling and pipe integrity.

Based on (DNV-RP-F110, 2007), local buckling check can be performed against two acceptance criteria; one is a criterion for load controlled condition (bending moment) and the other is a criterion for displacement controlled condition (strain based).

However, '*Due to the relation between applied bending moment and maximum strain in pipes, a higher allowable strength for a given target safety level can be achieved by using a strain-based criterion rather than a bending moment criterion*' (Søren and Yong, 1999).

The limiting parameter for a pipeline subjected to combined pressure, longitudinal force and bending moment due to effect from the installation, seabed contours and HPHT operating conditions is the Bending moment capacity (Søren and Yong, 1999).

The maximum bending moment can as well be used based on the load displacement criteria to deduce the maximum feed-in into the buckle.

In this thesis work, the strain based criteria will be used in this thesis to establish the maximum allowable feed-in length.

4.3.2 Hobbs' Predictive Analytical Method

In pipeline design for lateral buckling, an analytical method is always used to deduce the susceptibility of pipeline to lateral buckling. Hobbs method is the analytical method recognized by DNV standard for this analysis.

The reason for conducting the analytical approach is to:

- Determine if a pipeline is susceptible to lateral buckling;
- Determine which area of the pipeline is susceptible;
- Predict the positioning of the initial out-of-straightness that will be appropriate to trigger a sufficient thermal buckle along the pipeline.

There exist several analytical methods but Hobbs method is the most widely used (Sriskandarajah et al., 1999). Hobbs analytical method is based on force equilibrium and displacement compatibility after a lateral buckle has formed in the assumed straight pipeline (see Figure 4-4).

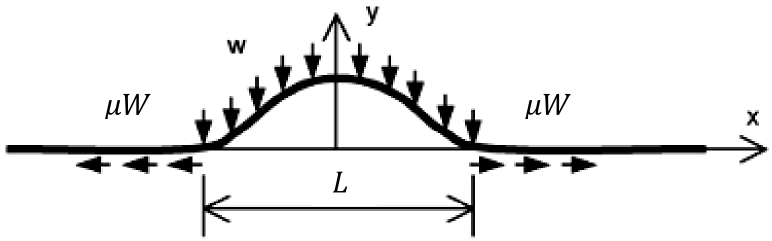


Figure 4-4: Lateral Buckling configuration (EINSFELD et al., 2003)

According to (Hobbs, 1984), the governing linear differential equation for the deflected shape of a pipeline in lateral mode is given as:

$$y'' + \frac{P}{EI}y + \frac{\mu_L WL}{8EI}(4x^2 - L^2) = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(11)$$

The method deduces the configuration of the buckle with the relation that the increase in arc length (i.e. reduction in axial force in the buckle) around the buckle must be equal to the axial feed-in from the slip zone. According to (Hobbs, 1984), using the constants from Table 4-1, the reduced effective axial compressive force, P, within the buckle is given as:

$$P = k_1 \frac{EI}{L^2}$$

$$Where: P = Effective\ compressive\ axial\ force\ within\ the\ buckle$$

Recall and compare with Equation (4), the Critical Buckling Load derived previously as:

$$\boldsymbol{P_{cr}} = \frac{n^2\pi^2 EI}{L^2} \ldots\ldots\ldots\ldots\ldots.. n = mode\ number$$

The maximum amplitude of the buckle is given as:

$$y = k_4 \frac{\mu_L W}{EI} L^4$$

The maximum bending moment M is:

$$M = k_5 \mu_L W L^2$$

While using the assumptions, (Hobbs, 1984) derived the final relation for the configuration of the buckle between the effective axial force N_{eff}, at full constraint and the buckle length, L as:

$$N_{eff} = P + k_3 \mu_a W L \left[\sqrt{1 + k_2 \frac{EA{\mu_L}^2 W L^5}{\mu_a (EI)^2}} - 1.0 \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (12)$$

This is the equilibrium relations in terms of buckle length and the fully restrained axial force.

Where:

$P = Effective\ compressive\ axial\ force\ within\ the\ buckle$

$\mu_a = Coefficient\ of\ axial\ friction$

$\mu_L = Coefficient\ of\ lateral\ friction$

$W = Submerged\ weight\ of\ the\ pipeline$

$L = Buckle\ Length\ corresponding\ to\ N_{eff}$

$E = modulus\ of\ elasticity$

$I = Second\ moment\ of\ area$

The constants for the lateral buckling modes according to (Hobbs, 1984) can be found in Table 4-1.

Table 4-1: Constant for Lateral Buckling Modes (Hobbs, 1984)

Modes	K_1	K_2	K_3	K_4	K_5
1	80.76	6.391 X 10^{-5}	0.5	2.407 X 10^{-3}	0.06938
2	$\boldsymbol{4\pi^2}$	1.743 X 10^{-4}	1.0	5.532 X 10^{-3}	0.1088
3	34.06	1.668 X 10^{-4}	1.294	1.032 X 10^{-2}	0.1434
4	28.20	2.411 X 10^{-4}	1.608	1.047 X 10^{-2}	0.1483
∞	$\boldsymbol{4\pi^2}$	4.7050 X 10^{-5}		4.4495 X 10^{-3}	0.05066

Finally, the equilibrium solution of Hobbs critical force can be obtained either by an iterative process or graphical means which will determine the appropriate value for the buckle length for fully restrained axial force N_{eff} (Kaye, 1996).

Graphically, the minimum of the obtained curve gives the lowest effective axial force N_{eff}, at which a buckle is stable. According to (Kaye, 1996), "This is the **SAFE** force which defines the maximum theoretical force which can be withstood without risk of buckling".

The above analysis can as well assist in deducing the axial feed-in on either side of the buckle, at full constraint given by (Kaye, 1996) as:

$$\Delta = \int_L \varepsilon . dx \; = \frac{(N_{eff} - P)^2}{2\mu WEA}$$

Since the axial feed-in from the outside the buckle must be equal to the increase in Length of the pipe inside the buckle. Based on compatibility of displacement (Kaye, 1996) and from equation (12), the increase in length inside the buckle 2Δ is given as:

$$2\Delta = k_2 {k_3}^2 L^7 \left(\frac{\mu_L W}{EI}\right)^2 - 2k_3 L \frac{(N_{eff} - P)}{EA} \dots\dots\dots\dots\dots\dots\dots (13)$$

"The first term, $k_2 {k_3}^2 L^7 \left(\frac{\mu_L W}{EI}\right)^2$ describes the axial displacement in the pipeline and the second term describes the tensile elongation due to the reduced compressive force within the buckle" (Kaye, 1996).

Hobbs predictive analysis stated above is based on certain assumptions such as:

- Perfectly Straight Pipe (no initial imperfection);
- Single Isolated buckle formation (No multiple buckle formation);
- Long pipeline having tendency for full axial constraint.

4.3.3 Pipeline Initial Imperfection

Pipelines are initially manufactured or designed to have straight configuration and hence will not buckle, either laterally or vertically. "For a perfectly straight pipeline, its failure mode will be by material yielding under axial loading" (Sriskandarajah et al., 2001). According to newton's first law of motion, a body remains at rest or in motion with a constant velocity unless acted upon by an external force. Similarly, in this thesis work, it can be reformulated that "*A perfectly straight pipeline will continue in the state of straightness and will not buckle provided there is no initial imperfection and pipe material yielding*". The initial imperfection in pipeline is also referred as pipeline out-of-straightness (OOS).

The out-of-straightness has a great effect on the critical buckling force at which buckling will occur. The exact critical buckling force that must be triggered for the onset of buckling depends on the magnitude of the pipeline initial out-of-straightness (Kaye, 1996).

For small OOS, the effective axial force easily reaches the bifurcation point and the lateral deflection increases rapidly as shown in Figure 2-4: Load Response in buckling (Robert) (snap buckling).

For larger initial imperfection, there is no bifurcation point and the deflection increases continuously as the axial force increases.

In reality, pipelines resting on the seabed will have a small imperfection and this could be either lateral or vertical. These imperfections could arise from different operational scenarios:

- **Installation vessel motion during pipe-lay**:
  The barge lateral sway motion during pipe-lay and anchor handling/slip can introduce horizontal out-of-straightness (Lateral initial imperfection).

- **Seabed Imperfection (Uneven Seabed)**:
  Seabed's are not naturally straight and will affect the outcome of pipeline configuration during and after installation. This could be as a result of presence of rock, the topography and soil property.

- **Third Party Activity**:
  Interference from fishing activities i.e. pullover of trawl beams and doors or anchor hooking or dragging can result in horizontal out-of-straightness (Sriskandarajah et al., 2001).

4.3.4 Virtual Anchor Spacing

This is spacing generated between the virtual anchors of an isolated lateral buckle in a pipeline. Virtual anchor point (VAP) is the apparent fixity point in a pipeline at which the effective driving force equals the soil frictional force.

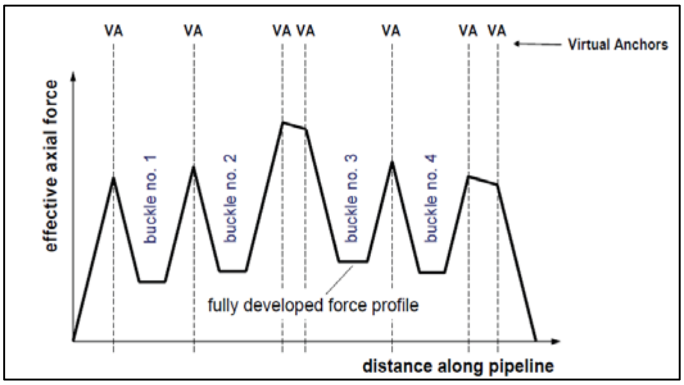


Figure 4-5: Force profile along pipeline showing Virtual anchor spacing and reduction in force at each lateral buckle (Bruton and Carr, 2011)

During buckle initiation, lateral buckle are introduced to share the axial loading between the buckle such that the loadings are distributed along the pipeline instead of concentrating on a particular buckle site. Between this buckle virtual anchors are formed due to soil friction and the effective axial force in the pipeline. The virtual anchors are the points where the axial feed-in occur in each buckle.

The Virtual anchor spacing defines the feed-in length which determines the amount of axial feed-in into the buckle with respect to the available soil resistance at the feed-in zone.

4.4 Snake-Lay Control Mechanism

Pipelines that are normally laid and exposed on seabed are naturally allowed to move. If the induced compressive axial forces are higher than the buckling force, it will buckle sideways. Uncontrolled buckling can lead to loss of pipeline integrity as a result of the limiting state failure modes.

According to (DNV-RP-F110, 2007), buckling can be controlled by sharing the expansion into buckles at regular intervals along the pipeline route. The controlled buckles must be located such that the resulting axial feed-in into each buckle does not exceed the limiting condition for the displacement controlled criterion.

As discussed previously, lateral buckles can be triggered using buckle initiators at selected locations. As mentioned before, the buckles can be initiated by several methods such as the use of mid-line spool, vertical triggers, rock dumping and **snake-lay**.

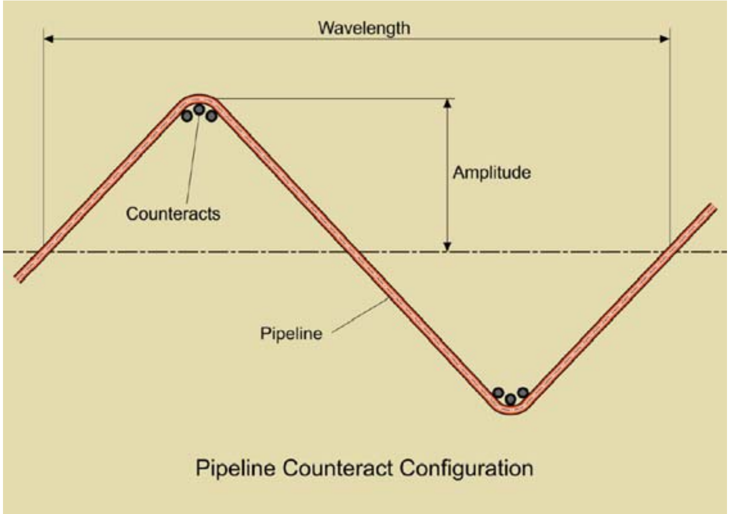


Figure 4-6: Snake-Lay configuration (Subsea7, 2012)

This report considers the snake-lay technology in initiating appropriate buckle at the planned location to control lateral buckling that could result from the axial compressive force induced in the pipeline. This method utilizes counteracts which are pre-installed on the seabed and the pipeline is snaked between them.

The main idea of the snake-lay configuration is to introduce deliberate horizontal lay imperfections to trigger sufficient thermal buckles at a pre-determined location along the pipeline such that the resulting thermal expansion is distributed among the possible buckles formed rather than concentrating the axial feed-in at some few buckle sites (Rundsag et al., 2008).

The snake lay pattern is created by the deviation of the lay barge from its nominal route and by the use of counteracts. The created curvature created makes the crown of snakes to act as a large curvature expansion spool and the pitch determines the axial feed-in at the crown (Kein et al.).

Snake-lay is one of the less expensive means of controlling lateral buckling by buckle initiation. It does not have any issue of span introduction that could lead to vortex induced vibration and dangers of trawl loading like the other methods. The major challenge of this method is the technique that will be employed to create the buckle spacing, which will ensure that buckles are initiated at desired locations. This could be a major problem on softer clay due to the high breakout force that is associated with the soil.

4.4.1 Lay Radius Imperfection

Lay radius is the radius of curvature created on the pipeline as a result of its initial imperfection or a deliberate radius created to initiate buckling at that location.

The aim of snake-lay method is such that the thermal buckling could occur at pre-determined location. The critical buckling load of a pipeline section that must be exceeded to form buckle depends largely on the lateral initial imperfection. In other words, the critical buckling load depends on the lay radius of the buckle curvature.

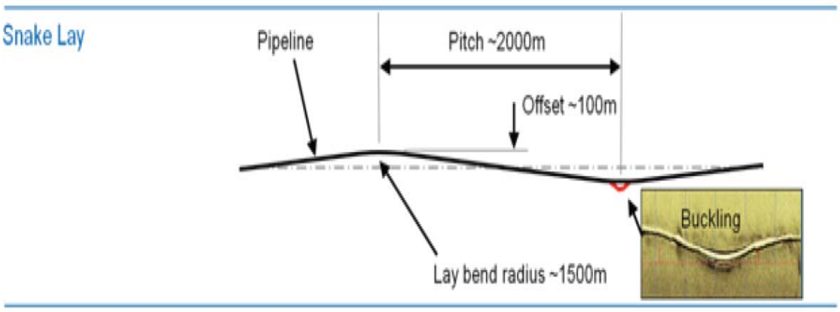


Figure 4-7: Snake-Lay with Lay Radius Imperfection (Bruton and Carr, 2011)

According to (Rundsag et al., 2008), large lateral initial imperfection which means a small **lay radius** is normally preferred since it allows buckling at lower effective compressive force which gives a higher probability that intended buckle will occur at the pre-determined location such that the required distribution is achieved. The lower effective axial force associated with small lay radius could also yield a gentle buckle than the radius with a higher effective force (Rundsag et al., 2008).

In order to trigger this buckle at larger initial imperfection (i.e. lower Critical buckling force), the lay radius should be as small as possible provided the design limit state conditions are not compromised. The critical buckling force P_{cr} which determines the onset of buckling is related to the lateral imperfection (Lay radius, R) and lateral resistance μ by the following equation:

$$P_{cr} = \mu_L W_{submerged}.R$$

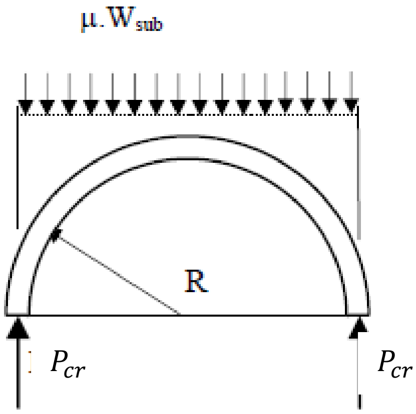


Figure 4-8: Critical Buckling Force Against the lateral soil friction (Rundsag et al., 2008)

This equation suggests that the pipeline will buckle laterally when the axial induced compressive stress exceeds the soil resistance force.

Therefore, since the curved section of the snake-lay is an arc, the size of the imperfection of the curved radius is equal to the inverse of the radius.

Hence, "*the reliability of buckle formation can be increased by reducing the lay radius or increasing the length of curvature in each snake*".

Therefore, the main thing in the design of snake lay is to establish a minimum Lay radius for an appropriate breakout force.

4.5 Design Limiting Criteria

Limit state is the condition beyond which a structure is deemed unsafe and no longer fulfills the relevant design criteria. The limit state that is usually applicable for lateral buckling effect on pipelines could range from the list below according to (DNV-OS-F101, 2012):

- **Local Buckling limit state**:
  The longitudinal compressive strain induced by the effective axial compressive force along the pipeline is displacement controlled, so the strain based design criteria based on requirement of (DNV-OS-F101, 2012) has been used for the local buckling failure mode.

- **Fatigue Limit state**:
  High temperature and high pressure pipelines are subjected to low frequency-high amplitude loading mainly from the startup-shutdown cycles and pipeline installation. The fatigue response of the girth weld is usually very critical in pipeline design with respect to this high stress-low cycle regime.

- **Weld fracture**:
  Fracture analysis could be carried out to examine accurately any undetected crack within the ranges as directed by (DNV-OS-F101, 2012) and other relevant standards.

- **Trawl Gear interaction**:
  The impact of trawl gear on buckled section could also be considered based on the environment impact and the area of operation and water depth.

5. Theoretical Background - Pipeline Walking

5.1 Pipeline Walking and its Mechanisms

The build-up of effective axial forces in pipelines do not only result to lateral buckling but could also lead to expansion of the pipeline ends when there are not enough constraint to hold back the axial forces.

As pipeline is heated up during operation, it will tend to expand but the expansion will be restricted by the soil friction thereby creating axial compressive movement to the ends along the pipeline. During shutdown (cooling), the pipeline will tend to contract but due to the seabed friction the pipeline will not be able to return back to its initial position.

Under symmetrical loading condition (i.e. when there is no differential tension between the ends of a straight pipeline and uniform heating and cooling operation), pipelines will expand and contract uniformly resulting in movement of the ends with respect to the virtual anchor at the middle of the line. This will cause the pipeline ends to move in and out while the pipeline remains in its initial position. This end movement can be managed by the use of jumpers, spool and sliding mechanism (Chaudhury, 2010).

For asymmetrical loading (i.e. if there is an unbalanced axial force or non-uniform heating and cooling operation), the expansion and contraction at the two ends will move non-uniformly along the pipeline resulting in a shift of the virtual anchor points of the two ends.

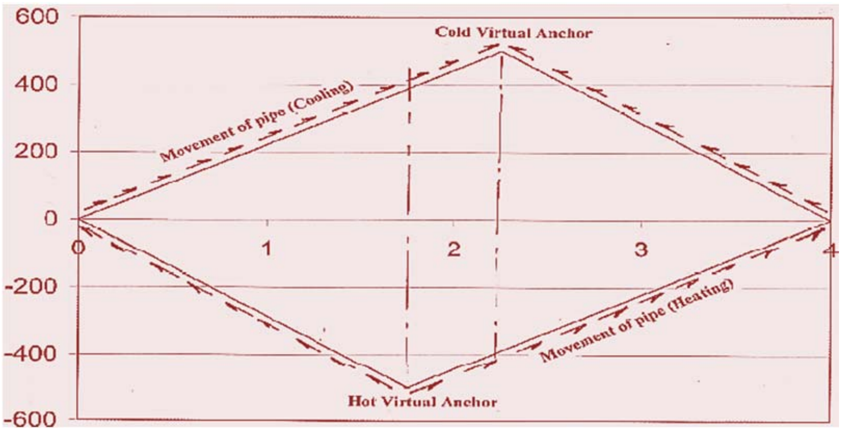


Figure 4-9: Schematic View of Pipeline walking due to separation of Virtual Anchor (Chaudhury, 2010)

According to (Chaudhury, 2010), “In a heating and cooling cycle operation of a pipeline, if there exist a shift between the two virtual anchor points, an unbalanced axial force is generated in between the virtual anchor points resulting in a small amount of movement of the entire pipeline if the pipeline is fully mobilized (i.e. not enough frictional resistance to reach full constraints (e.g. short pipeline))”. This is known as **WALKING.**

Heating Mechanism:

The heating process occurs from the hot end (well) towards the cold end (e.g. SCR) in several transients at constant gradient along the pipeline until a steady state point is attained. During the first heating and cooling process, compressive axial force builds up from each transient at constant thermal gradient. As the pipe expands during heating process a virtual anchor will be formed at the mid-line when the pipeline become fully mobilized and also during cooling another virtual anchor will be formed at the midline as the pipe contracts. This is shown in Figure 4-10 with the red line for heating and blue line for cooling, and the other colors represents the transient stages.

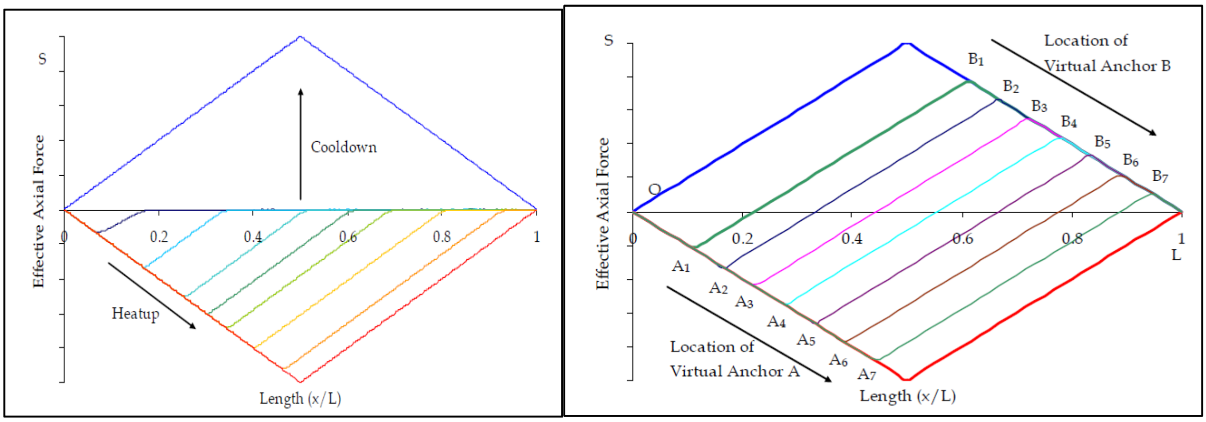


Figure 4-10: Force Profile during the first and second heating stage (Carr et al., 2006)

As the heating continues, the pipeline expands after each transient making the remaining portion of the pipeline to remain at colder temperature. This scenario causes a **non-uniform expansion** of the pipeline creating a virtual anchor from A1 to A7 for each of the transient. Due to the expansion and movement, subsequent virtual anchors are created from B1 to B7 to maintain an equilibrium state as shown in Figure 4-10.

Cooling Mechanism:

Alternatively, the pipelines unloads (cooldown) at a uniform rate and forms a virtual anchor at the mid-line. This symmetrical cooling ensures that there is no reversal of the displacement of the pipeline, hence the shift that occurred during heat-up will not be recovered (Carr et al., 2006). As this occurs in each cycle, the pipeline walks towards the cold end.

These cycles of plastic expansion and contraction could range for several start-ups and shut-downs and will result in the accumulation of axial displacement along the pipeline.

According to (Carr et al., 2006), Pipeline walking is " *a phenomenon that can occur in short, high temperature pipeline that does not reach full constraint in the middle, but instead expands about a virtual anchor point (VAP) located at the middle of the pipeline*.

The phenomenon can also occur in long pipeline (pipeline that develops full constraint force) where lateral buckling has already occurred.

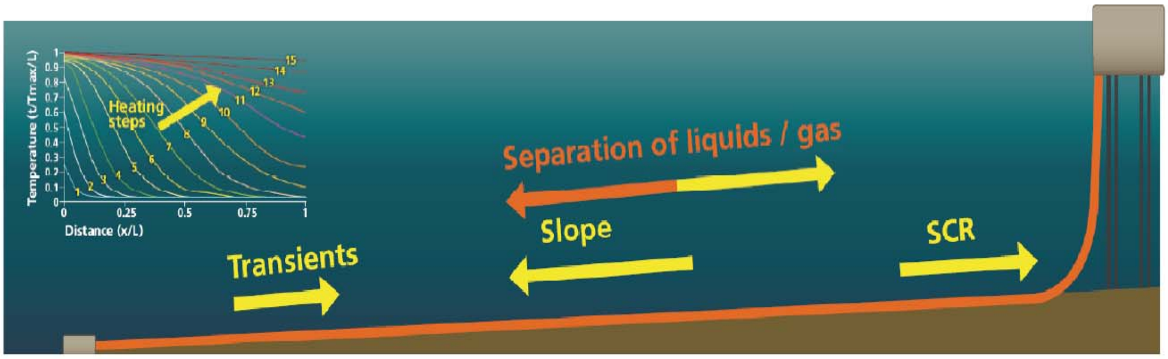


Figure 4-11: Illustration of Pipeline waking and its contributory factors (Bruton and Carr, 2011)

As shown in Figure 4-11, pipeline walking can occur in one of the following conditions:

- Short pipeline with steep transient thermal gradient (axial movement towards the cold end);
- Pulling force at the end of a flowline, associated with a SCR (moves towards the pulling end (SCR));
- Seabed slope along the pipeline (downward movement);
- Multiphase flow behavior during startup and shut-down operations.

Pipeline walking is not a limit state but under no critical examination could lead to the following undesired situations:

- Overstress of the spools/Jumpers due to end expansions;
- Loss of tension in the Steel catenary Riser (SCR);
- Increased feed-in within lateral buckle.

Initiating factor in pipeline walking is the tendency for short pipeline to become fully mobilized and not reaching full constrain and this depends on the axial friction force and non-uniformity of the heating and cooling operation.

5.2 Steep Thermal Gradient

As shown in Figure 4-12, the transient thermal gradient down the slope increases the expansion towards the cold end as the pipeline weight acts in that direction.

The driving force down the slope is a function of the weight and the slope angle, which result to axial walking down the hill during heating and cooling. This can be seen by the analysis conducted by (Carr et al., 2006).

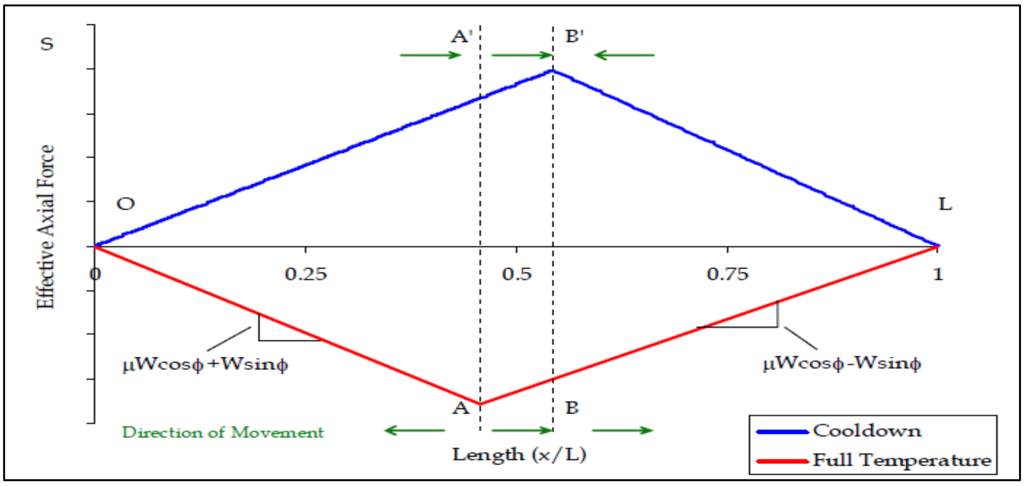


Figure 4-12: Force - Sloping Seabed (Carr et al., 2006)

5.3 Pulling Force at SCR

For pipelines attached to the steel catenary riser (SCR), the pipeline will experience a pulling force at the connection point due the induced force in the SCR as shown in Figure 4-13. This constant tension can build up walking effect during heating and cooling process.

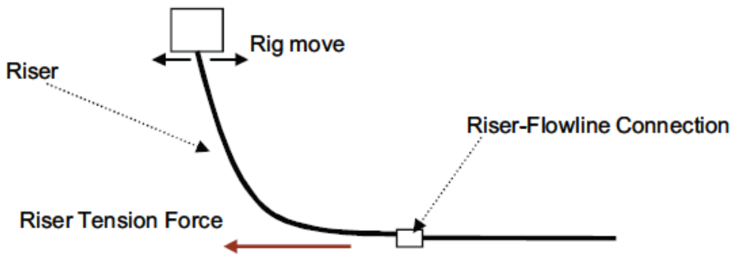


Figure 4-13: Schematic of Pipeline-Riser tension at the end connection

The tension applied by the SCR creates asymmetric force profile and hence result in movement of virtual anchors towards the SCR during heating and towards the pipeline during cooling but the asymmetric force profile causes walking towards the SCR as stated by (Carr et al., 2006).

5.4 Steep Thermal Gradient

During start-up of an operation, there is always a temperature change as the flow moves from hot end to the cold end. As this happens, there exists a resultant transient thermal gradient from the hot to the cold end until the operation reaches a steady state.

The transient thermal gradient builds up expansion after each cycle of heating and cooling operation. As shown in Figure 4-14, due to the heat lost to the environment the transient gradually reaches a steady state.

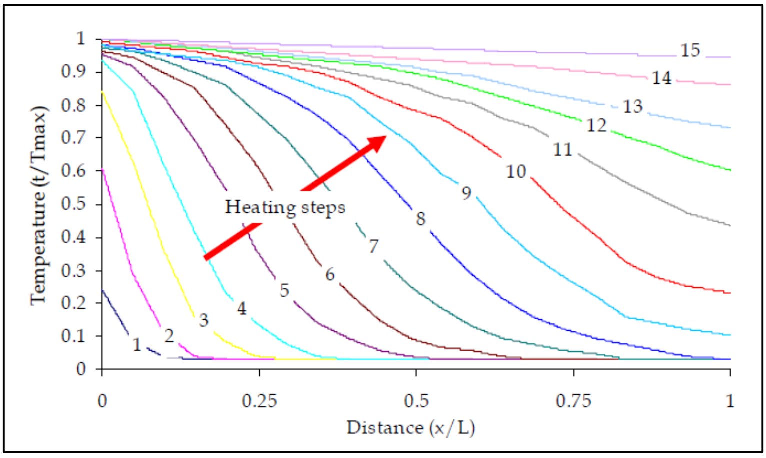


Figure 4-14: Thermal Transient

5.5 Interaction between Pipeline Walking and Lateral Buckling

The lateral buckling of an exposed subsea pipeline could provide avenue for the line to walk under certain conditions of operational loads and pipe – soil interaction. Lateral imperfections, seabed imperfection and other disturbances (e.g. trawl) will always create such avenues. When a pipeline becomes fully mobilized, pipeline walking is likely to occur if it is not controlled. The interaction between lateral buckling and the pipeline walking should be analyzed and it is based on the type of pipeline described below:

Short Pipeline:

A short pipeline does not reach fully restrained condition but the compressive force may exceed the lateral buckling limit for certain combination of axial and lateral friction coefficients and this could result in lateral buckling. The pipeline may also be susceptible to walking under thermal transients and/or seabed slope. This is shown in Figure 4-15.

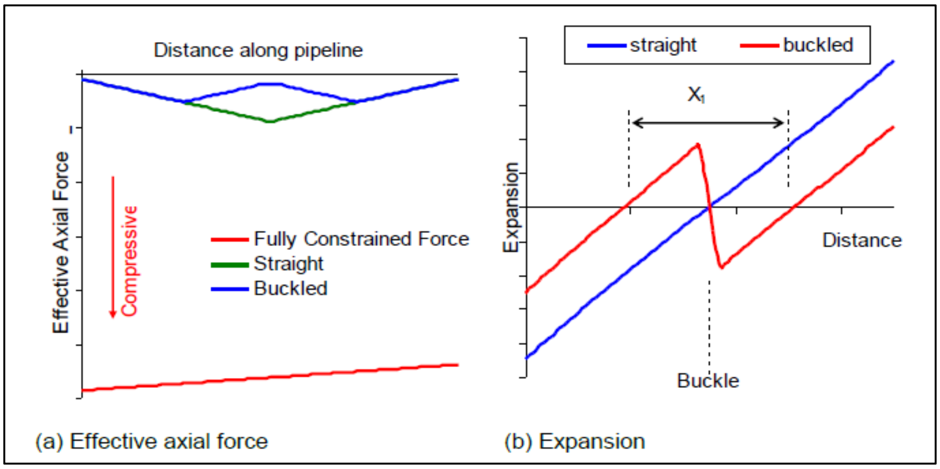


Figure 4-15: Effective axial force in a short pipeline

Long Pipeline

As shown in Figure 4-16, a long pipeline will reach a fully restrained condition and the compressive force is likely to exceed the lateral buckling limit. The lateral buckling tendency may be mitigated by introducing predefined buckling locations (e.g. laid on sleepers) and hence the long pipeline is effectively split into several short pipelines with each buckle acting as a pipeline end.

These “short” pipelines may be susceptible to walking under thermal transients and/or seabed slope.

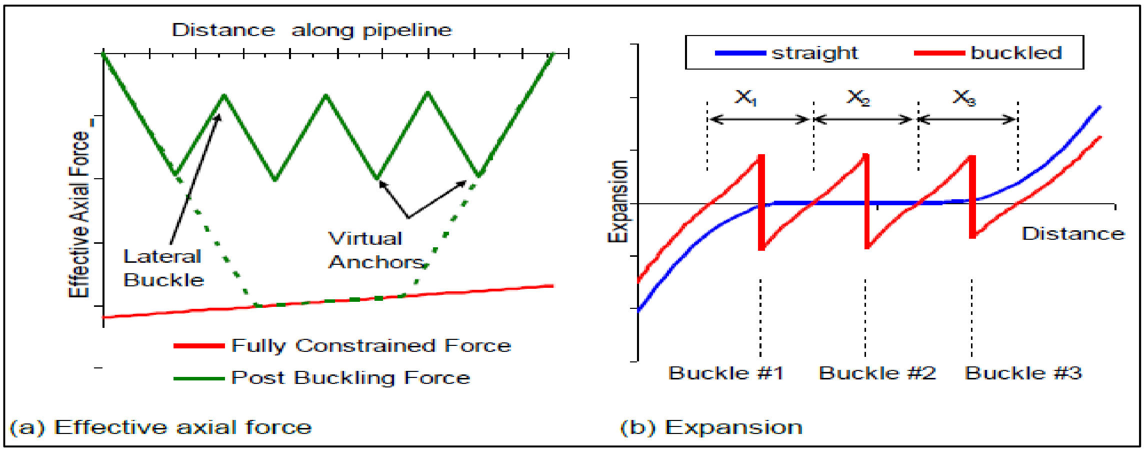


Figure 4-16: Effective Axial force for long pipeline

6. Design Methodology

6.1 General

The design for lateral buckling and axial walking of surface laid subsea pipeline is carried out according to Subsea7 design guideline for lateral buckling and axial walking (Subsea7, 2012) with respect to DNV OS F101, DNV RP F110 and SAFEBUCK guideline.

According to the SAFEBUCK guideline and DNV RP F101, during pipeline design analysis prior to installation, pipelines shall be checked for its susceptibility to buckling.

If the pipeline is found to buckle under thermal and pressure loading, a control measure of deliberate lateral buckles will be introduced at predetermined location along the pipeline such that the total effective compressive causing the buckling will be shared among the buckles along the pipeline.

6.1.1 Design objective

The thesis objective is to study and understand the influence of pipeline-soil interaction on the design of surface laid subsea pipeline that is susceptible to **lateral buckling** and **pipeline walking**. The main focus is on:

- The use of snake-lay configuration as a mitigating measure under controlled buckling design and rock dumping if needed to limit feed-in into buckle and end expansions.

- The effect of thermal gradient on axial walking and the use of direct electric heating (DEH) to reduce rate of walking

The snake-lay configuration is achieved by installing deliberate horizontal lay imperfection to trigger a sufficient number of thermal buckles at a pre-determined location along the pipeline. The aim is to limit pipeline expansion at the connecting ends by using snake-lay design with intermittent rock dumping.

The acceptability of snakes as engineered buckle will be verified based on lateral buckling criteria by performing a design check in accordance with DNV RP F110.

This is done using local buckling check (displacement control criteria) which is the main criteria to obtain the allowable virtual anchor spacing

The work shall include performing analytical investigations and verifying them with a non-linear finite element analysis (FEA) by modeling the soil-pipeline interaction of as-laid pipeline using general finite element software ANSYS.

Secondly, the effect of thermal gradient in pipeline walking phenomenon is investigated and the use of direct electric heating (DEH) system to reduce axial walking shall be discussed based on FE analysis results.

6.1.2 Design Assumptions and Requirement

Requirement

- The critical buckling force shall be taken as equal to the minimum value between the Hobbs Force and the force associated with pipeline OOS;

  $N_{critical} = \min(N_{OOS}, N_{HOBBs})$ …………………. (SAFEBUCK-JIP, 2011)

- Design feed-in Length $(L_{feed-in})$for each buckle shall be equal to the maximum feed-in length into the buckle that will not cause pipeline failure under all limiting states;

  $$L_{feed-in} = \Delta\varepsilon * L_{buckle}$$

- The limiting states are the allowable axial strain and maximum bending moment in the pipeline;
- The probability of maximum feed-in length exceeding the design feed-in shall be less than 10^{-4} (DNV-RP-F110, 2007);
- Axial friction force during pipeline walking shall be less than the force associated with the thermal gradient: $(f < f_{\theta})$;
- Rock dumping at the hot and cold end shall b used to reduce end expansion while applying snake-lay configuration.

Design Assumptions

Lateral Buckling

- Hobbs analyses for lateral buckling is based on a straight pipe with no initial out-of – straightness (OOS);
- The effect of the hydrodynamic forces (drag force, lift force and Inertia) are not considered;
- The temperature profile is assumed to be exponentially distributed along the pipeline;
- The capacity of the pipeline shall be calculated in accordance with DNV-RP-F110 which is expressed as the allowable feed-in length (how much the pipe is allowed to expand into a buckle).

Pipeline Walking

- The heating steps during pipeline walking analyses for FE method and analytical method utilized linear thermal transient;
- Temperature profile with constant gradient is used for the analytical calculation and FE analyses of pipeline walking;
- The pipeline is fully mobilised (short pipeline);
- No pressure variation at each heatups and cooldown;
- Only the effect of thermal gradient is considered.

6.2 Design Process and Roadmap - Lateral buckling

The design process of lateral buckling with respect to the steps outlined in figure 3.1 involves the following:

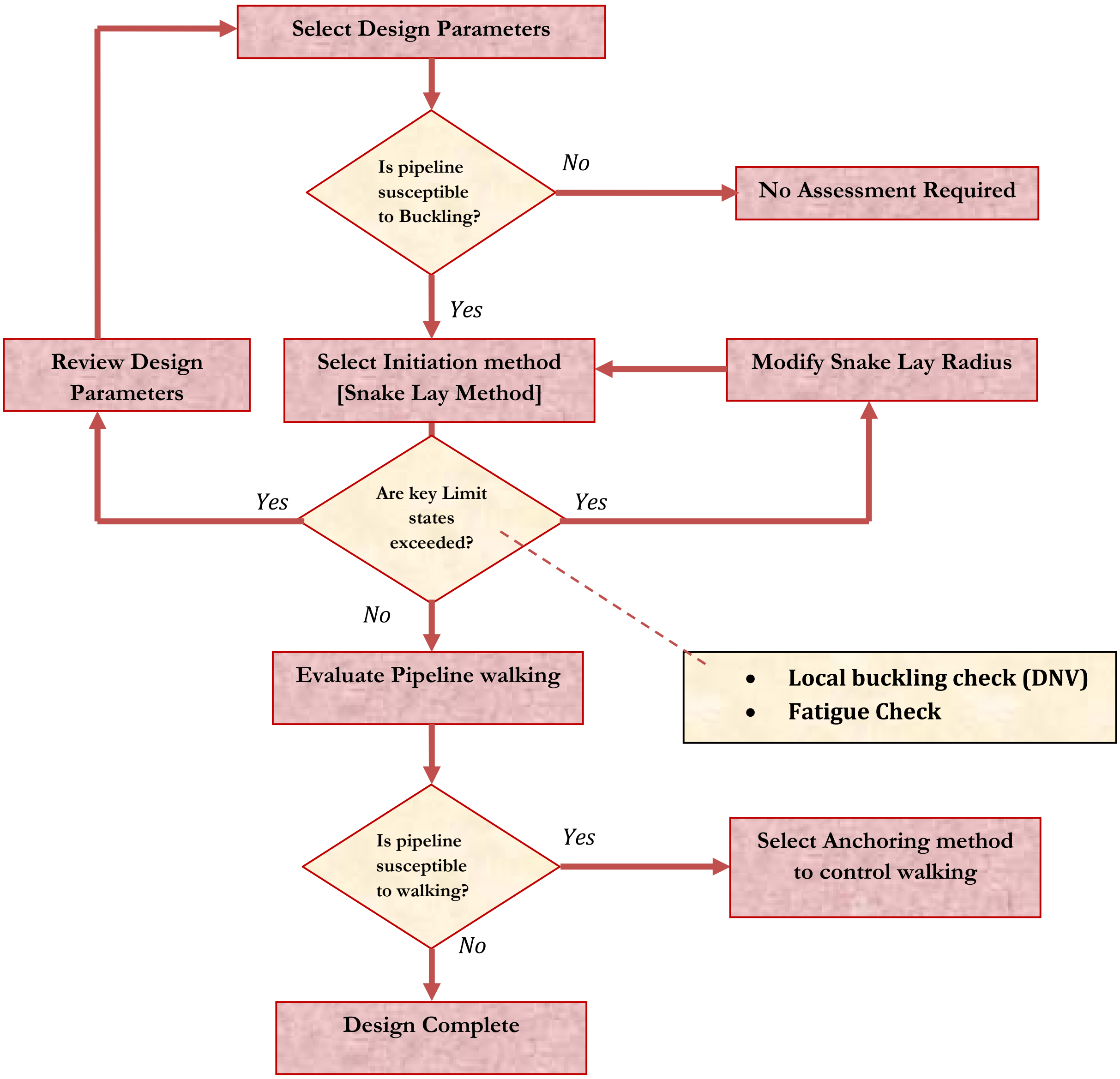


Figure 6-1: Design steps for Pipeline Lateral buckling controlled using Snake-lay configuration

As described in Figure 6-1, analytical calculation is done based on Hobbs Lateral buckling analytical method, to determine the critical buckling force that had to be exceeded before buckling can occur. The pipeline post buckling behavior under cyclic loadings is investigated with respect to the susceptibility to walking. This will be done using a Mathcad 15 and FE analyses.

The design road map is discussed as follows:

a. **Selection of Pipeline Parameters:**
The Pipeline parameters are selected based on recommended project which subsea7 is undertaking for her client. This will involve the seabed data, pipeline data, friction coefficients and the temperature profile.

b. **Analytical Calculation**:
This section details the end expansion calculations, verification of pipeline length scale for short and long pipeline, Hobbs buckling critical buckling assessment, effective axial compressive force for full constraint pipeline and fully mobilized pipeline.
The results from the above calculations yields the critical force required to buckle the pipe, the expansion at the ends which the spool or tie-ins will accommodate and the possible anchor point for the short pipeline. This is achieved using Mathcad 15 calculation software.

c. **Finite Element Analysis:**
FE analyses is carried out to validate the results of effective axial compressive force and end expansion calculated obtained from the analytical method. Further, it is used for the non-linear analysis of surface laid pipeline that is susceptible to lateral buckling.

If the pipeline is susceptible to buckling, based on displacement controlled condition, ANSYS mechanical APDL is utilized to obtain the maximum feed-in corresponding to the applied pressure, thermal and frictional loading along the pipeline.

This is done using a 2km VAS model, initiating or triggering a lateral buckle by applying a lateral imperfection corresponding to a given lay radius.

Note: A straight pipe will never buckle if there is no imperfection or horizontal/vertical force applied to the line that will trigger the buckling along the pipeline.

From the ANSYS model, the equivalent axial strain, bending moment, effective axial force will be extracted. The computation from above extraction gives the maximum feed-in into the buckle and the corresponding bending moment. This is used to generate the number of snakes that will be pre-installed to control/share the effective axial compressive force built up by the thermal and pressure loading during operation.

Expansion sharing is done to control excessive lateral deformation of the pipeline which could lead to pipeline failure or fracture if not mitigated.

d. Snake-Lay Configuration

Snake lay involves the introduction of horizontal-lateral imperfection into the pipeline in form of curves having a given radius of curvature at predetermined location.
This is done to deduce the critical buckle spacing required to prevent the maximum strain and cyclic strain range from exceeding the allowable design strain obtained from the DNV- OS - F101.

To address the issue of buckling on even seabed, it has been proved a better option is to adopt a method that allows buckling to happen provided it could be demonstrated that the resulting high loads and deformations are acceptable.

To ensure that expansions are shared into pre-installed snakes along the pipeline, the pipeline capacity need to be determined based on DNV lateral buckling check.

Pipe Capacity:

The pipeline capacity which determines the feed-in capacity is determined based on DNV-OS-F101. In this thesis work, displacement controlled method (strain based criteria) is used to deduce the capacity.
The allowable compressive strain can be deduced from the displacement controlled condition criterion (strain based) as given stated in (DNV-OS-F101, 2012):

$$\varepsilon_{ca} = \frac{0.78}{\gamma_\varepsilon * SNCF}\left(\frac{t_{st}}{OD_{st}} - 0.01\right)\left(1 + 5.75\frac{P_{min} - P_e}{P_b}\right)\alpha_h{}^{-1.5} * \alpha_{gw} * \varepsilon R_c$$

Where:

$\varepsilon_{ca} = the\ allowable\ compressive\ strain\ in\ the\ pipe$

$SNCF = Strain\ concentration\ Factor$

$\gamma_\varepsilon = resistance\ strain\ factor$

$P_{min} = minimum\ internal\ design\ pressure$

$P_e = external\ pressure\ due\ to\ maximum\ water\ deptH$

$P_b = the\ burst\ pressure\ for\ uncorroded\ pipe\ section\ \ldots\ldots.see\ Equ.5.8\ DNV\ F101$

$\alpha_h = \frac{R_{t0.5}}{R_m} \ldots\ldots\ldots yield/tensile\ strengt\ \ ratio$

$\alpha_{gw} = girth\ weld\ factor$

$\varepsilon R_c = allowable\ compressive\ strain\ reduction\ factor$

The maximum allowable feed-in length is established for displacement controlled condition on the basis of the relation below

$$\varepsilon_{max} \leq \varepsilon_{ca}$$

Where:

$\varepsilon_{max} = Maximum\ reported\ compressive\ axial\ strain\ in\ pipeline$

$\varepsilon_{ca} = Allowable\ compressive\ strain\ in\ pipeline$

By comparing the reported strain which shall be determined from the ANSYS model against the criteria stated above, the allowable feed-in to the buckle is be established.

From the ANSYS model, the maximum feed-in is determined using the allowable compressive strain obtained previously. This is estimated with the relation below:

$$L_{feed-in} = \Delta\varepsilon * L_{buckle}$$

Lay Configuration:

The lay configuration is achieved based on the principle of expansion sharing outlined in DNV-RP-F110 for sharing into adjacent buckle. Following the steps, it is to be ensured that the allowable feed-in lengths are not exceeded.

According to the guideline, expansion sharing into adjacent buckle can occur if the following relations are fulfilled:

$${F_{post}}^{LB} + \Delta S^{LB} \geq {F_{critical}}^{UB}$$

Where:

${F_{post}}^{LB} = the\ lower\ bound\ post - buckling\ force\ for\ the\ given\ snake\ configuration$

$\Delta S^{LB} = effective\ axial\ force\ build - up\ between\ adjacent\ based\ on\ LB\ factor$

${F_{critical}}^{UB} = Upper\ bound\ critical\ force\ for\ the\ given\ snake\ configuration$

Note:

To build up effective force between the buckles and limit the pipeline end expansion without exceeding the allowable feed-in length in the buckle, snake-lay design and intermittent rock damping is utilized.

e. **Lateral Buckling Check**
   A local buckling is conducted analytically based on recommended displacement controlled criteria of DNV RP F110 see Appendix A4.

f. **Pipeline Walking Check**
   Analytical check based on SAFEBUCK guideline is to be carried out to check if the pipeline is susceptible to axial walking. Also, cyclic loading for about 3 cycles is applied to investigate walking at the crown of the buckle.

6.3 Design Roadmap for Pipeline Walking – Thermal Transient Effect

When pipeline is laid on seabed and heated up by hot fluid content passing through it, it expands axially and circumferentially. Upon cooling, since this expansion is restricted by axial friction generated by pipe-soil contact, the pipeline will not return to its original position.

With subsequent heating and cooling, an accumulation of axial displacement towards the cold end is generated. This is known as pipe-walking. The methodology herein is based on the SAFEBUCK design guideline which Subsea7 was one of the sponsors.

The analysis considers a 2km flowline under thermal asymmetric heating steps with considerations mainly based on the effect of walking due to thermal loadings.

Analytical Method
The flowline is checked for susceptibility to walking using an analytical method based on SAFEBUCK design guideline. If walking is identified, the rate of walking for each transient cycle will be calculated.

The corresponding axial displacement (rate of walking) will be determined and validated with the results from Finite element analysis.

Finite Element Method
Once the flowline is confirmed to be susceptible to walking, a finite element (FE) analysis is conducted using ANSYS v13 to analyze the non-linear walking mechanism. The analysis involves the incorporation of constant thermal gradient into the FE model and deducing the corresponding rate of walking.
The effect of thermal gradient is investigated using FE for two (2) different thermal gradients and comparable the result obtained.
Finally, the need to use of DEH to reduce pipeline walking is investigated and explained using FE result.

The overall road map can be seen from the Figure 6-2 below:

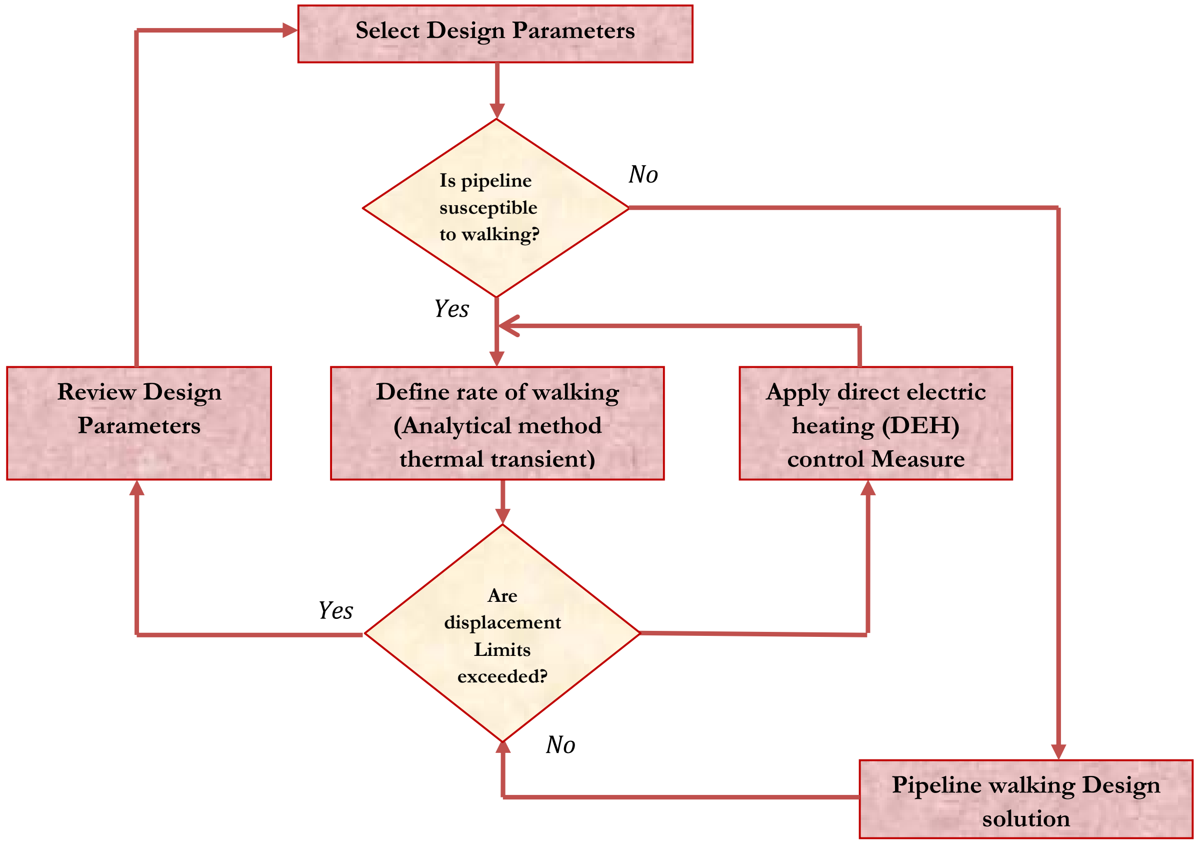


Figure 6-2: Design roadmap for Pipeline walking under thermal transient

6.4 Design Analysis

This section details the design steps taken to achieve the analytical and finite element solution. This is done in accordance with the design guidelines and relevant procedure specified above.

6.4.1 Analytical Method

The analytical method in this thesis will be based on the several points: End expansions calculations and Hobbs critical buckling assessment, pipeline susceptibility to walking and Snake-lay radius determination.

a. End Expansion:
Assuming a straight-fully constrained pipeline, the end expansion due to pressure (end-cap and Poisson effect) and thermal loadings is calculated. This deduces the maximum expansion that the effective axial compressive force will yield which the ends must accommodate.

b. Effective Axial Force – The expansions at the ends are built-up because of the effective axial forces generated from the pressure and thermal loadings when fully constrained at the ends. Thus, the effective axial force along the pipeline is calculated based on the relation below:

$$N_{FULL} = N_{Lay} - N_{Endcap} + N_{poisson} + N_{Thermal}$$

This force is sometimes called the **Anchor Force**. The results of the end expansion reveals if the pipeline is a short or a long pipeline based on the value of the anchor length obtained.

Recall: if the anchor length obtained is greater than the length of the pipeline then the pipeline is termed a short pipeline i.e. **fully mobilized**. If the pipeline is a long pipeline, the two virtual anchor points will be deduced for the hot and the cold end.

The expansion at the ends is calculated using the below equation based on subsea7 design guideline:

$$\Delta expansionHOT = \sum_{anchor\ hot\ end}^{KP0} \frac{(N_{FULL} - N_{frictional})}{EA_s}$$

$$\Delta expansionCOLD = \sum_{KPend}^{anchor\ cold\ end} \frac{(N_{FULL} - N_{frictional})}{EA_s}$$

Thus, the minimum spool length required can be calculated with the following relations:

$$L_{minimum} = \sqrt{\frac{2.25 * D_o * \Delta expansionHOT}{\delta_{Bending}}}$$

….See Appendix A

Submerged weight calculation – The submerged weight is calculated with respect to the pipeline data's. This is achieved by using the relation:

$$W_{submerged} = content\ weight + steel\ weight + coating\ weight - buoyancy$$

c. Hobbs Critical Buckling Force Assessment:

The Hobbs critical buckling force analysis is done to determine the susceptibility of the pipeline to lateral buckling as well as determine the Hobbs critical buckling force. The axial forces described by Hobbs with respect to several modes (modes 1, 2, 3, 4 and infinity) are used to obtain the critical buckling forces for the corresponding nodes.

The method traces the equilibrium path in terms of buckle length and fully restrained axial force. The Effective axial force according to Hobbs is given as:

$$P_0 = P_{buckle} + K_3 \mu_{axial} W_{submerged} L_{buckle} \left[\left(\sqrt{1 + K_2 \frac{EA \mu_{Lat}{}^2 W_{submerged} L_{buckle}{}^5}{\mu_{axial} (EI)^2}} \right) - 1 \right]$$

…………………………….See Appendix A for details.

The corresponding buckle wavelength is also given according to Hobbs as:

$$L_{buckle} = \left[\frac{2.7969 * 10^5 (EI_s)^3}{\left(\mu_{Lat} * W_{submerged}\right)^2 * A_s E}\right]$$

The effective axial P_0 is obtained for all the modes and plotted against buckle wavelength L_{buckle}. From the graph, the Hobbs critical buckling force will be obtained by the deducing the minimum value of the axial forces of all the modes plotted.

$$N_{HOBBs} = \min(P_0 mode1, P_0 mode2, P_0 mode2, P_0 mode3, P_0 mode4, P_0 modeinfinity)$$

The Critical buckling force along the pipeline according to SAFEBUCK guideline is computed with respect to the equation below:

$N_{critical} = \min(N_{OOS}, N_{HOBBs})$ …………………. (SAFEBUCK-JIP, 2011)

Where $N_{OOS} = \mu_{minimalLat} * W_{submerged} * R$

$$N_{OOS}\ is\ the\ Axial\ Force\ associated\ with\ pipeline\ initial\ Imperfetction$$

According to (SAFEBUCK-JIP, 2011), Pipelines is susceptible to buckling if the condition below is exist:

$$N_{max} \leq N_{critical}$$

$$The\ maximum\ force\ in\ the\ pipeline: \qquad N_{max} = \min(N_{Full}, N_{fmax})$$

$\left\{N_{fmax} = \mu_{max.axial} * W_{submerged} * \frac{L}{2}\right\}$ = Maximum axial restriction force for a Short pipeline

$N_{Full} = Fully\ constrained\ axial\ Force$

The analytical method stated above is based on several assumptions (straight pipeline, no initial imperfection) which did not meet the actual scenario of pipeline-soil interactions on seabed. Hence, Hobbs method is generally used to determine the susceptibility of pipeline to lateral buckling and the critical buckling force.

d. Pipeline Walking

Using the procedure outlined in SAFEBUCK guideline, the analytical solution for pipeline rate of walking at different thermal gradient is obtained. This is done on Mathcad 15 (see Appendix A).

According to the guideline, pipeline is not susceptible to walking if the axial friction force [f] exceeds the following value:

$$\boldsymbol{f > \beta \frac{(EA_{st}\alpha\Delta T)}{L}}$$

If the pipeline is susceptible to walking, the rate of walking per cycle under constant thermal gradient will be deduced using the relation below:

$$\Delta_\theta = \frac{fL^2}{8 * EA_s} - - - - - - - - - - if\ f \leq \frac{f_\theta}{6}$$

$$\Delta_\theta = \frac{L^2}{16 * EA_s}(\sqrt{24 * f_\theta * f} - f_\theta - 4f) - - - - - - - - - - if\ f > \frac{f_\theta}{6}$$

This gives the accumulated axial displacement as a result of the thermal transient based on constant gradient along the seabed.

6.4.2 Finite Element Method (ANSYS Mechanical APDL) - Lateral Buckling

This is a detail description of the non-linear solution method for lateral buckling of subsea pipeline laid on even seabed with an initial imperfection. The model is done using ANSYS mechanical APDL.

- **Reason for Finite Element Method:**

Based on the Hobbs analytical assumptions stated previously, Hobbs critical buckling force analyses did not account for initial imperfection and post-buckling behavior in the pipeline. Hence, a non-linear finite element method is necessary so as to determine the effect of initial imperfection on lateral buckling.

The main reason for a non-linear solution is to overcome the shortcomings that were created while applying the analytical method. The material modeling, the seabed modeling, the non-linearity of pipe-soil interaction, the initial imperfection, the temperature profile and the pipeline boundary conditions which could not be implemented in the analytical method.

The finite element (FE) analysis uses iterative newton Raphson solution method by applying the loading in an increment with respect to time step (transient analysis). This is done to locate an equilibrium path defined by the load and nodal variable.

- **Pipeline Model:**

A local model approach (VAS model) of 2km pipeline section with an initial imperfection is modeled with respect to the material properties of the pipeline. The VAS model is used to determine the effective axial force, the bending moment and the lateral displacement acting on the buckled section of the pipeline.

The initial out-of-straightness (OOS) is achieved as a function of lay radius for the snake lay configuration with respect to the available operational corridor.

i. Pipe Element:

The pipeline is modeled with PIPE288 element, which supports nonlinear modeling of Elasticity, hyper-elasticity, plasticity, creep, and other nonlinear material models. PIPE288 is a linear, quadratic, or cubic two-node pipe element in 3-D. The element has six degrees of freedom at each node (the translations in the x, y, and z directions and rotations about the x, y, and z directions). The element is well-suited for linear, large rotation, and/or large strain nonlinear applications (see Figure 6-3).

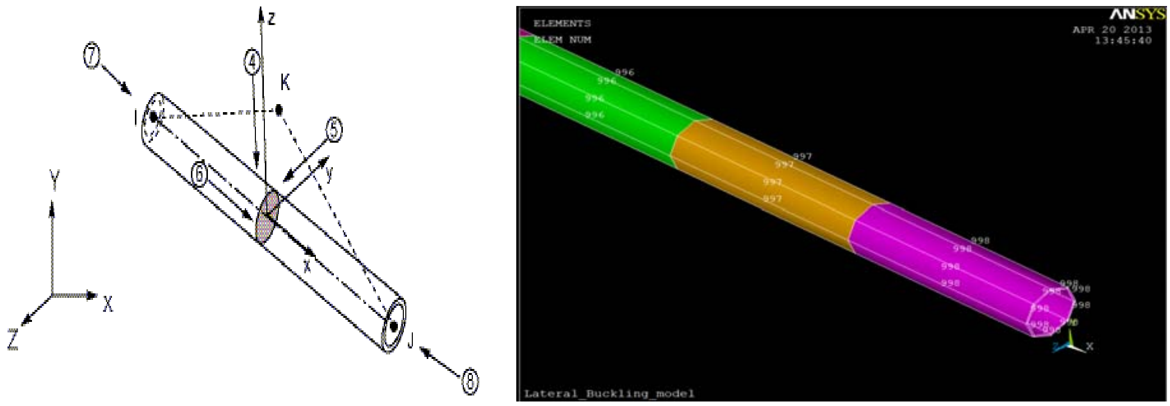


Figure 6-3:Pipe288 Geometry and the ANSYS model

PIPE288 supports the thin-pipe (KEYOPT (4) = 1) option. The thin-pipe option assumes a plain stress state in the pipe wall and ignores the stress in the wall thickness direction.

To obtain a better lateral displacement distribution and bending moment, the pipe element is subdivided into a unit length per element. Activating KEYOPT (6) = 0 generates end-caps loads from the internal and external pressure.

Setting KEYOPT (7) = 0 generates output section forces/moments, strains/curvatures, internal and external pressures, effective tension, and maximum hoop. This enables the maximum feed-in length and bending moment in the buckle section to be deduced.

ii. Initial Horizontal Out-of-Straightness:

In practice, pipelines laid on seabed will always have an imperfection probably induced due to uneven seabed, barge motion during installation or by fishing gear activity. A perfectly straight pipeline without any imperfection will not buckle when subjected to pressure and thermal loading.

To generate an initial imperfection that will trigger lateral buckling, a pre-determined axial force associated with pipeline out-of-straightness (OOS) , N_{OOS} is introduced at some section in the middle-nodes of the pipeline.

Depending on the Lay-radius required and the buckle amplitude, the pre-load is initiated which will trigger buckling based on the submerged weight and the lateral friction coefficient as shown in Figure 6-4.

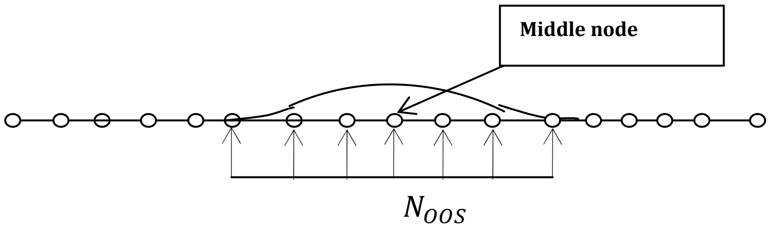


Figure 6-4: A Pre-load associated with pipeline OOS

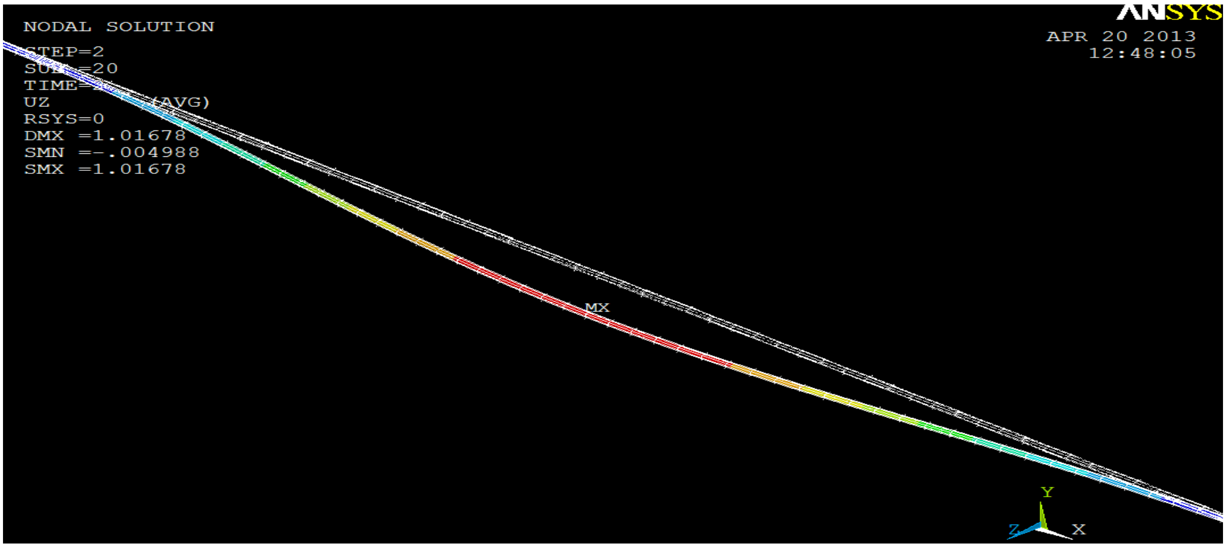


Figure 6-5: Pipeline showing an Initial OOS of 1m

Lay-Radius Deduction: From the model shown in Figure 6-5, an initial pre-load of ***7500N per node*** along a section of ***40 nodes*** (node 480 – node 520) displaced the pipeline ***1m*** laterally.

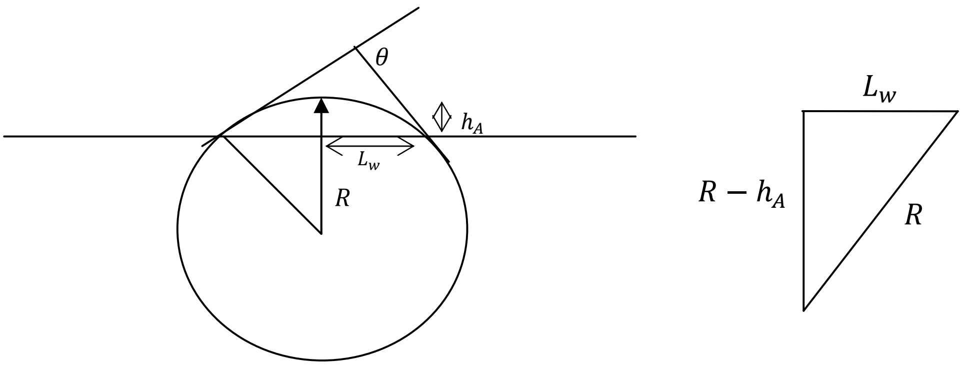


Figure 6-6: Lay-radius deduction

Applying Pythagoras theorem, we have: $R^2 = (R - h_A)^2 + {L_w}^2$

The Lay-radius becomes: $R = \frac{{h_A}^2 + {L_w}^2}{2h_A}$

Where:

$h_A = initial\ lateral\ imperfection$

$L_w = half\ wavelength$

In the model, $h_A = 1.0m$

$L_w = 50m$……………therefore, the Lay-radius becomes $R = 1250m$

iii. Material Modeling:

The non-linearity that is associated with lateral buckling due to the thermal expansion and large bending moment is modeled into the program to care of the plasticity or yielding of the material that could occur during loading. In ANSYS, this is inputted using TB command based on the below stress-strain curve as shown in Figure 6-7.

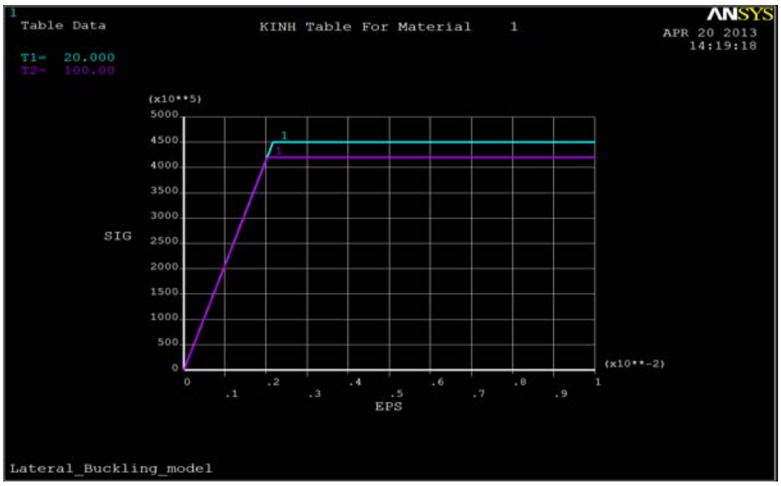


Figure 6-7: Stress-Strain relationship in ANSYS model

iv. Boundary Condition:

The boundary condition is obtained by fixing the ends of the pipeline in all direction which forms a basis from our theory that the pipeline is fully restrained by axial fictional resistance. The submerged weight of the pipeline is introduced along the nodes to act as the frictional force resisting lateral and axial movement. This is shown in Figure 6-8 below:

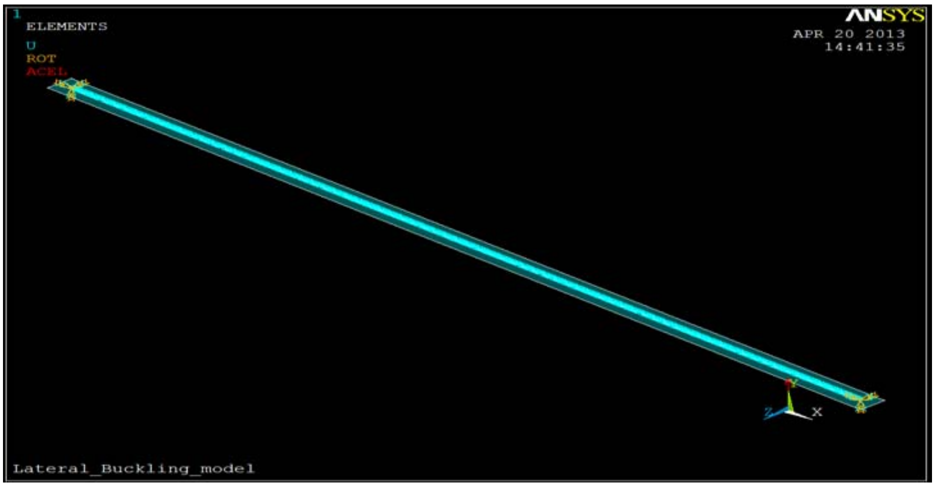


Figure 6-8: Boundary condition showing pipe ends fixed in all direction

- **Seabed Modeling:**

The seabed is modeled on the soil surface along the z-axis using element TARGE170. TARGE170 is used in ANSYS APDL to represent a rigid target surface for associated 3D node-to-contact element. The element can be set into a 4 node by applying shape as QUAD using a TSHAPE command. This is shown in Figure 6-9 below.

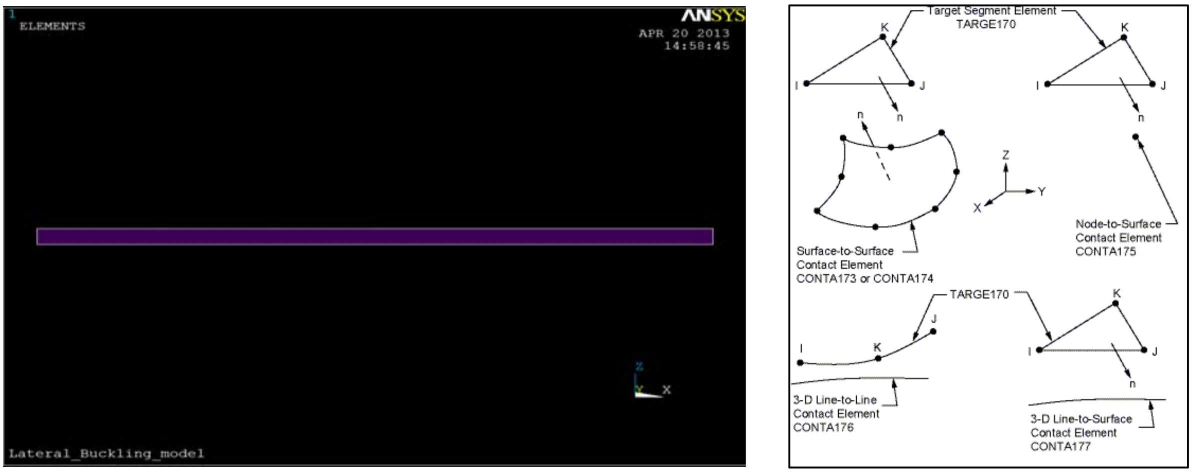


Figure 6-9: Seabed Model on z-plane

- **Pipe-Soil Interaction (Contact model):**

The submerged weight introduced in the pipeline model creates a self-weight on each of the pipe element. As a result, the need to create a contact between the pipeline and the seabed (TARGE170) arises. The contact is modeled using CONTA175 in ANSYS. As shown in Figure 6-10, this element supports the orthotropic coulomb friction, a pipeline-seabed model with both axial and lateral friction coefficient. ESURF command is used to generate a surface contact in y-direction of the all the contact nodes between all the pipe-nodes and the associated seabed nodes (TARGE170).

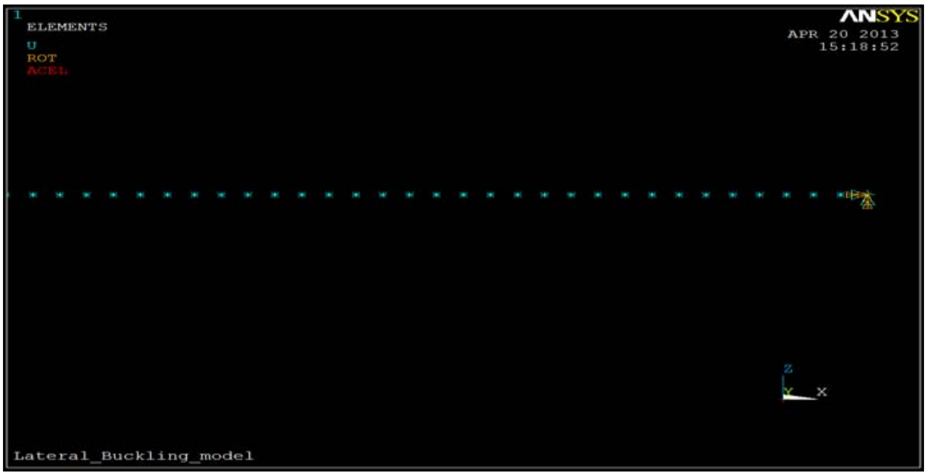


Figure 6-10: Model showing the contact element generating friction Force on the Seabed

- **Loading Sequence:**

The model is divided into two (2) sections; the lateral buckling section, the cyclic loading and unloading section.

a. Lateral Buckling Loading Sequence:

The lateral buckling of the 2km VAS model in ANSYS will be operated/simulated exactly the way installation and operation of pipelines on seabed is done.

1. Model the Pipeline;
2. Lay Pipeline on even seabed;
3. Apply boundary condition at the ends (fixed end nodes);
4. Apply Submerged weight of the entire content;
5. Applying Initial imperfection (OOS) due to the installation motion of the vessel;
6. Apply internal pressure to retain the initial imperfection (OOS) against collapse from external pressure effect;
7. Apply external pressure $\rho_{water} * g * Water\ depth$;
8. Remove lateral force that generated initial imperfection;
9. Applying operating pressure and temperature.

b. Cyclic loading and Unloading Sequence:

The lateral buckling of the 2km VAS model in ANSYS is loaded the way installation and operation of pipelines on seabed is done as shown below:

1. Model the Pipeline;
2. Lay Pipeline on even seabed;

3. Apply boundary condition at the ends (fixed end nodes);
4. Apply Submerged weight of the entire content;
5. Applying Initial imperfection (OOS) due to the installation motion of the vessel;
6. Apply internal pressure to retain the initial imperfection (OOS) against collapse from external pressure effect;
7. Apply external pressure $\rho_{water} * g * Water\ depth$;
8. Remove lateral force that generated initial imperfection;
9. Applying operating pressure and temperature **– First heat-up;**
10. Apply hydrostatic pressure $[\rho_{content} * g * (Water\ depth + 20m)]$ to replace the operating pressure. **– First cooldown;**
11. Repeat the process for second and third heat-up and cooldown.

6.4.3 Finite Element Method - Pipeline Walking

The finite element analysis for the axial walking of 2km flowline is done with the same pipe-soil interaction, pipe element and contact element used in the lateral knuckling model. Below are the process taken to achieve the model and the results.

- **Reason for Finite Element Method:**

The main reason for a finite element analyses in pipeline walking is to overcome some of the short-comings that was introduced while applying the analytical method. The analytical method described according to SAFEBUCK guideline were based on certain assumption and certain pipe material properties that was used to obtain the defining parameter, β.

Realistically, the analytical method is mostly used during design to determine if a non-linear analysis should be conducted based on the susceptibility and the rate of walking obtained. Hence, it is not used as a validation method for a finite element analysis due to its sort-comings.

The analytical method gives a guide on axial displacement that could be encountered during the heating cycles based on certain assumptions stated on the guideline but FEA provide a better approximation to the walking that is to be experienced during operation.

<u>Design Steps</u>:

- A 2km flowline is modeled using Pipe288 in ANSYS without any lateral imperfection;
- Seabed Contact and target modeled using Conta175 and Targe170 respectively;
- A temperature profile for the flowline is derived using excel spreadsheet corresponding to different thermal gradient for each heating steps.

$$\boldsymbol{T_{gradient} = T_{inlet} + q_{\theta} * l_i \ \ldots\ldots\ldots\ldots\ldots\ldots..\ i\ \ varies\ from\ node\ i\ to\ node\ n}$$

- A constant thermal gradient is generated until steady state is reached;

- A total of 15 asymmetrical heating steps were done for each cycle and a uniform cooling at the end overall heating steps;
- The pressure variation remained at zero along the pipeline and solutions obtained for each cycle.

Loading Steps without Direct Electric Heating (DEH):

1. Model the Pipeline;
2. Lay pipeline on even seabed with both ends free to move;
3. Apply Submerged weight of the entire content;
4. Apply external pressure $\rho_{water} * g * Water\ depth$;
5. Apply the operating pressure along the pipeline;
6. Start the heating steps until steady state is attain;
7. Cooldown to ambient temperature.

Loading Steps with Direct electric heating (DEH):

1. Model the Pipeline;
2. Lay pipeline on even seabed with both ends free to move;
3. Apply Submerged weight of the entire content;
4. Apply external pressure $\rho_{water} * g * Water\ depth$;
5. Apply the operating pressure along the pipeline;
6. Apply a temperature of 20^{o}C along the pipeline length;
7. Apply the heating steps until steady state is attained;
8. Cooldown to DEH temperature.

7. Description of Case

7.1 Field Description

The work of this thesis is based on a typical subsea field development as shown in Figure 7-1. The scope includes the installation of two 22-inch pipelines of length 10km and 2km. The flowline are made of X65 grade steel. The Field is a typical subsea field with a water depth of approximately 800m. A riser is connected from a topside tie-in point of 20m above the mean sea level (MSL) to a tie-in spool which is connected to the pipeline at the touchdown point. The 2km flowline is connected between the two tie-in spools before the end structures while the 10km pipeline is tied to PLET as shown in Figure 7-1 below.

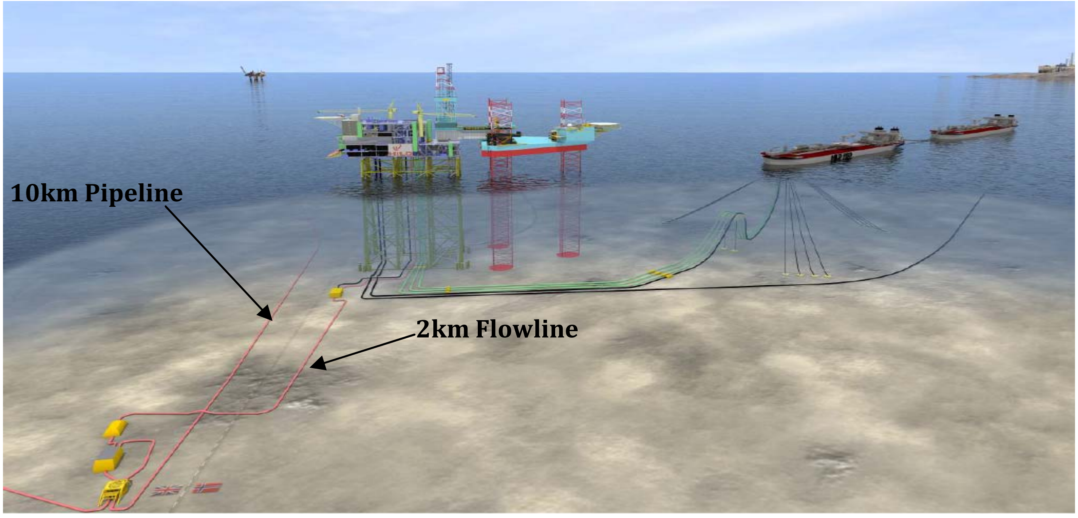


Figure 7-1: A typical Subsea field with Pipeline on even seabed (Subsea7, 2011).

CASE study:

Lateral Buckling

- Pipeline end expansion assuming straight pipe on even seabed;
- Deduction of the hot and cold end expansion using analytical and finite element model;
- Verification of the 10km pipeline susceptibility to lateral buckling due to thermal, pressure loading during operation;
- Control of lateral buckling using snake-lay initiation method during installation;
- Sensitivity analysis of the optimum lay radius required during installation of snakes.

Pipeline Walking

- Susceptibility of Pipeline to walking (A check);
- Deduction of rate of axial displacement in each cycle (rate of walking);
- Sensitivity analysis of walking with respect to thermal gradient;
- Analysis of the maximum strain that the tie-in spools can accommodate and corresponding remedies.

7.2 Design Parameters – Lateral Buckling

This section describes the design parameters used in the analysis. The parameters include the data related to pipeline geometry, material, operating and environmental loads, pipe-soil interaction.

The design parameters used in the analysis are shown in the Table 7-1 below.

Table 7-1: Basic Design parameters

Parameter	Abbreviation	Value
Pipeline Length	L_L	10km
Flowline Length	L_S	2km
Outside Diameter	D_o	22-inches (559mm)
Wall thickness	t_{st}	19.1mm
Corrosion Allowance	t_{ext}	3mm
Pipeline Material	-	X65
Steel Density	ρ_{st}	7850kg/m^3
Pipe Submerged weight	$W_{submerged}$	2.52kN/m
SMYS < 20 ^{o}C	-	450MPa
SMTS < 20 ^{o}C	-	535MPa
Minimum Radius of Curvature in Normally straight Pipe	R	1000m
Operating temperature	T_{op}	95^{o}C
Ambient temperature	T_{amb}	5^{o}C
Operating Pressure	P_{op}	15MPa
Water depth	WD	800m

The coating parameter below gives the insulation coating and concrete weight coating according to operational practice in Subsea 7.

Table 7-2: External coating parameter

Parameter	Value
External coating thickness	5mm
External Coating density	910kg/m^3
Concrete coating thickness	55mm
Concrete coating Density	2400Kg/m^3

a. Temperature Profile:

The operating temperature variation along the entire pipeline length was generated using the general exponential relation between the inlet and the ambient.

$$T = T_{amb} + (T_{inlet} - T_{amb})e^{(-\lambda L)}$$

The temperature for the 10km pipeline is as shown in Figure 7-2 below:

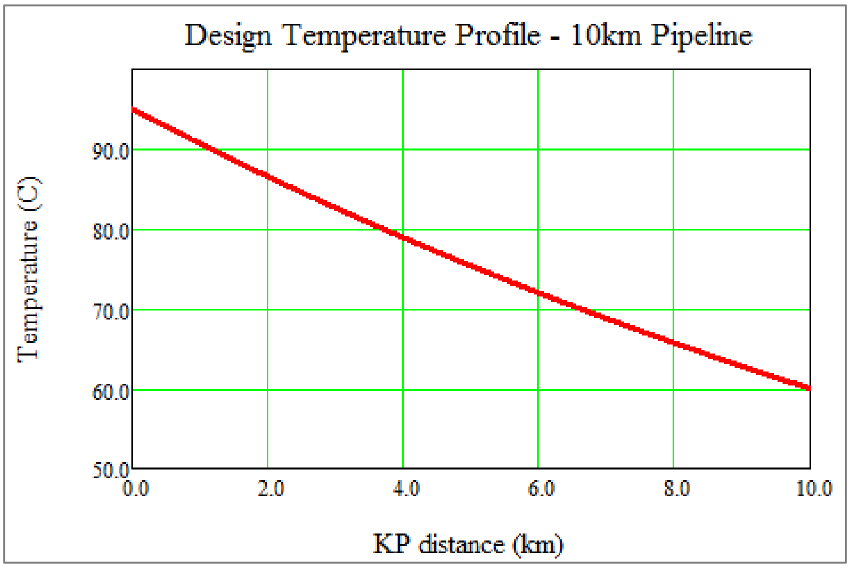


Figure 7-2: Temperature profile - 10km Pipeline

The temperature profile in Figure 7-2 was also used for deducing the end expansion for both short and long pipelines. See Appendix A for details. This profile was used to estimate pipeline expansion at both cold and hot ends.

b. Seabed Soil Condition and Frictional Data:

The seabed is assumed to be flat with a soft clay type soil. The axial and lateral frictional factors are represented by their corresponding lower, upper bound and best estimate values of coefficients as shown in Table 7-3 below.

Table 7-3: Friction Coefficients

Direction	Lower Bound (LB)	Best estimate (BE)	Upper Bound (UB)
Axial	0.35	0.45	0.50
Static lateral	0.60	0.70	0.80
Dynamic lateral	0.43	0.85	1.28
Soil Mobilization	2mm – 4mm		

c. Applicability of Pipeline:

According to SAFEBUCK guidelines, pipeline data should be checked to ensure that pipeline is considered within the range of validity. This is shown in Table 7-4:

Table 7-4: Applicability of Pipeline

Parameter	Calculated Value	SAFEBUCK rage of Validity
D/t	29,26701571	ration between 10 and 50
Design Temperature	95°C	< 180°C
Ovality	less than 1.5%	< 1.5%
PIP	NA	-
FLUID	oil	HC based product
Installation Plasticity	No significance plastic deformation during installation	No significance plastic deformation during installation not considered
Inspection	Valid	100% girth weld UT inspection
Seabed roughness	Flat Seabed	Relatively Flat seabed only

Hence, the pipeline falls within the range of applicability of SAFEBUCK guideline.

d. Pipe Material Yield Stress:

Based on the stress – strain characteristics of X65 material, the de-rating of SMYS yield strength with temperature is shown in Figure 7-3. Based on the given temperature profile, the de-rated material properties are used in FE modeling analysis.

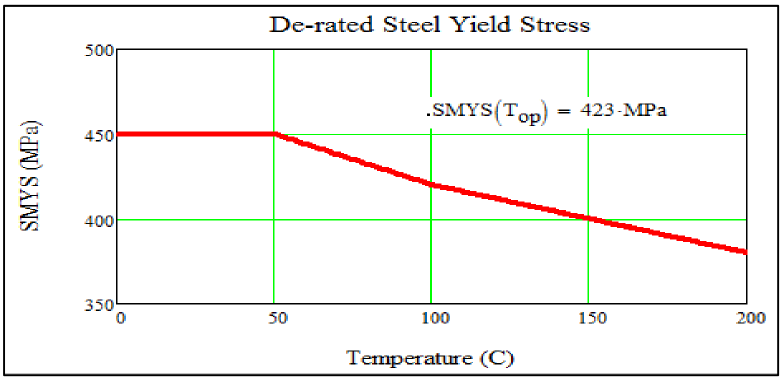


Figure 7-3: Pipeline Steel Material DE rating

e. Hydrostatic pressure:

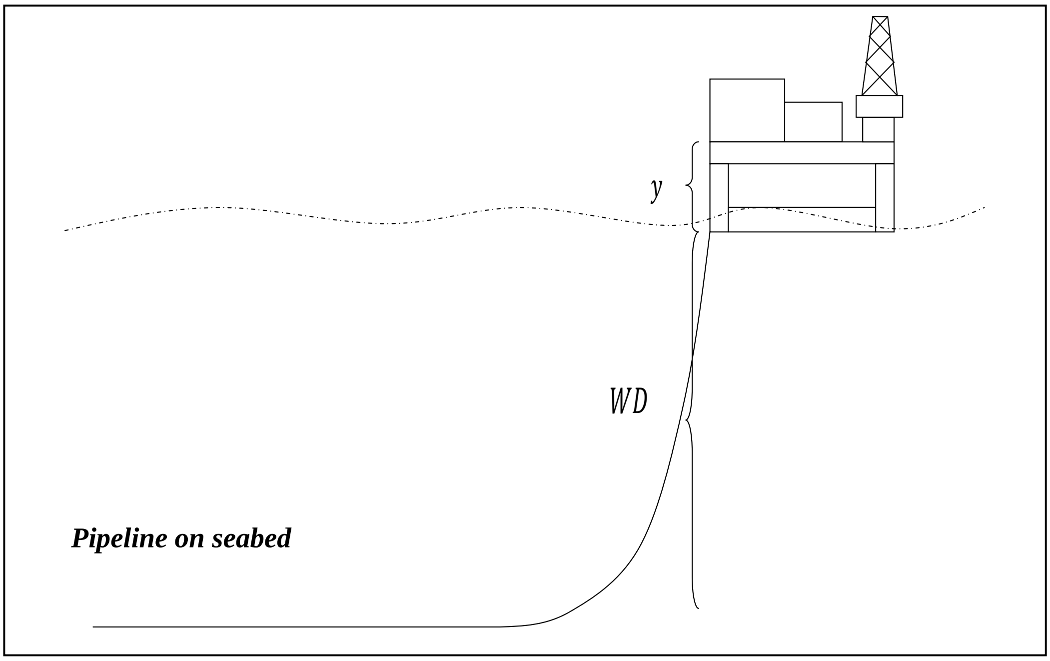


Figure 7-4: Hydrostatic Effect from the topside connection

$$where\ y = distance\ betweeb\ the\ topside\ tie - in\ and\ the\ mean\ sea\ level\ (MSL)$$

$$WD = Water\ depth\ (800)$$

Therefore, the hydrostatic pressure on the pipeline surface is given as:

$$P_{Hydrostatic} = \rho_{content} * g * (WD + y)$$

7.3 Design Parameters – Walking

The design parameters for the 2km flowline are the same as the properties used for the lateral buckling analysis.

The pressure variation for pipeline walking is taken as zero and this helps in deducing the actual walking due to thermal gradient. The Axial friction coefficient is taken for the all the cases such that the effect of walking can be deduced with respect to axial frictional forces.

Pipeline walking mechanism depends largely on the steps of heating profile developed during heat-up cycles. As a result of this, a constant thermal profile is used for the heating steps until the steady state is reached to ensure the effect was obtained due to thermal gradient alone.

This profile was developed in an excel spreadsheet, by interpolation of the inlet temperature at each node along the flowline in the FE model.

The analytical method used a constant thermal profile as well through –out the heating steps.

The temperature profile used in the heating steps was developed in Excel using the relation:

$$T = T_{hot\ end} - q_{\theta} * L_i$$

$$i = 0, 1 \ldots lastnode$$

a. Thermal Transient – Asymmetric Heating Steps:

The temperature was determined such that the asymmetric heating steps still retains the remaining section of the pipeline at the ambient temperature. The heating process will continue with the same profile until steady state is reached. The heating steps will be done in such a manner that a large movement from a section to another is avoided and hence a continuous heating interval is obtained.

The linear transient presented below exhibits a constant gradient along the pipeline involving 10 heating steps and the final steady state heating. This is the basis for walking mechanism along the pipeline and it is visible at the cold end.

The Profiles are as follows:

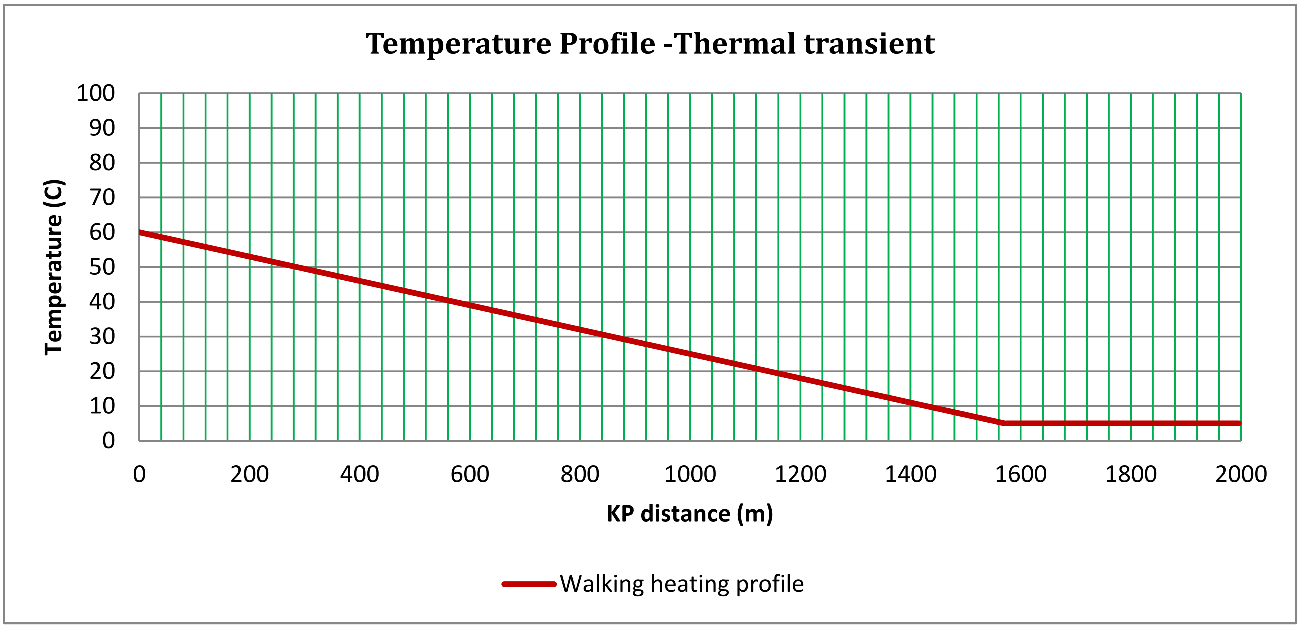


Figure 7-5: Temperature Profile

8. Results and Discussion

8.1 Results and Discussion

This section presents results from the analyses carried out for the design of pipeline lateral buckling and axial walking. The results are discussed against the design guide lines based on DNV-FS-101.

The results are presented in relation to the main focus of the thesis work which is:

- The use of snake-lay configuration as a mitigating measure under controlled buckling design and rock dumping if needed to limit feed-in into buckle and end expansions.
- The effect of thermal gradient on axial walking and the use of direct electric heating (DEH) to reduce rate of walking.

8.1.1 Verification of Pipeline Length Scale

Using the pipeline parameters and soil properties, the length scale of 10km pipeline and the 2km flowline is investigated. The detail of the verification is shown in Appendix A1.

According to the guidelines (Subsea7, 2011), pipeline is regarded as **short pipeline** if the calculated anchor length is larger than the length of the pipeline. This also means that the pipeline is having insufficient friction to attain to full constrained axial force and it is hence said to be fully mobilized. Otherwise it is regarded as a **long pipeline**.

Details of end expansion calculation are as shown in Appendix A: The following were obtained as shown in Table 8-1.

Table 8-1: Anchor Length results

Pipeline	Hot end Anchor length	Cold end Anchor length
10km Pipeline	3.272km	2.79km
2km Flowline	4.83km	

As shown in Table 8-1, the 10km pipeline is now established as a long pipeline which develops full constraint axial force while the 2km flowline is a short pipeline which never develops full constraint axial force.

This is further verified by deducing the corresponding effective axial force and frictional resistance forces generated by soil-pipe interactions (see Appendix A1).

8.1.2 Effective Axial Force

Applying the temperature profile and the pipeline properties outlined in the previous section, the effective axial forces for the 10km and 2km pipelines were calculated. The results are shown in Appendix A1 using.

Short Pipeline:

The effective axial force and the fully constrained axial force (See Appendix A for details) generated along the 2km pipeline is plotted and shown in Figure 8-1. Based on the results for the anchor length and the effective axial force, it is clear that the 2km pipeline is fully mobilized and thus it is a short pipeline.

As seen from Figure 8-1, the total axial frictional force is not enough to fully constrain the pipeline. During expansion, the two pipe-ends move in opposite direction to each other and develop maximum friction at the middle of the pipe where no expansions occur and this point is termed as virtual anchor point.

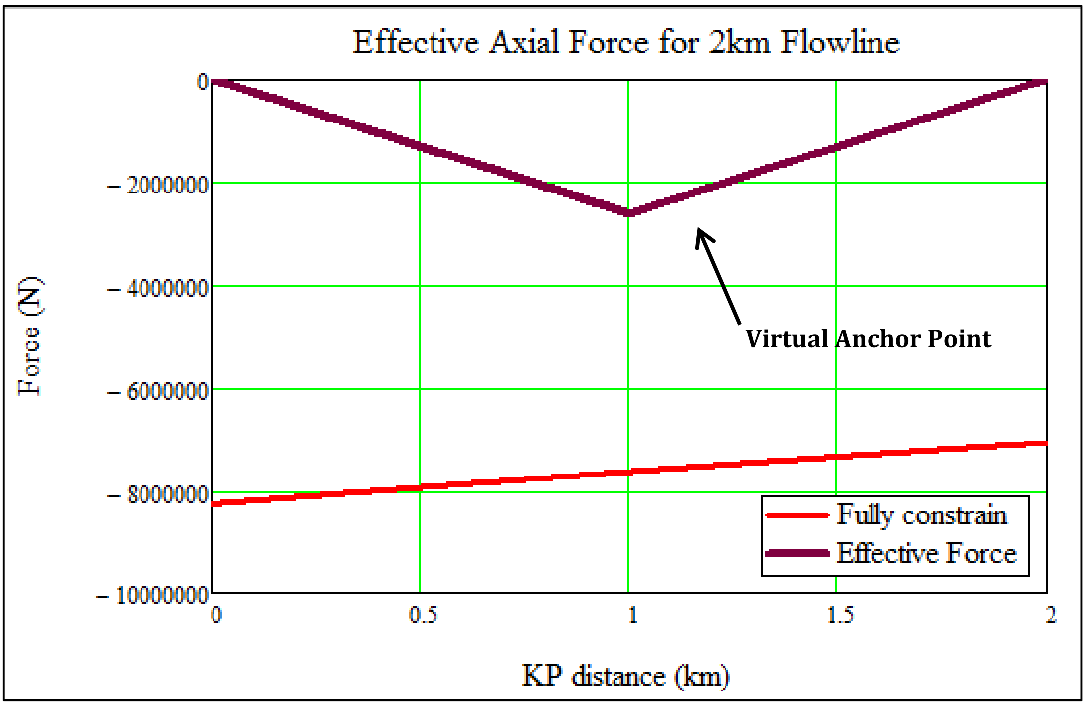


Figure 8-1: Effective Axial force of a short Pipeline

Long Pipeline:

For the 10km pipeline, it is evident from Figure 8-2 that the buildup of frictional force exceeds the axial force required to fully constrain the pipe. As a result, it generates two virtual anchor points towards the hot and cold ends. This shows that certain section of the pipeline is fully constrained while the end sections are free to expand.

The effective axial force developed during thermal and pressure loading reaches full constraint as the frictional forces builds-up. This could also yield larger end expansion at both ends if the lateral and axial frictional forces are decreased. See Appendix A2 for detail calculations.

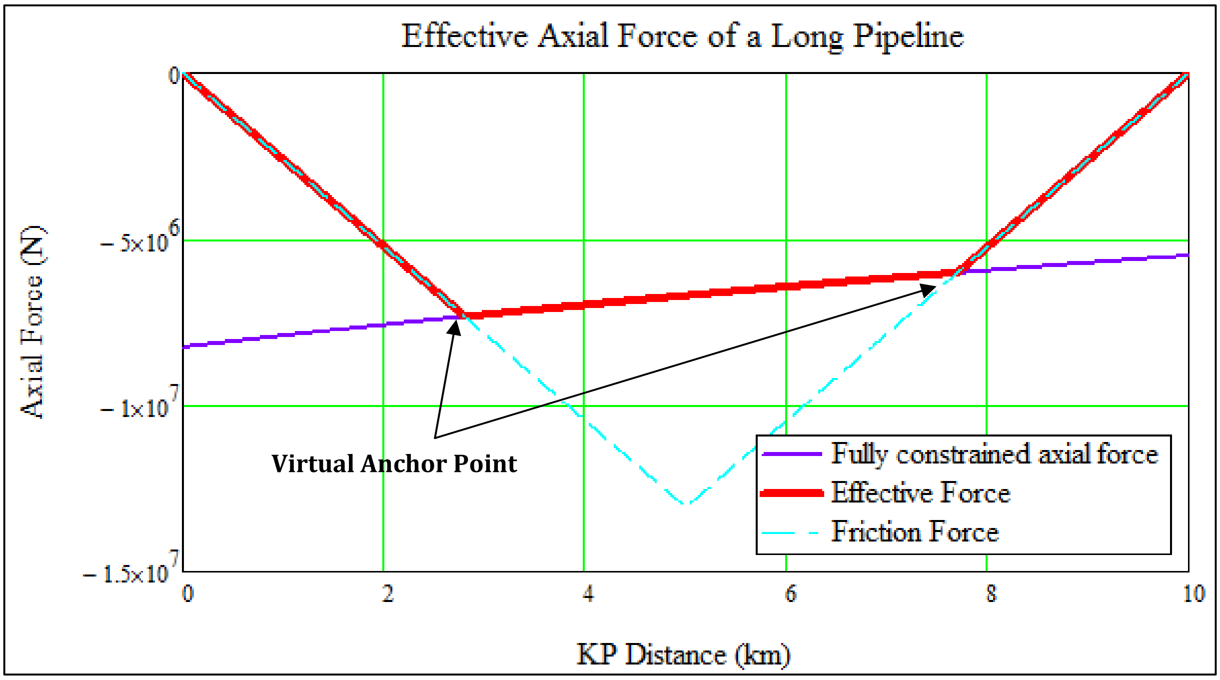


Figure 8-2: Effective Axial Force of a long pipeline

8.1.3 End Expansions

The build-up of frictional force induces compressive axial forces while restricting the axial expansion generated by temperature and pressure loading. This end expansion shows impacts on the design of tie-in/spool connected to the pipeline. Hence, the results are important during lateral buckling and axial walking design. The results for end expansion at different coating thicknesses are shown in Table 8-2 and Table 8-3 for long and short pipelines respectively.

Table 8-2: End Expansion Long pipeline

End Expansion of 10km Pipeline				
	Analytical		**FE Model**	
Concrete thickness	**Hot-end**	**cold-end**	**Hot-end**	**Cold-end**
25mm	2.007m	1.14m	1.96m	0.96m
40mm	1.858m	1.037m	1.864	0.858
55mm	1.725m	0.945m	1.765m	0.816m

Note: The results stated above are for end expansions without lateral buckling control measure.

This is also a testament that the 10km pipeline builds up more frictional force and hence has tendency more to buckle as seen from the results of the two pipelines.

Table 8-3: End Expansion of short pipeline

End Expansion of 2km Flowline				
	Analytical		FE Model	
Concrete thickness	Hot-end	cold-end	Hot-end	Cold-end
25mm	1.021m	0.933m	1.0509m	0.869m
40mm	1.006m	0.918m	1.0547m	0.8862m
55mm	0.99m	0.902m	1.08m	0.909m

Note: See Appendix A1 for the detail calculation steps

Controlled lateral buckling by sharing expansion reduces the end expansion. If the end expansion is found higher than the spool capacity designed for the pipeline connection, a measure will be re-established to accommodate the expansions at the ends, either by rock dumping or in-line spool connection.

8.1.4 Susceptibility of Pipeline to Lateral Buckling

It is a standard requirement to check for susceptibility of pipeline to buckling (See Appendix A2 for detailed calculation steps). Pipelines are said to be susceptible to lateral buckling if the following inequality holds:

$$N_{maximum} \geq N_{critical}$$

Where:

$N_{maximum} = The\ maximum\ compressive\ effective\ axial\ force,$

$N_{critical} = The\ critical\ Buckling\ force,$

$N_{maximum} = \min(N_{full\ constrain}, N_{fmax}),$

$N_{critical} = \min(N_{OOS}, N_{Hobbs}),$

$N_{full\ constrain} = Full\ onstrained\ effective\ axial\ force,$

$N_{fmax} = maximum\ compressive\ effective\ axial\ force\ in\ short\ pipeline,$

N_{OOS} = critical buckling force associated with Pipeline out of straightness (OOS),

$N_{Hobbs} = Hobbs\ minimum\ buckling\ force,$

$N_{Hobbs} = \min(mode_1, mode_2, mode_3, mode_4, mode_{infinity}),$

The Hobbs critical buckling force is calculated based on a spreadsheet developed using Mathcad 15. The critical buckling force for each of the buckling modes is based on the pipeline input and using the Hobbs constants K1, K2, K3, K4, and K5 as shown in Table 8-4.

Table 8-4: Constants for Lateral buckling mode

Modes	K_1	K_2	K_3	K_4	K_5
1	80.76	6.391 X 10^{-5}	0.5	2.407 X 10^{-3}	0.06938
2	$4\pi^2$	1.743 X 10^{-4}	1.0	5.532 X 10^{-3}	0.1088
3	34.06	1.668 X 10^{-4}	1.294	1.032 X 10^{-2}	0.1434
4	28.20	2.411 X 10^{-4}	1.608	1.047 X 10^{-2}	0.1483
∞	$4\pi^2$	4.7050 X 10^{-5}		4.4495 X 10^{-3}	0.05066

From the spreadsheet, the buckling force within the buckle was plotted against the buckling length for a certain section as described in Hobbs papers. Below is the result of one of the plots in Figure 8-3 (see Appendix A for details).

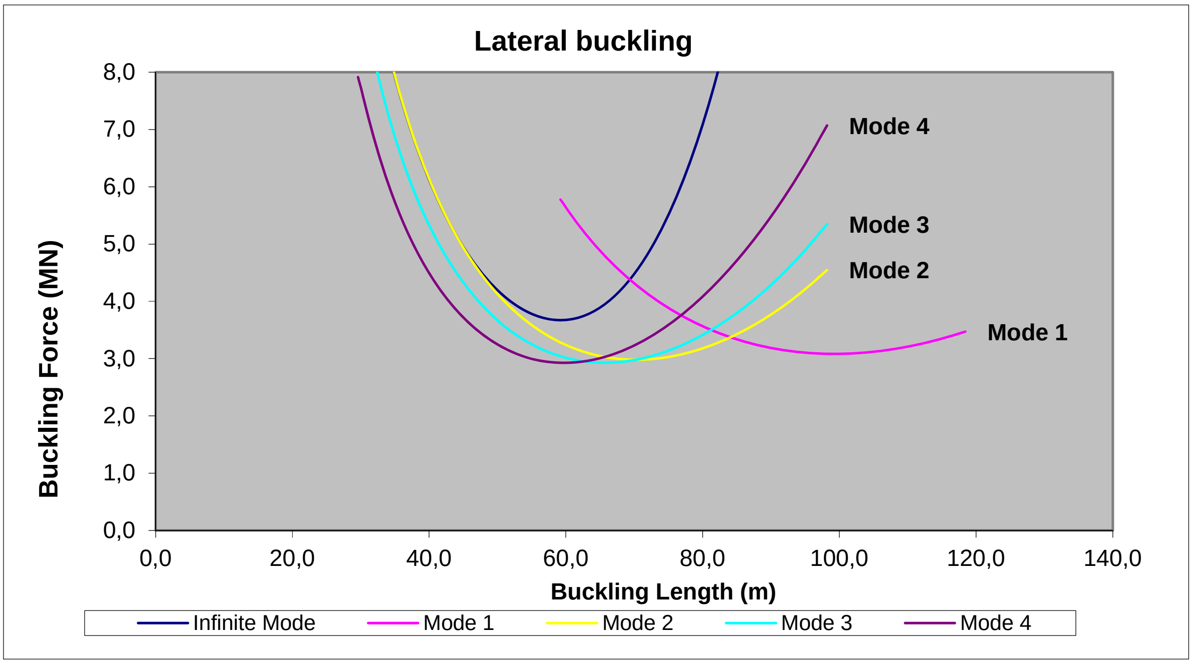


Figure 8-3: Hobbs Critical Buckling Force

The values for the Hobbs critical buckling force obtained are as shown in Table 8-5 for different lateral friction factors:

Table 8-5: Hobbs Critical Buckling force at different friction factors

Buckling mode	Units	Analytical Results		
		LB = 0.6	BE =0.7	UB =0.8
Mode 1	KN	3086.5	3354.0	3603.8
Mode 2	KN	3001.4	3240.2	3482.2
Mode 3	KN	2937.4	3190.0	3425.2
Mode 4	KN	2927.8	3180.7	3417.5
Mode ∞	KN	3672.4	3966.6	4240.5
Minimum values (KN)		**2927.8**	**3180.7**	**3417.5**

$$N_{Hobbs}{}^{LB} = 2927.8\ KN$$

$$N_{Hobbs}{}^{BE} = 3180.7\ KN$$

$$N_{Hobbs}{}^{UB} = 3417.5\ KN$$

Note: Hobbs' critical buckling force is based on assumption of a straight pipeline which is not obtainable in reality due to deformation from lay barge, seabed contours and initial imperfection (OOS). The results are summarized in Table 8-6.

As stated previously, the critical buckling force associated with pipeline out of straightness (OOS) is obtained with the following relation:

$$N_{OOS} = \mu_{Lat} W_{submerged} R$$

Table 8-6: Analytical Result - Critical Buckling Force

N_{OOS}	$W\_submerged$ KN/m	Radius R (m)	Analytical Results		
			LB = 0.6	BE =0.7	UB =0.8
N_{OOS}	3345	1500	3010	3512	4014
N_{OOS}	**3345**	2500	4014	4683	5352

Hence,

$$N_{critical} = \min(N_{OOS}, N_{Hobbs})$$

$$N_{critical}{}^{LB} = 2927.8\ KN$$
$$N_{critical}{}^{BE} = 3180.7\ KN$$

$$N_{critical}{}^{UB} = 3417.5\ KN$$

Given that the maximum compressive axial force along the pipeline is obtained from calculation as:

$$N_{Maximum} = 8252\ KN$$

The pipeline is therefore, susceptible to BUCKLING because the inequality is true.

$$N_{maximum} \geq N_{critical}$$

8.1.5 Regions Susceptible to Lateral Buckling

Since the 10km pipeline is now known to be susceptible to lateral buckling, the area that is prone to such lateral movement is to be determined. Critical buckling force is used as a limiting criterion to define the areas that are susceptible to buckling. These areas are those with effective axial force greater than the critical buckling force as shown in Figure 8-4 below:

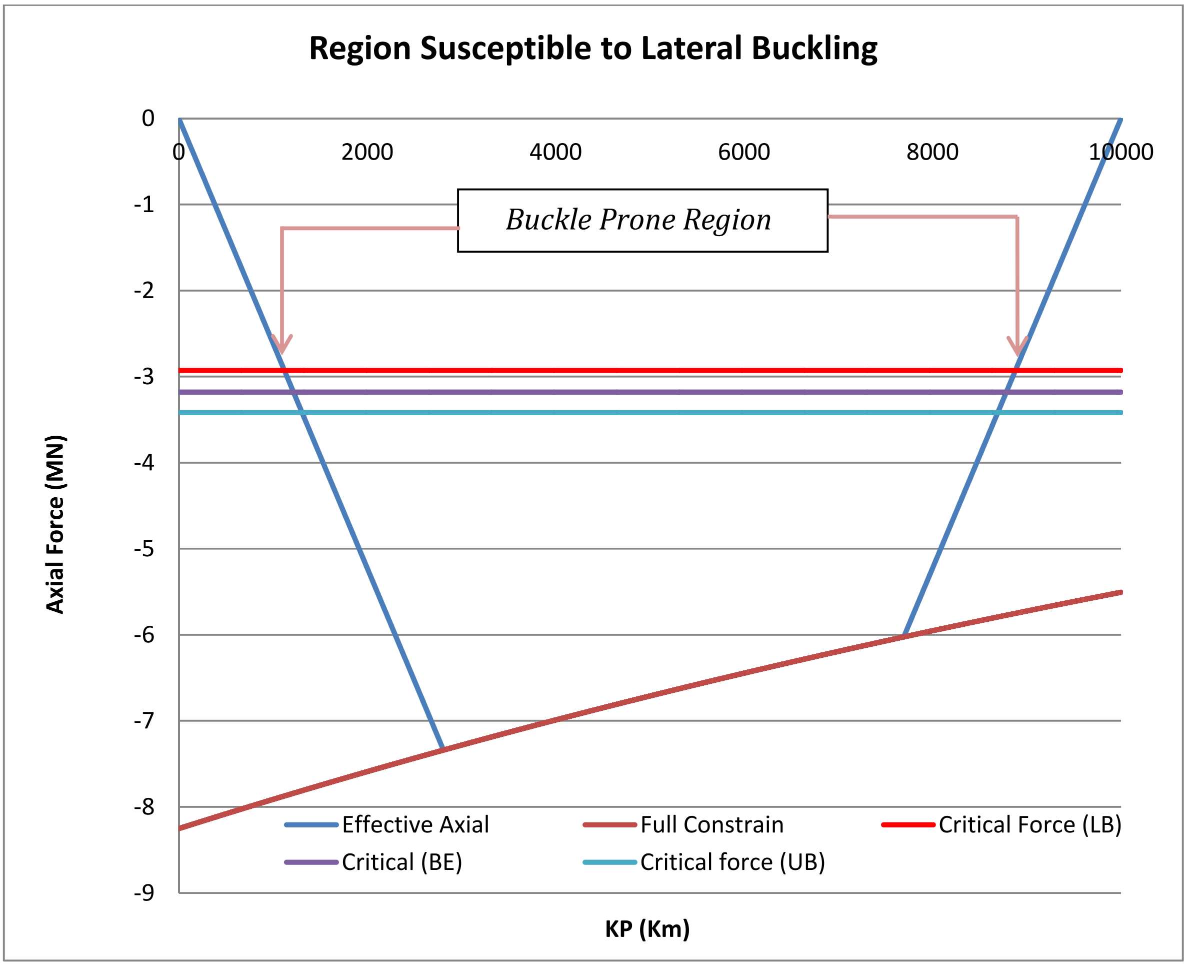


Figure 8-4: Region Susceptible to lateral Buckling

The section that are prone to buckle as seen from Figure 8-4 above ranges from KP1 to KP9, resulting in about 8km pipeline length having the potential to buckle.

8.2 Lateral Buckling Behaviour

As observed from the previous analysis, about 8km of the pipeline length is susceptible to lateral buckling within KP1 and KP9. Naturally, pipeline laid of seabed with an initial imperfection will buckle on thermal and pressure loadings.

If the induced compressive force is sufficiently high, uncontrolled buckling could occur and the pipeline integrity could be lost. This effect can lead to the following limit state:

- Excessive Plastic deformation of the pipe which could lead to local buckling collapse
- Cyclic fatigue failure due to continuous heat-up and cool-down

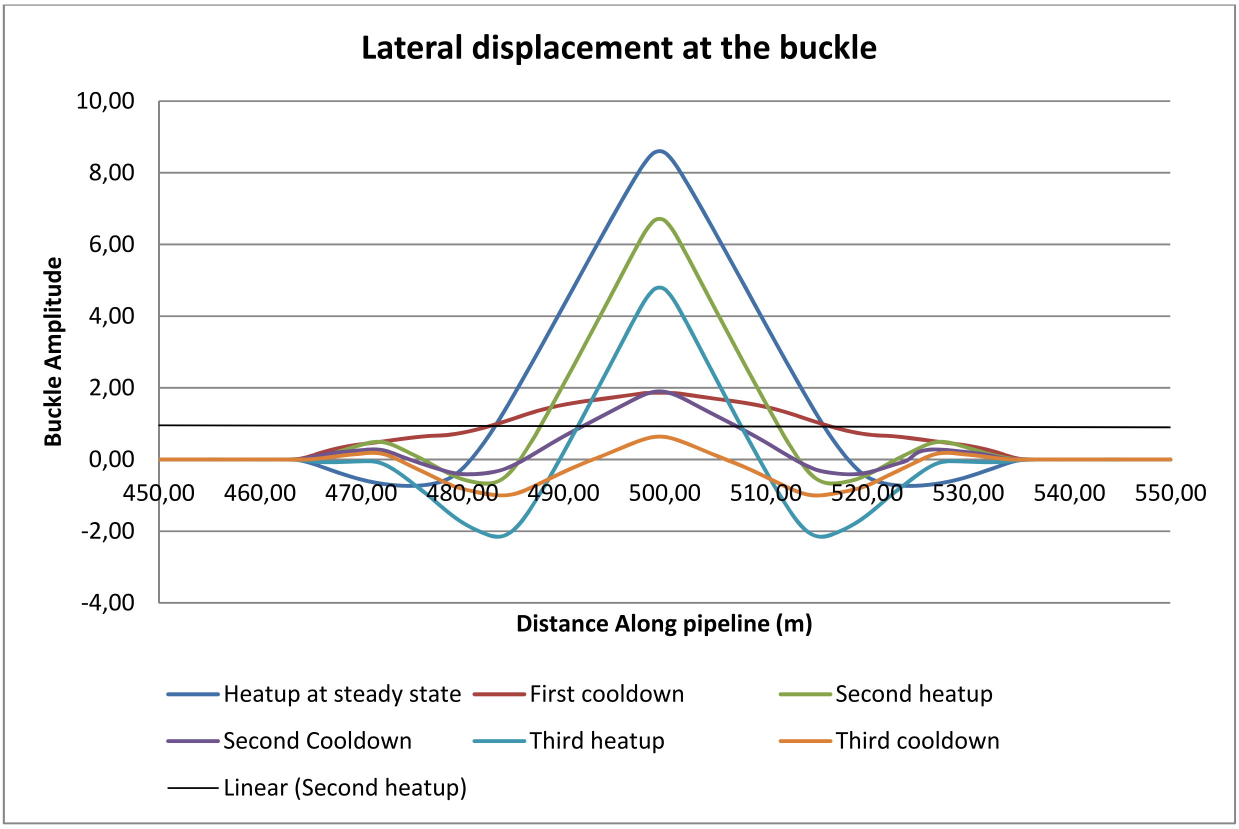


Figure 8-5: lateral displacement at the buckle site

As shown in Figure 8-5, the non-linear analyses of the 2km VAS model with a 2m initial imperfection and 1500m radius generated a lateral displacement of 8.56m under operating temperature and pressure considering the operation corridor of not more than 20m. This is as shown in the Figure 8-5 with corresponding cyclic loading at shut-down and cooldown steps.

Based on the results shown in Figure 8-5, maximum lateral displacement of 8.56m occurred at a particular buckle site along the pipeline. This effect will be detrimental to the pipeline and need to be reduced to an acceptable limit.

During cyclic loading, it can be seen that the pipe-soil interaction cannot be predicted during cooldown steps. The cooldown step from operating temperature of 90°C to ambient temperature of 5°C resulted in non-linear behavior of the buckle section which resulted in strain build up within the buckle site.

Since this is a displacement controlled condition, the capacity of pipeline is based on allowable strain. For the pipeline, the predicted strain from the FE analyses was compared against allowable strain. It was observed that predicted strain reached maximum allowable strain can be predicted to occur at lower operating temperature.

The effective axial force at different soil friction is important to extract the result of the post buckling force from FE analyses. Figure 8-6 presents the results for the effective axial force at different friction factors.

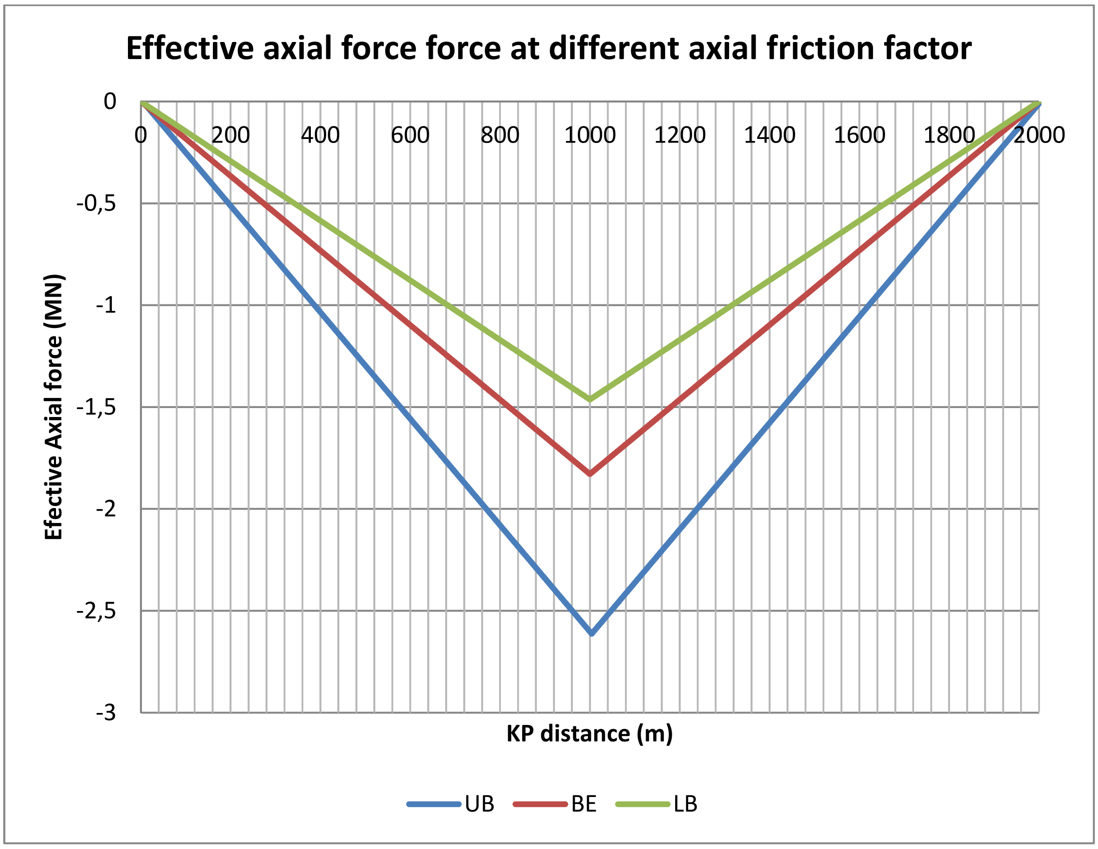


Figure 8-6: Effective axial force for different friction factors

This is also a conformational statement that the worst case scenario for pipeline to fail occurs at the lower bound friction. At the lower bound friction, there will be a lower effective axial force due to less frictional resistance from the soil and hence more length of the pipe is fed-into the buckle section.

The above results from FE analyses result are the basis for Snake lay configuration and expansion sharing into adjacent buckle such that total strain developed by the thermal loading and pressure loading be shared among the pre-determined buckles.

8.3 Snake Lay Control Measure

There are many ways of reducing or controlling lateral buckling of pipeline on seabed depending on the criticality of the problem. The conventional way is by rock dumping at some certain pre-determined areas along the pipeline.

Here in this thesis work, one of the Buckle initiation method (expansions sharing) called Snake-Lay configuration is applied. The snake Lay configuration is based on the principle of sharing expansion into adjacent buckles as stated in DNV-RP-F110.

Note: *The obtained snake lay configuration in the present work is based on the allowable capacity of the pipeline. However, the required number of snakes is dependent on allowable end expansion taken by the spools connected to the pipeline. As the capacity of the connecting Spool (expansion Limit) to the 10km pipeline is not known, the result of expansion sharing will be acceptable based on further analysis*

The purpose of the snake lay configuration and intermittent rock dumping is to ensure the feed-in into buckle shall be within allowable capacity of the pipeline and further to ensure that end expansion limit can be kept within the limit given by the spool capacity.

As stated previously, the expansion sharing between the adjacent buckles shall be established when the following relation is fulfilled:

$$F_{post}{}^{LB} + \Delta S^{LB} \geq F_{critical}{}^{UB}$$

This relation is used in developing the spreadsheet for snake lay configuration.

At the hot and cold ends, there is less frictional force available to build up effective forces between the buckle so there is need to build up frictional forces at those ends. To obtain this, rock dumping of some height TOP was employed at the hot and cold ends.

8.3.1 Lay Configuration for 10km pipeline – *R1500m*

As shown in Figure 8-7, the FE model for snake-lay configuration of radius **1500m** was developed with an initial imperfection of 2m for a 2km VAS model on even seabed. Based on the limiting condition stated previously from DNV-OS-F101, the post buckling force at the lower bound friction coefficient were obtained.

By applying several time steps, the FE analyses were run to obtain the post buckling force corresponding to the maximum allowable strain based on displacement controlled condition (strain based criteria) as given below:

$$\varepsilon_{max} \leq \varepsilon_{ca}$$

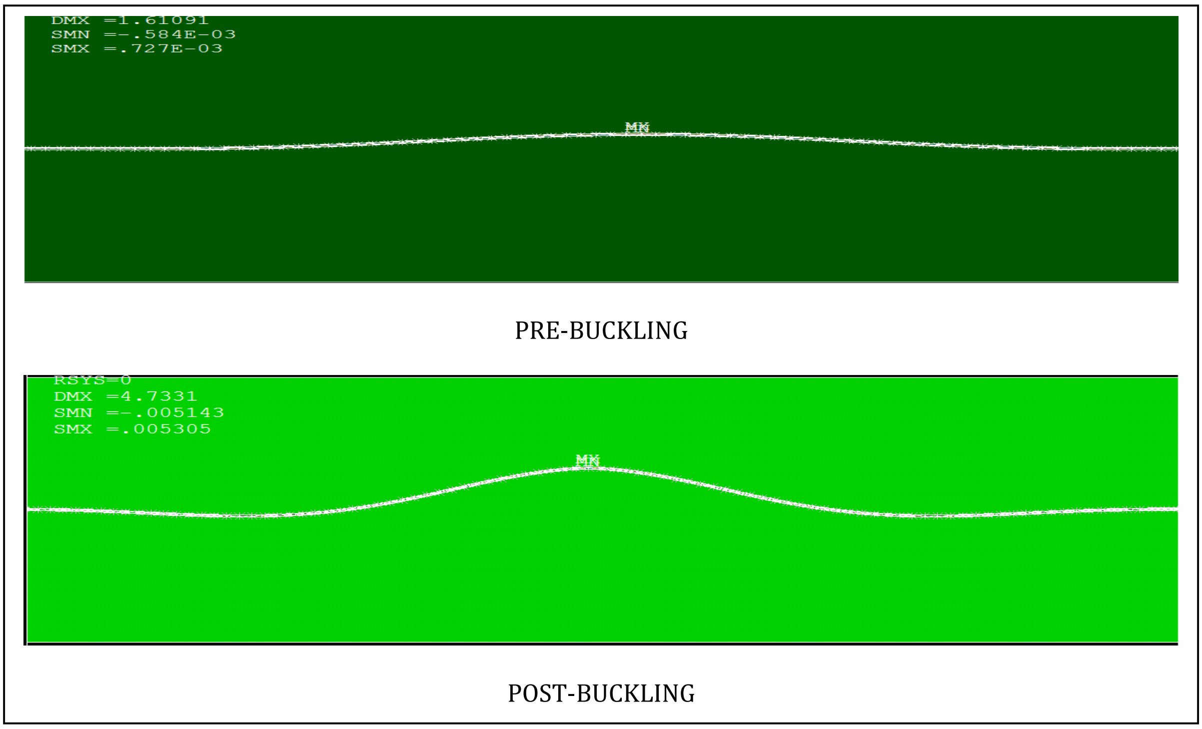


Figure 8-7: Pre-Buckling and Post Buckling of a pipeline snake Configuration

Also allowable feed-in was calculated based on displacement controlled condition. Based on the results from FE analyses, the predicted post buckling forces and the allowable feed-in are summarized below in Table 8-7 for several combinations of frictional factors.

Table 8-7: Feed-in Results for R1500m

Axial Friction	Lateral Friction	$F_{critical}$	Strain Limit Displacement controlled condition		
			F_{post}	ε_{ca}	$Feed-in$
		KN	KN	m/m	m
LB	LB	-2408.4	-1756	0.004	1.20
BE	BE	-3010.5	-1864	0.004	1.12
BE	UB	-3010.5	-1894	0.004	0.9
UB	UB	-3417.5	-1910	0.004	1.12

Adopting the results from the ANSYS model and using the snake –lay excel spreadsheet; the expansion sharing was generated for each snake based on acceptance criteria stated previously.

By applying the R1500m configuration, the upper bound critical buckling force is -3010.5kN and the lower bound post-buckling force is -1756kN.

To ensure that allowable feed-in of 0.9m at the hot end, rock dumping of 2m rock height TOP was applied over the section of 100m. Figure 8-8 presents the effective axial force distribution obtained from snake-lay configuration.

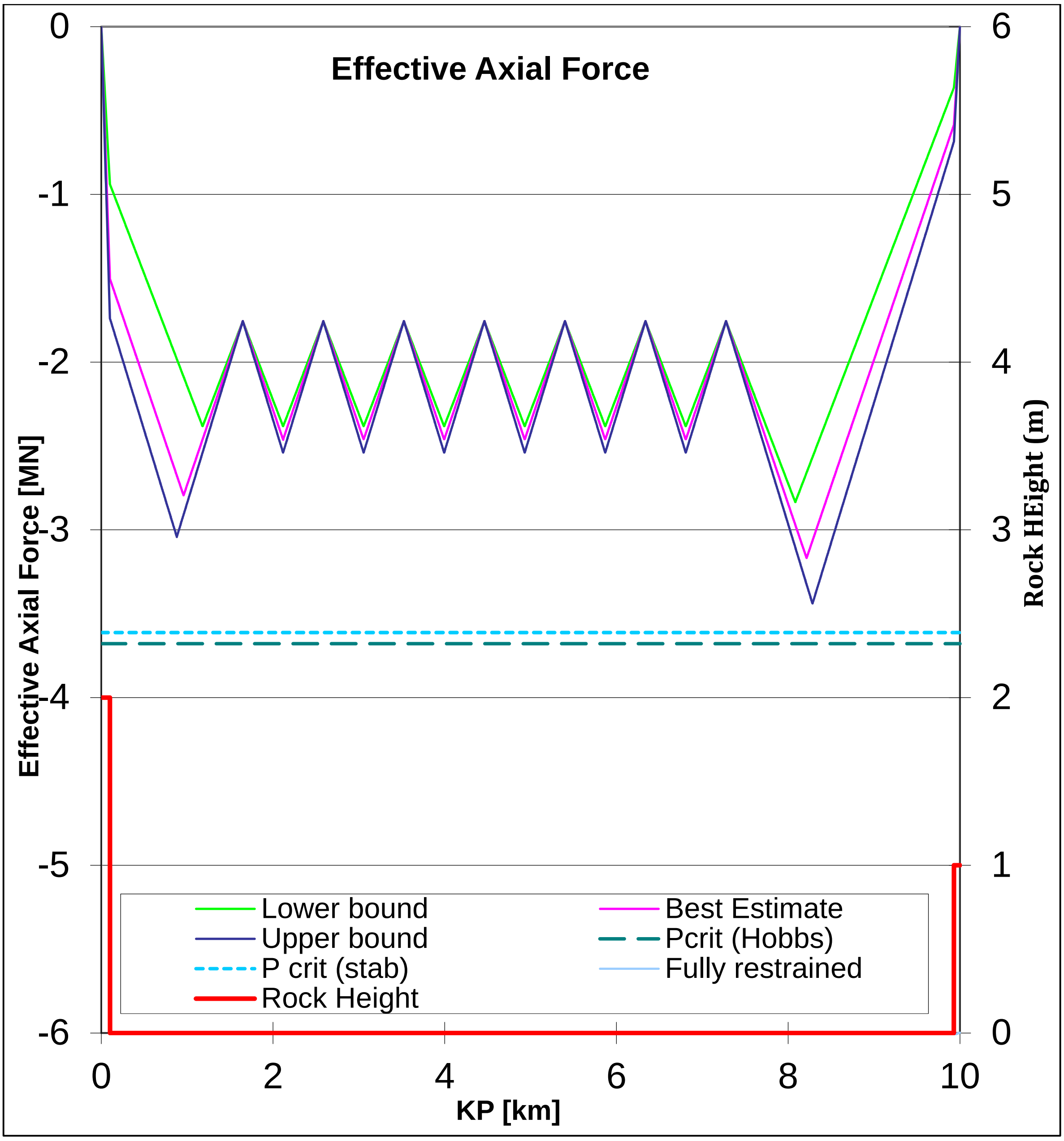


Figure 8-8: Effective axial force distribution for Snake Lay configuration

The result in Figure 8-8 shows that the 10km pipeline requires 7snakes, rock dumping to limit end expansions. Table 8-8 shows the results obtained for the 1500m radius lay configuration.

Table 8-8: Expansion Summary for the R1500m configuration

	Lay radius	Virtual anchor #1 KP	Virtual anchor #1 KP	Total feed-in	Allowable feed-in
	m	m	m	m	m
Hot end	1500	Free end	840	0.800	-
Snake 1	1500	840	2064	0.814	0.9
Snake 2	1500	2064	3014	0.778	0.9
Snake 3	1500	3014	4002	0.747	0.9
Snake 4	1500	4002	4870	0.714	0.9
Snake 5	1500	4870	5816	0.683	0.9
Snake 6	1500	5816	6766	0.652	0.9
Snake 7	1500	6766	8236	0.625	0.9
Cold End	1500	8236	Free end	0.60	-

The predicted end expansion and the buckle feed-in length are listed in Table 8-8 and compared against allowable values. Note that pipeline end expansions are within the allowable capacity of the pipe and these shall be compared against the allowable end spool expansions which are not known.

From Table 8-8, it is seen that the computed pipeline feed-in lengths satisfy the acceptable limit which is based on strain based criterion. The effect of rock dumping at the hot end reduces the number of snakes that are used in the expansion.

The snakes can as well be reduced further but with a higher cost of rock dumping at the buckle crest. Depending on the project, the client requirement, the capacity of end spools and hub capacity, the expansion can be re-established if needed.

It is worth to note that the hub capacity where the spool is fitted into must not be compromised and the expansions that the spool must accommodate are not to be exceeded. Otherwise the sharing expansion shall be re-considered with respect to the limiting capacities.

In the present case, the end spool capacities are unknown. But according to the results presented in Table 8-8, the spool shall accommodate expansion of 0.80m at the hot end and 0.6m at the cold end. These results for the pipeline end expansion can be used along with operational loads to design end spools and to assess interface loads at the hub.

This shows that the integrity of our pipeline is recovered and intact according to DNV-RP-F110.

Figure 8-9 shows the expansion distribution. At the hot end the 2m rock height TOP was used to build up the effective axial force in order to reduce end expansion. This helps to reduce the expansion in the adjacent snake along the pipeline.

From Figure 8-9, it can be seen that the expansion towards the cold end is reduced as a result of the sharing of the feed-in into the snakes. Also due to the use of rock at the end, an expansion of 0.60m was induced to achieve the desired configuration with an acceptable displacement control condition.

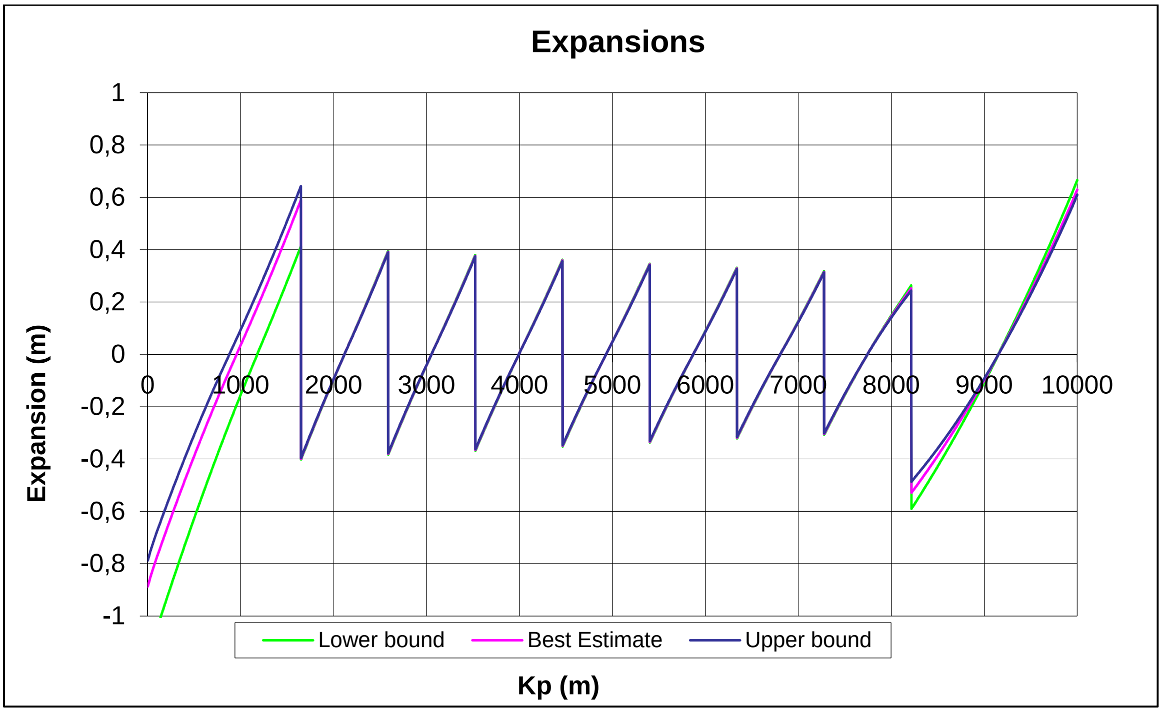


Figure 8-9: Expansion Distribution

The purpose of snake lay configuration has therefore been achieved which is to trigger sufficient number of thermal buckles at pre-determined location along the pipeline so that the expansion is distributed among the buckles rather than being concentrated at a few buckle sites.

This is shown in Figure 8-10 where the effective axial for the snakes lay control were compared with the effective axial force without snake lake measure.

It can also be seen that the planned buckle occurs prior to the unplanned buckle with regard to the 2km model used in obtaining the post buckling force. This is done to ensure that the required buckle distribution is achieved.

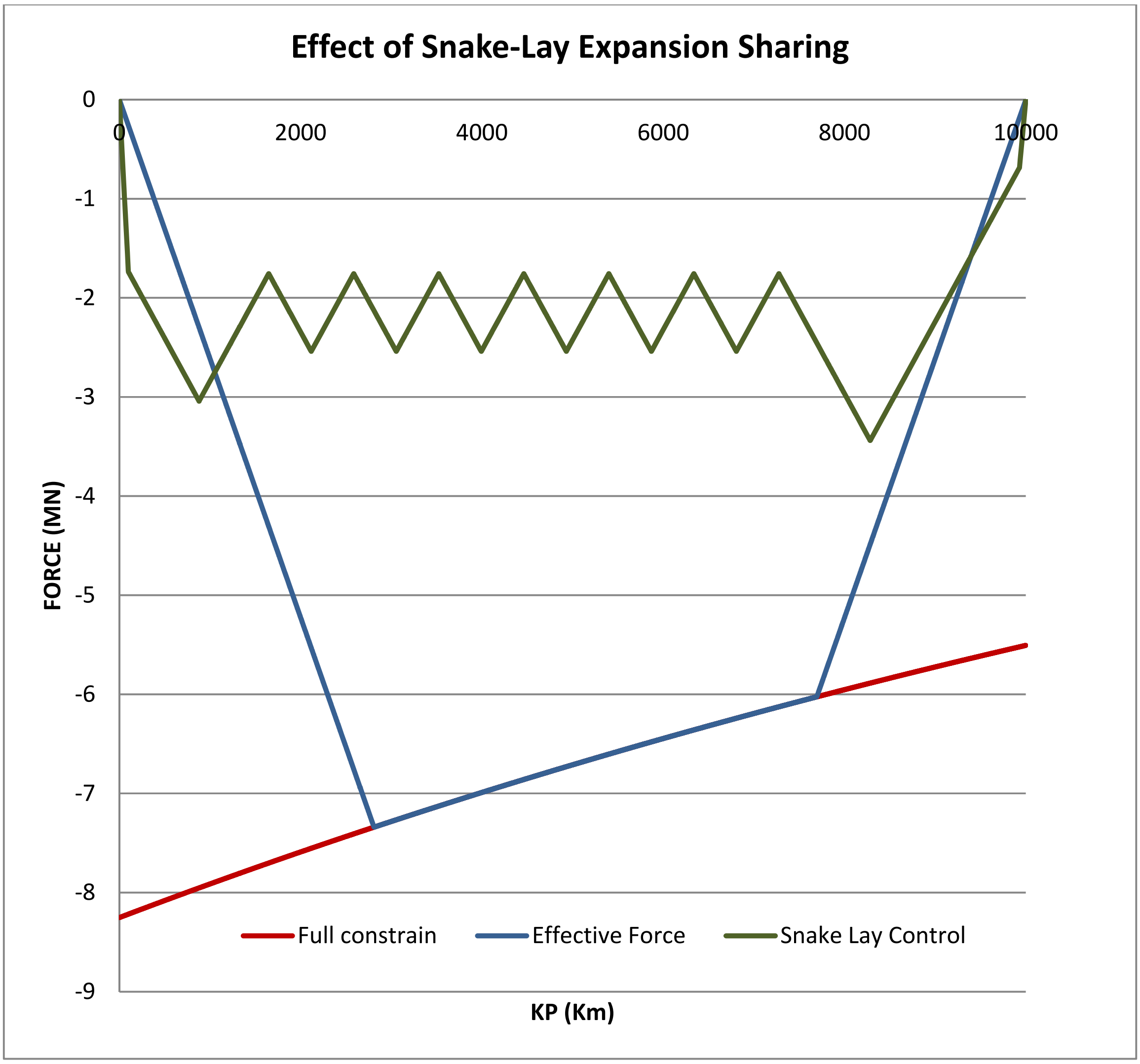


Figure 8-10: Effect of Snake Lay configuration

Figure 8-10, shows the distribution of total feed-in into several buckles. Here, the crown of the snake behaves like a curvature expansion spool while the feed-in is controlled by the distance between two successive crowns.

The effective axial force increases as the frictional restraint builds up due to the seabed interaction. But the introduction of snakes modifies the development of the effective axial force and causes effective axial force to drop within the buckle site as the pipe feeds-in to the buckle.

As a result, the effective axial force drops to a value much less than the critical buckling force. This is achieved at the lower bound friction factor which is worst case scenario for the pipe to fail during an operation.

8.3.2 Parametric Study of Lay Configuration

The previous section considers snake lay generated by using a lay radius of 1500m and 2m imperfection. The response of the pipeline shows that a total of 7 snakes are formed while using rock dumping at both hot and cold-ends. The present section considers a lager lay radius of 2500m having the same initial imperfection of 2m.

Table 8-9: Feed-in Results for lay radius of 2500m

Axial Friction	Lateral Friction	Radius	$F_{critical}$	Strain Limit Displacement controlled condition		
				F_{post}	ε_{ca}	$Feed-in$
		m	KN	KN	m/m	m
LB	LB	2500	-2927.8	-2376	0.004	1.52
BE	BE	2500	-3180.7	-2501	0.004	1.50
BE	UB	2500	-3417.6	-2540	0.004	1.1
UB	UB	2500	-3417.6	-2641	0.004	1.48

It is known that Critical Buckling force $F_{critical}$ is a function of Lay radius (R), submerged weight and the friction coefficient as given by:

$$F_{critical} = \mu_L * W_{submerged} * R$$

It can be seen from Table 8-9, that the larger the radius the more the critical buckling force. The increase in the buckle length from 160m (R1500m) to 200m (R2500m) results in larger radius and smaller initial imperfection. The results based on this lay radius show less feed-in compared to the radius of 1500m. In this case rock was applied only at the hot end. The snake lay with lay radius of 2500m increases the number of snakes to 9 as seen in Figure 8-12.

Also, it is noticed that the post buckling force at higher radius of 2500m was higher than the R1500m due to the unpredicted pipeline embedment and the resultant breakout force.

With the use of more rock dumping at the crown of each snake, we will be able to obtain less number of snakes as shown as dashed lines in Figure 8-11. But, this can be achieved at higher cost of rock dumping which also depend on the operation corridor for the pipeline.

The dashed lines are the new snakes generated upon using the rock dump at the crest and along a buckle region in between two buckles. There is a tendency of reaching the critical buckling force with this solution.

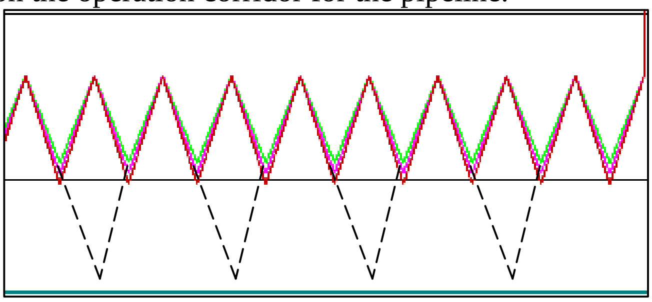


Figure 8-11: Rock Dumping between snake

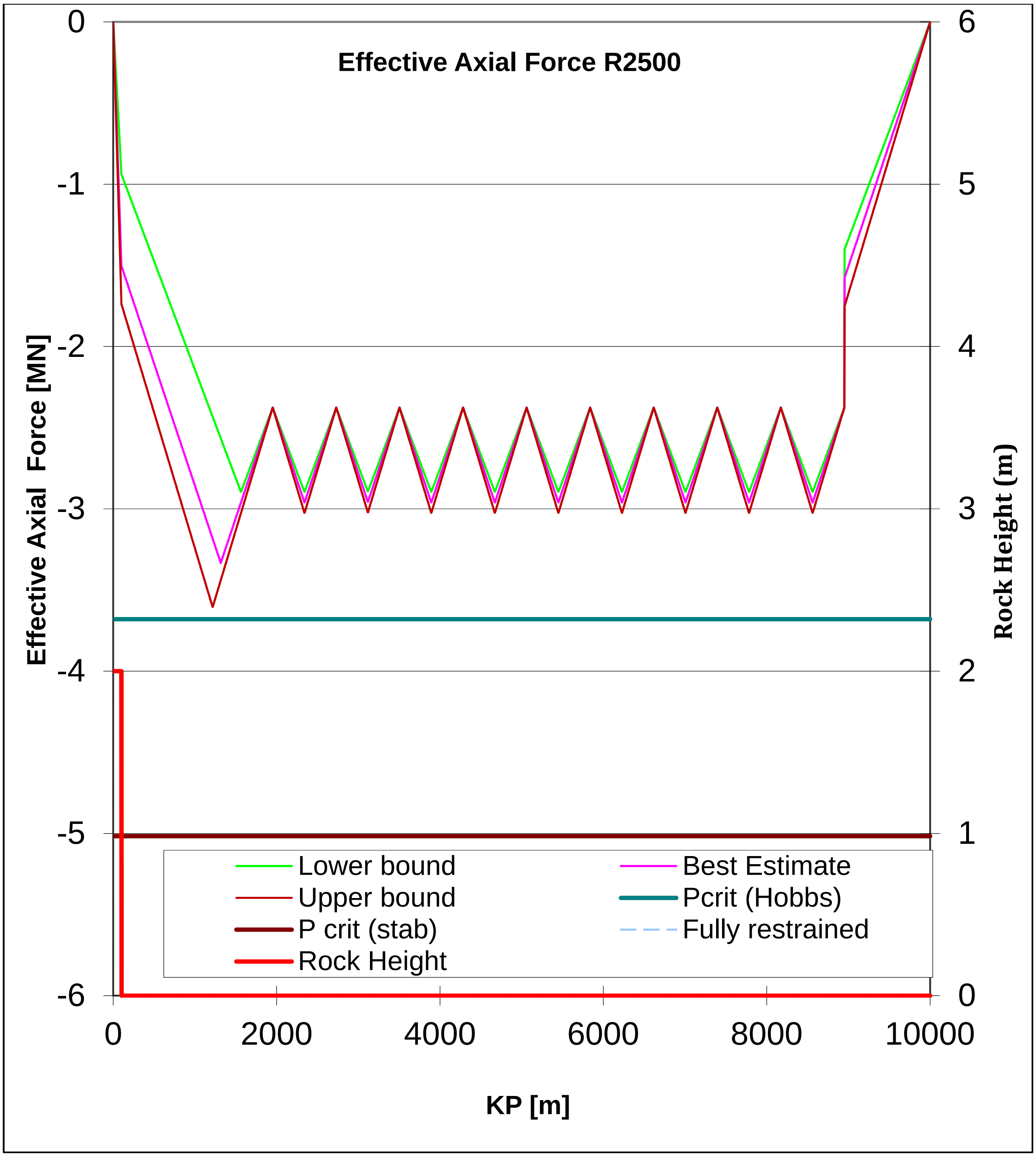


Figure 8-12: Effective force distribution of snake lay (R2500m) configuration with Rock dumping

For the R2500m configuration shown in Figure 8-12, the lowest expansion at the cold and hot reduced by 0.2m due to the lower feed-in in the buckle site as compared to R1500m. This is testament that the expansion the spool can accommodate can be re-established to suit the spool design value by increasing the radius or rock dumping at the opposite end. This is shown at the expansion result in Figure 8-13 below:

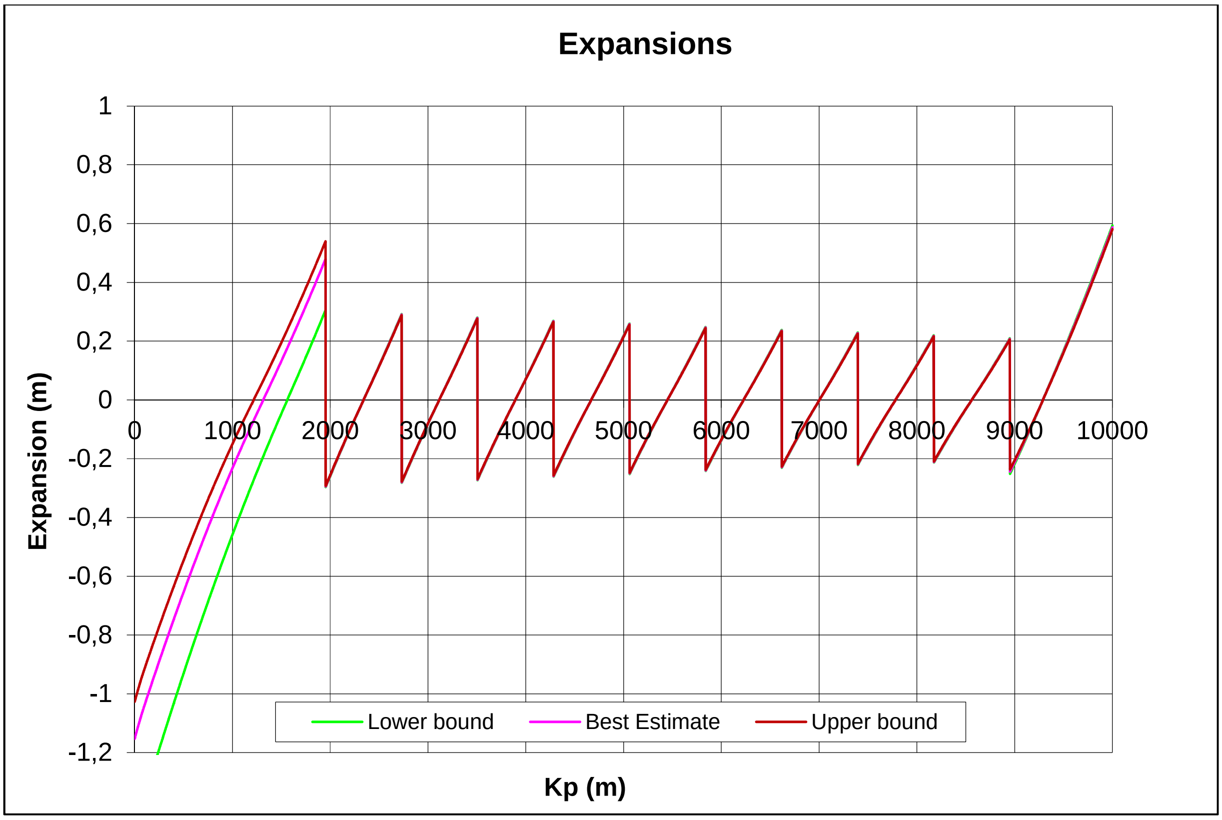


Figure 8-13: Expansion results for R2500

The resulting post buckling force within the buckle is the basis in deriving number of snakes on seabed. The post buckling force is extracted from FE analyses based on predicted strain corresponding to the allowable design strain from displacement controlled criterion. As mentioned previously, the expansion sharing between the adjacent buckles shall be established when the following condition is fulfilled.

$$F_{post}{}^{LB} + \Delta S^{LB} \geq F_{critical}{}^{UB}$$

Based on this condition, the lower bound the post buckling force is a requirement for a conservative solution such that the pipeline integrity will be maintained even at lower bound value of the soil-pipe interaction.

Upon using the lower bound friction factor in the FEA, the worst feed-in length is obtained based on the stated condition. The result shows that more feed-in is generated with R2500m as compared with R1500m as shown Figure 8-9.

It has also been observed also, that there are uncertainties regarding the post buckling force and it depends strongly on the soil-pipeline interaction. This is one of the challenges during snake lay configuration.

Table 8-10: Expansion Summary for R2500

	Lay radius	Virtual anchor #1 KP	Virtual anchor #1 KP	Total feed-in	Allowable feed-in
	m	m	m	m	m
Hot end	2500	Free end	1172	1.000	-
Snake 1	2500	1172	2296	0.83	1.1
Snake 2	2500	2296	3060	0.57	1.1
Snake 3	2500	3060	3828	0.55	1.1
Snake 4	2500	3828	4620	0.53	1.1
Snake 5	2500	4620	5398	0.51	1.1
Snake 6	2500	5398	6188	0.48	1.1
Snake 7	2500	6188	6980	0.46	1.1
Snake 8	2500	6980	7712	0.45	1.1
Snake 9	2500	7712	8508	0.43	1.1
Cold End	2500	8508	Free end	0.58	-

The computed expansion and the buckle feed-in lengths are summarized in Table 8-10. The results show that the computed feed-in lengths are within the acceptable feed-in based on the strain based criterion.

Note: It can be deduced from the FE analysis and the snake lay result that the planned buckles occurred at the center of the VAS model or prior to the location chosen during the FE modeling. This is in accordance with the expansion sharing described in DNV-RP-F110.

8.4 Pipeline Walking Results and Discussion

As stated previously, 'when pipeline is laid on seabed and heated up by hot fluid content passing through it, it expands axially and circumferentially. Upon cooling, since this expansion is restricted by axial friction generated by pipe-soil interaction, the pipeline will not return to its original position. Over number of cycles of subsequent heating and cooling, an accumulation of axial displacement of pipeline towards the cold end is generated. This is known as pipe-walking'.

Note: *This thesis work considers only the effect of thermal loading and transient along the 2km flowline.*

8.4.1 Susceptibility to Pipeline Walking

According to SAFEBUCK guideline, pipelines are regarded to not to be susceptible to walking if the axial friction force $\boldsymbol{f}$ exceeds the following value:

$$\boldsymbol{f} > \boldsymbol{\beta}\frac{(\boldsymbol{EA_{st}\alpha\Delta T})}{\boldsymbol{L}}$$

The results from the calculation summarized in Appendix A3 for the 2km flowline. From the results, it can be seen that the 2km flowline is susceptible to walking based on the SAFEBUCK guidelines for pipeline walking.

Pipeline being susceptible to walking do not necessarily suggest danger to the life of the field unless otherwise proved that the walking rate will be detrimental to the connecting ends.

Thus, there is need to obtain the extent the pipeline will walk by using an analytical method based on the relation stated on the SAFEBUCK guideline.

A spreadsheet was developed on Mathcad 15 (see Appendix A4) and the rate of walking per cycle under constant thermal gradient was deduced using the relation below:

$$\Delta_\theta = \frac{fL^2}{8 * EA_s} - - - - - - - - - - if\ f \le \frac{f_\theta}{6}$$

$$\Delta_\theta = \frac{L^2}{16 * EA_s}\left(\sqrt{24 * f_\theta * f} - f_\theta - 4f\right) - - - - - - - - - - if\ f > \frac{f_\theta}{6}$$

The above expression gives the accumulated axial displacement as a result of the thermal transient based on constant gradient along the seabed and the results are as shown below in Table 8-11:

Table 8-11: Analytical Result for rate of walking at 35°C/km

Axial Friction Factor	Thermal gradient [°C/km]	Rate of walking [mm]
LB	35	51
BE	35	44
UB	35	40

From the above results, it is seen that for lower bound friction, the rate of walking towards the cold end is higher than that for best estimate and upper bound friction. This response was expected.

The axial friction coefficient is the dominating factor during pipeline walking and this has to be taken into consideration in order to minimize the effect of walking.

From the calculation using the analytical method, it is found that at higher axial frictional factor and lower thermal gradient the SAFEBUCK relations do not give a good approximation based on the assumption stated on the guideline (see Appendix A4). Hence, it requires performing a finite element analysis and to obtain a better approximation of the rate walking at different thermal gradient.

Hence, the analytical method of calculation is not used for final conclusion of results but it is used as a basis to predict the response of walking along the pipeline.

8.4.2 Finite Element Analysis - Axial Walking

Temperature profile presently in Figure 7-5 with constant thermal gradient of 35^{o}C/km was used to generate asymmetric heating step along the pipeline. The response from the heating steps is as shown in Figure 8-14 below:

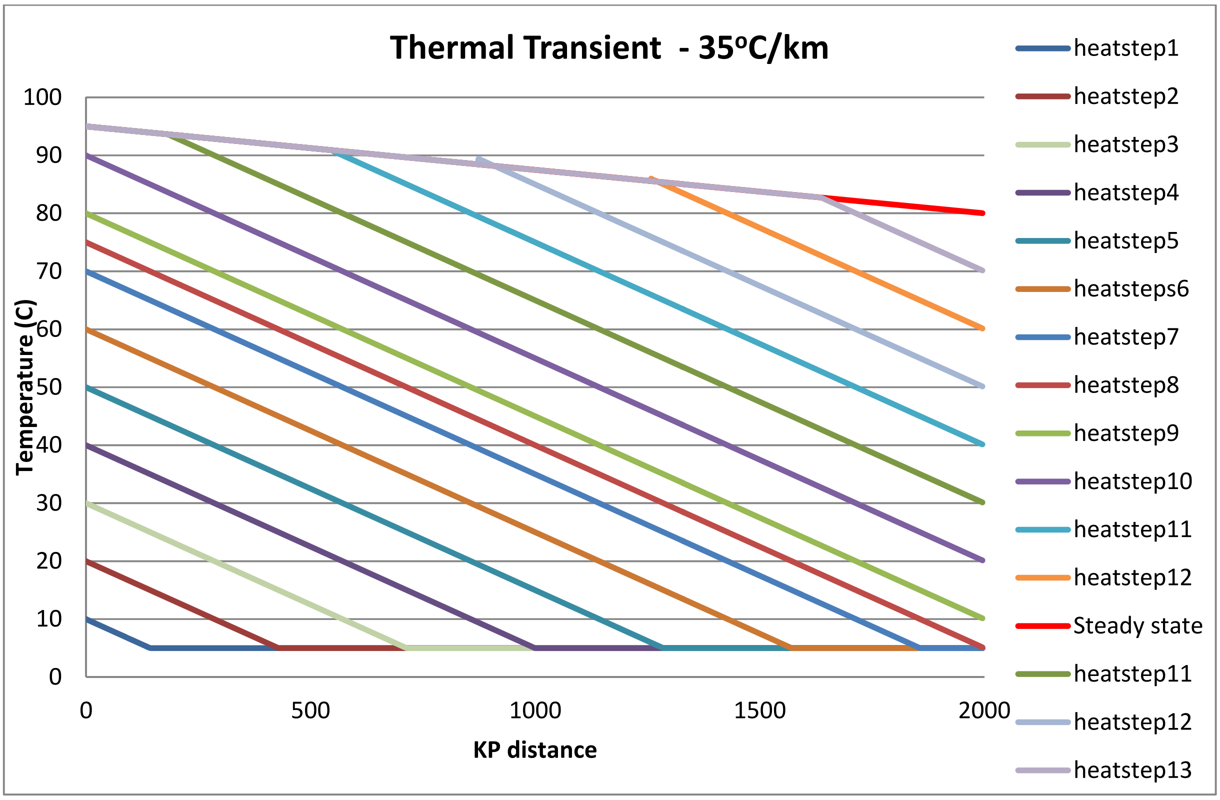


Figure 8-14: Thermal transient at 35ºC/km

When the 2km flowline is subjected to the above heating steps, it experiences a non-uniform expansion due to the distribution of the hot fluid from the hot end. The region of the pipe close to the hot end expands from the center of virtual anchors that are formed along the center pipeline at each heating step, while the rest of the pipeline remains cold approximately at the ambient temperature. Due to this reason, non-uniform heating along the pipeline induces walking.

Figure 8-15 presents the results for axial displacement prior to full mobilization for heat-up steps. From the figure, it is seen that, the displacement at the hot region increases from the heat-step 1 to heat-step 7. But the displacement at the cold region remains to be almost zero.

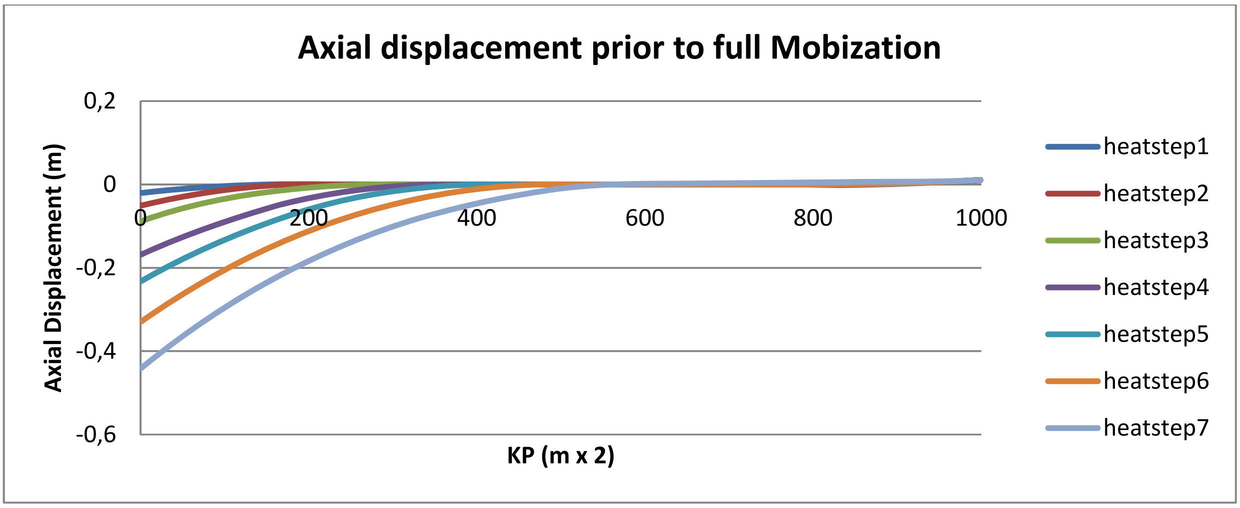


Figure 8-15: Axial displacement prior to full mobilization

When the pipeline approaches heating-step 8, the entire pipeline is heated up and the cold end begins to expand with increase in temperature as seen from the results shown in Figure 8-16:

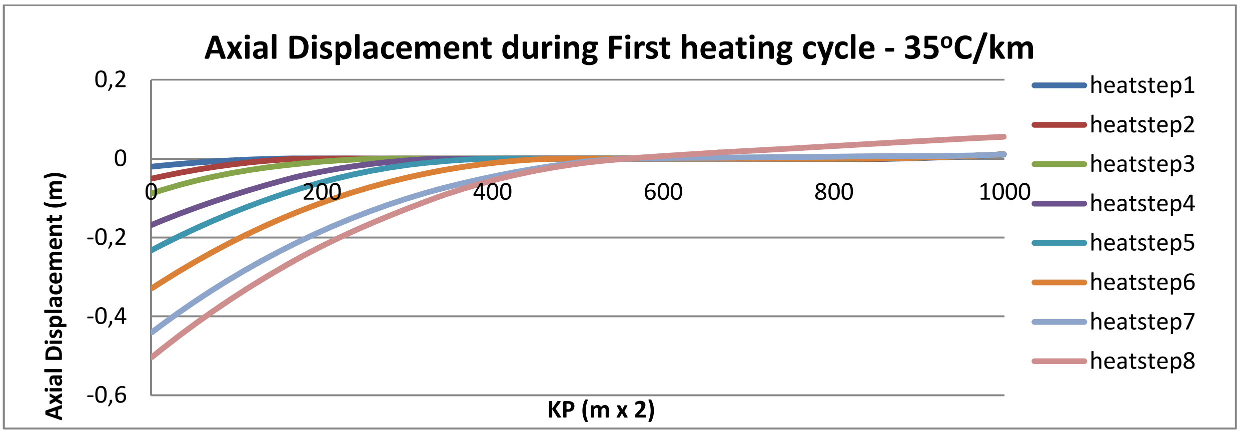


Figure 8-16: Axial displacement at full mobilization

From the results shown Figure 8-17, it is further observed that as heating continues the pipeline experiences expansion at both hot and cold ends and it forms a virtual anchor at the center of the pipeline.

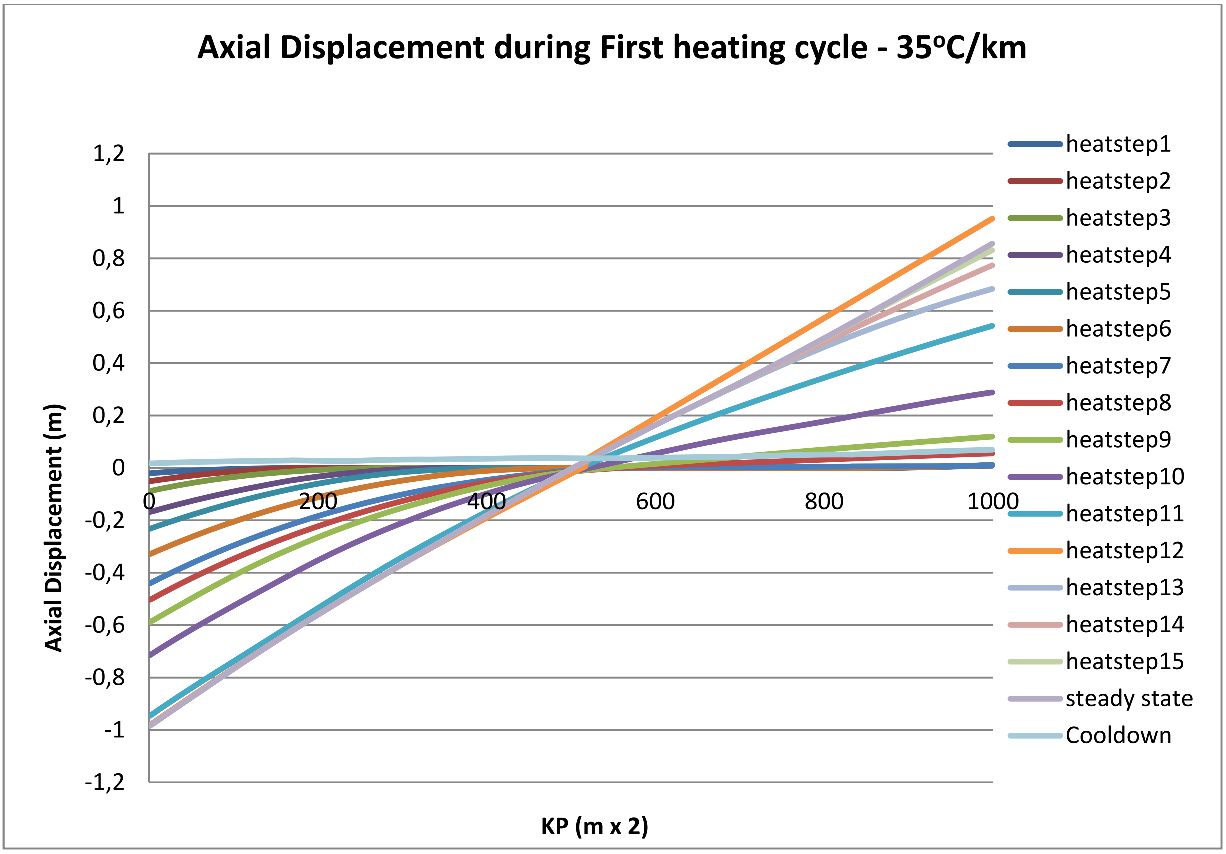


Figure 8-17: Axial Displacement during the First heating cycle

From the above mentioned analyses, the predicted axial displacements are summarized below in Table 8-12 for the case of upper bound (UB) friction coefficient.

Table 8-12: Rate of walking for several cycles

Axial Friction Factor	Thermal gradient [°C/km]	Cycles	Displacement [m]	Cumulative displacement (mm)
UB	35	1	0.0724	-
UB	35	2	0.1318	59.40
UB	35	3	0.2104	78.50
UB	35	4	0.2686	58.20
UB	35	5	0.3402	71.50
UB	35	6	0.3988	58.50

Operational Implication: Assuming that the pipeline is subjected to a total of 100 full shut-down and start-up cycles over its lifetime, the pipeline would walk axially a total of 6m towards the cold end connection. This scenario could result in a serious damage and a threat to the integrity of the pipeline system which must be mitigated.

Finite element analyses were carried out for different friction coefficients to understand the sensitivity of method of analyses on predicted results when compared from analytical calculations. Table 8-13 compared the results obtained from both analytical calculations and FE analyses.

Table 8-13: Results from FE Analyses and Analytical Calculation for Different Axial Frictions.

Methods	Axial Friction	Walking displacement (mm)
Analytical	UB	40
FE analysis	UB	59
Analytical	BE	44
FE analysis	BE	60.4
Analytical	LB	51
FE analysis	LB	106.3

As was concluded by (Carr et al., 2006), the above results confirms that the walking phenomenon is dependent on the axial frictional force.

8.4.3 Effect of Thermal Gradient on Pipeline Walking

Several authors have analyzed the pipeline walking mechanism based on its causing effect and the operational assumptions. One of the factors is the effect of the axial frictional force as was confirmed in the previous discussion. As explained by (Carr et al., 2006), the causing effect of pipeline walking in short pipelines could be one of the following:

- Tension at the end of the flowline tied to an SCR;
- Seabed slope;
- Thermal gradient along the pipeline.

In this thesis work, the effect of thermal gradient has been considered by modeling a 2km short pipeline which is susceptible to walking based on SAFEBUCK guidelines. The study is based on the two thermal gradients of 35°C/km and 20°C/km with the same 2km length as shown in Figure 8-18:

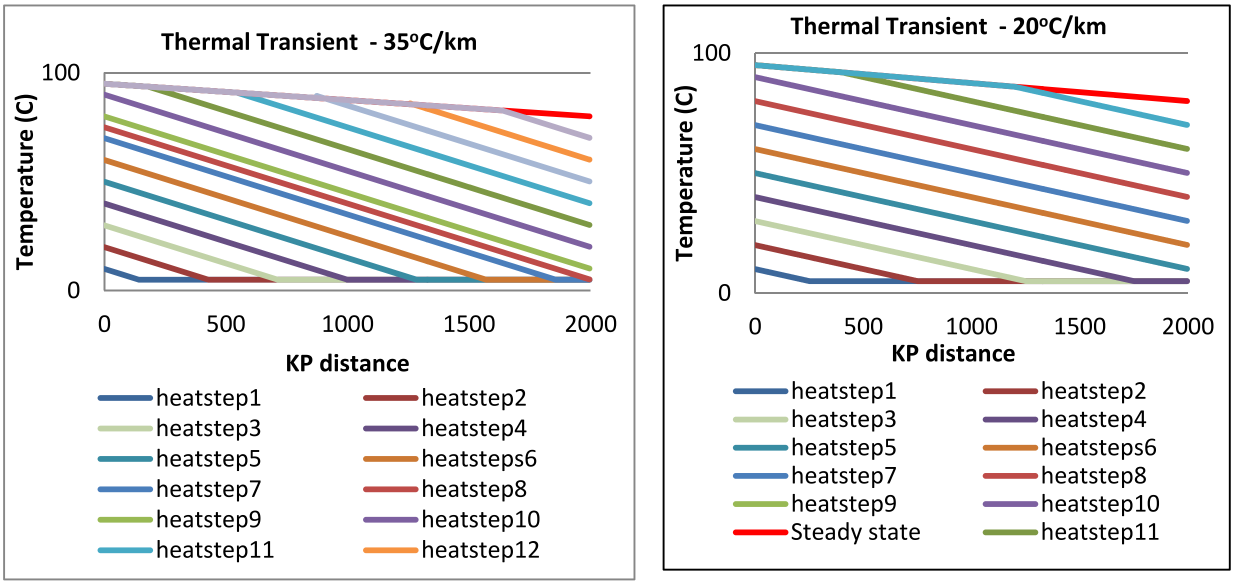


Figure 8-18: Thermal gradient showing two different Scenarios (35°C/km and 20°C/km)

From the heating profiles presented above in Figure 8-18, it is evident that the steeper profile of 35°C/km induces more heating steps (8 heating steps) before reaching the end of the pipeline compared to the five (5) heating steps induced by the 20°C/km thermal gradient.

The steepness is a function of temperature change since the steeper the gradient the faster the temperature is transferred towards the downstream of the pipeline. Irrespective of the temperature profile, this is a dominating effect as seen in the above plots.

From the result of the finite element analyses for the two thermal gradients, the predicted axial displacements prior to full mobilization are shown in Figure 8-19.

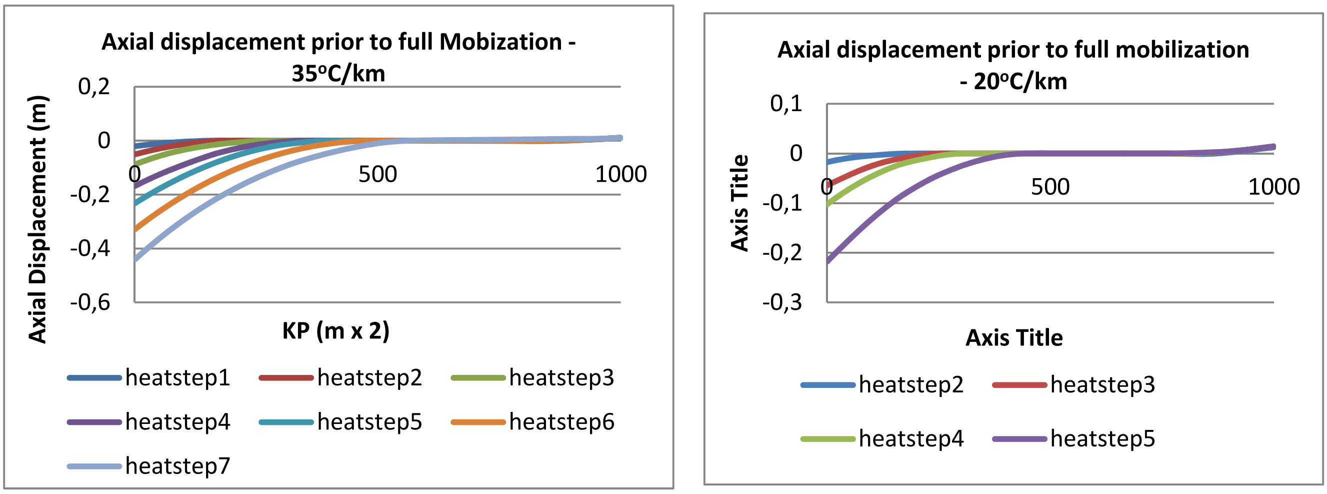


Figure 8-19: Axial displacement for prior to full mobilization for two different thermal gradient

The two cases were subjected to the same temperature with increasing 10°C in each heating step down the pipe length. At 70°C and heating step 8, the 35°C/km case attained full mobilization while at 50°C and heating step 5 the 20°C/km attained full mobilization.

As shown in the Figure 8-19, the hot end of the 35°C/km case expansion of about 0.45m before reaching full mobilization while the case of 20°C/km shows expansion of about 0.23m at full mobilization. This concludes that the case of 20°C/km reaches full mobilization earlier than the case of 35°C/km at the same temperature. Once full mobilization is reached, to attain steady state, the case of 35°C/km requires another 8 heating steps to attain to steady state temperature while the case of 20°C/km requires only 6 heating steps. This is as shown in Figure 8-20.

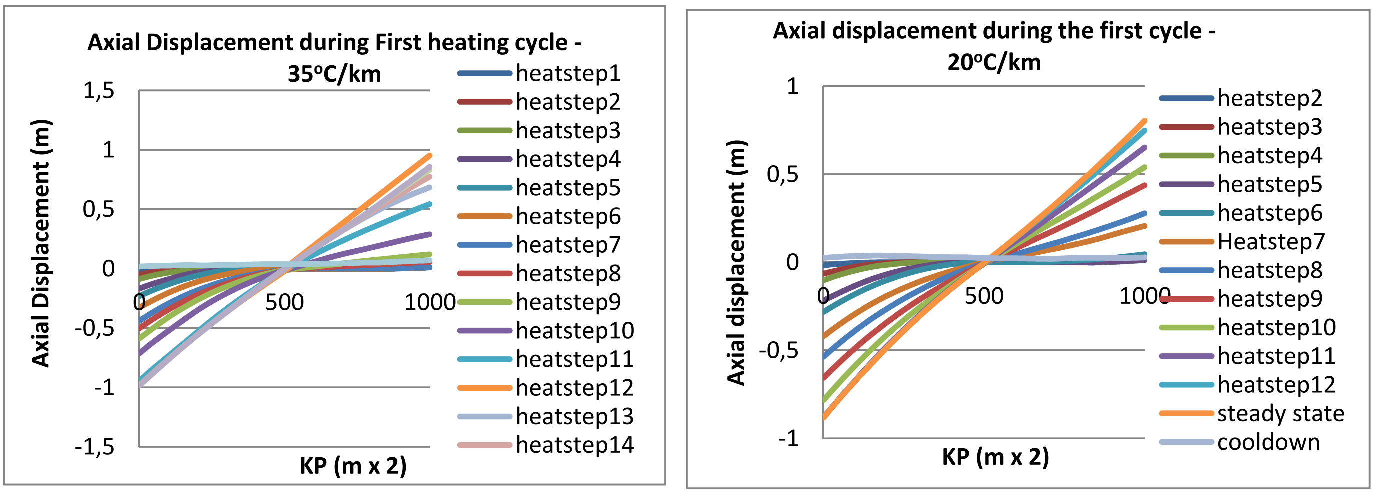


Figure 8-20: Axial displacement of the two cases after full mobilization.

As a result of the enormous amount of heat induced on the pipeline prior to full mobilization by the 35°C/km gradient, over shutdown/cooling cycles, the pipeline axial walking towards the cold end is more than the walking from the case of 20°C/km as seen in Figure 8-21. This can also restated that the heating that results in walking phenomenon is mostly the heating steps prior to full mobilization stage.

The case of 20°C/km requires 5 heating steps and yields walking of 39.5mm while the case of 35°C/km requires 8 heating steps and yields walking of 59mm.

The cumulative displacements obtained from the two cases are shown Figure 8-21:

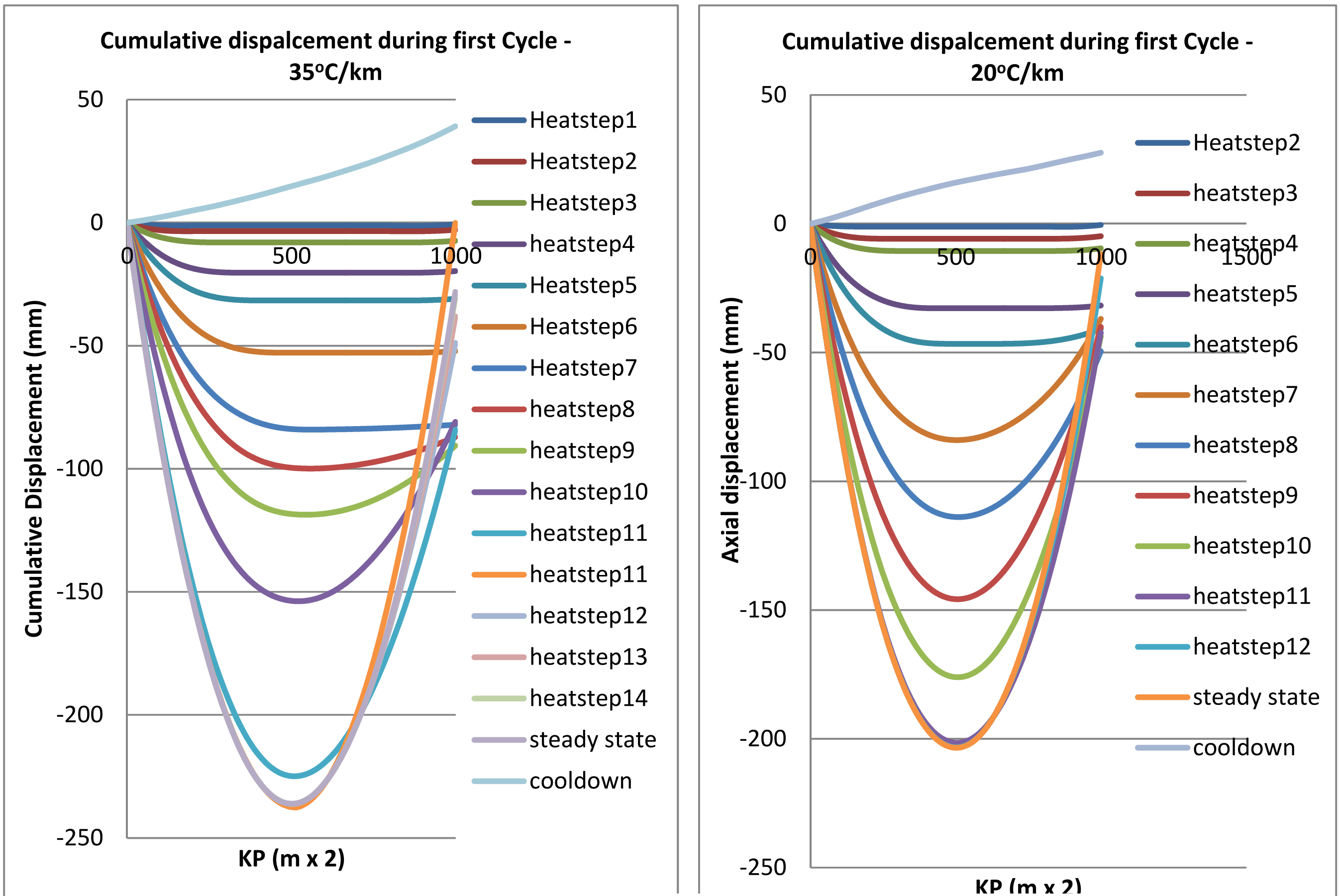


Figure 8-21: Cumulative displacement for 35°C/km and 20°C/km

From Figure 8-21, the full curvature shows the attainment of full mobilization and also shows that it took enormous heating for the 35°C/km gradient to reach full mobilization. Because of the asymmetric expansion from the heating steps prior to full mobilization, the 35°C/km gradient induces an axial movement giving rise to **59mm** pipe movement towards the cold end while the 20°C/km gradient gives **39.5mm** pipe movement after the cooling step as shown above Figure 8-21. Once full mobilization is attained, the walking stops and the middle section remains fixed as noticed in Figure 8-20.

8.4.4 Operational Effect of Walking due to Thermal Gradient

As stated previously, assuming that the pipeline is subjected to a total of 100 full shut-down and start-up cycles over its lifetime, the pipeline for the case 35°C/km gradient would walk axially to about **6m** towards the cold end connection, while that for the case of 20°C/km gradient would walk axially to about 4m towards the cold end for the same star-up and shut-down cycles.

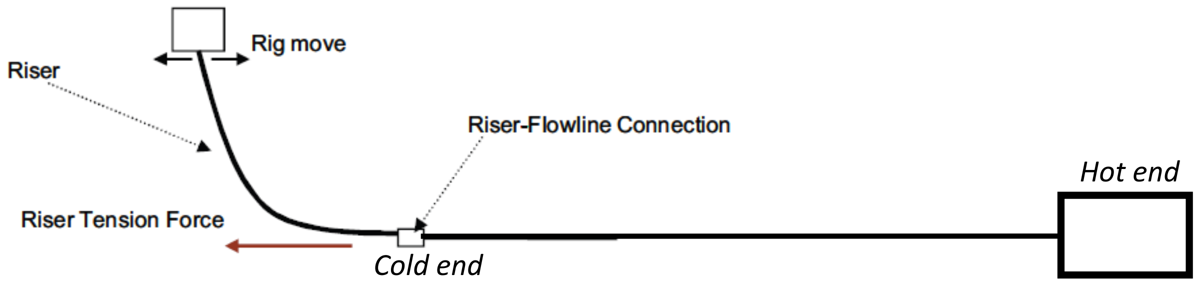


Figure 8-22: Effect of walking due to thermal gradient in SCR

This effect could appear to be little in millimeters but for the lifetime of the field, the accumulation of this axial displacement will become excessive and disastrous to the end connections like SCR as illustrated Figure 8-22.

Since higher thermal gradient means more walking per cycle, then the thermal gradient should be reduced in order to reduce the rate of walking.

To reduce thermal gradient such that the rate of walking be reduced, a gradual warming of the pipeline is required possibly to achieve some extent of uniform heating before reaching full mobilization.

8.4.5 Control of Walking Phenomenon by Direct Electric Heating (DEH)

Direct electric heating (DEH) is the method direct heating of pipe through the use of electric cables strapped onto the pipeline. The heat is generated by applied AC current from a power supply located on a topside platform (see Figure 8-23).

DEH system has been used for several flow assurance problems in controlling hydrate formation mostly in multiphase flows in pipeline by maintaining fluid temperature above the hydrate formation temperature during shutdowns.

This is normally done by increasing the temperature from ambient to above hydrate formation temperature.

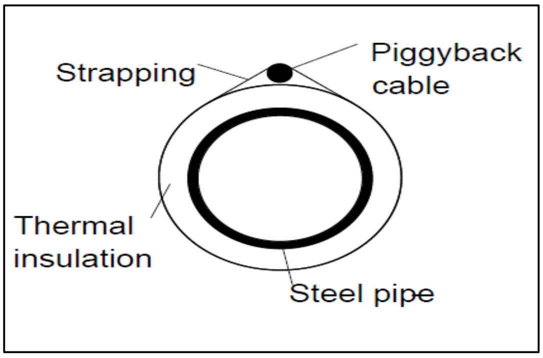


Figure 8-23: Direct Electric heating of pipeline cross-section (Harald, 2008)

Hypothesis:

Gradual warming of cold section of short pipeline reduces the effect of thermal gradient in pipeline axial walking such that some extent of uniform heating is achieved prior to full mobilization.

Task:

In order to use this measure as a means of controlling axial accumulation (walking), investigations with FE analysis is carried out to determine the difference it yields by gradual warming of the pipeline cold end section prior to start-ups and shutdowns.

Conditions:

Same thermal gradient of 35^{o}C/km and the same heating steps are maintained. The cold end is heated from 5^{o}C ambient to a temperature of 20^{o}C using direct electric heating (DEH) during the start-up and shut down by allowing the tail end of heating steps to heat to 20^{o}C until full mobilization.

This is shown in the heating profile in Figure 8-24:

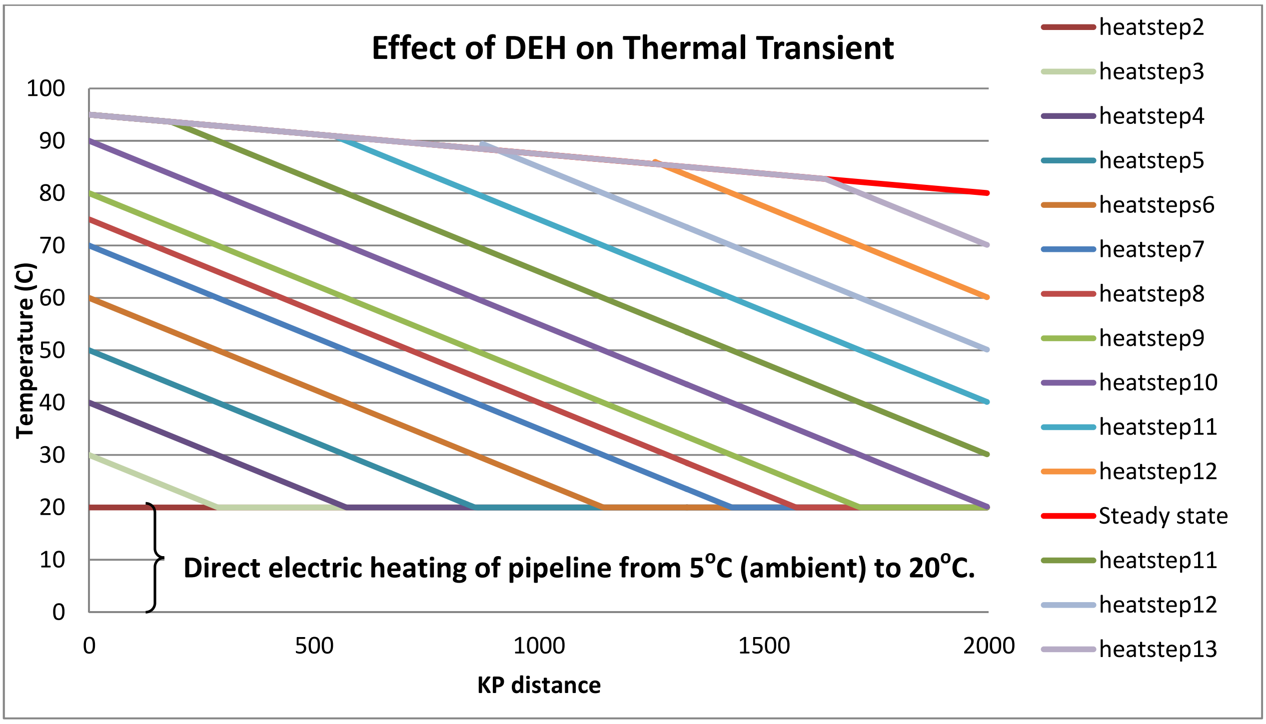


Figure 8-24: Effect of DEH on thermal transient

Process: The pipeline is initially heated to 20^{o}C by the DEH and the heating step maintains 20^{o}C at the cold end as shown in Figure 8-24.

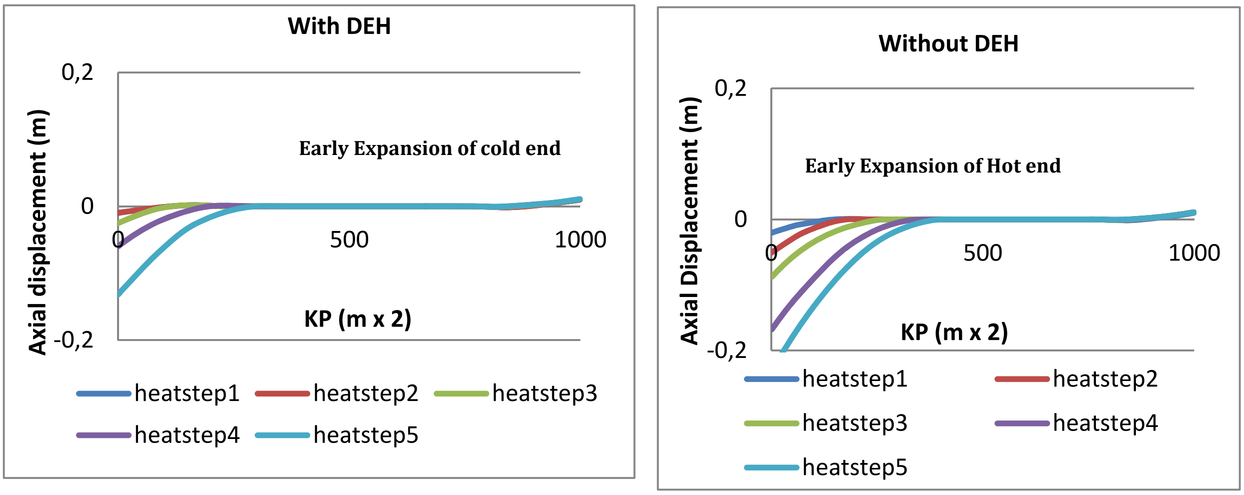


Figure 8-25: Axial displacement for both DEH and normal heating step

The results from see Figure 8-26 shows that prior to full mobilization, the pipeline with direct electric heating along the pipeline expands at both hot end and cold ends while the other does not remain cold but moves axially towards the cold end.

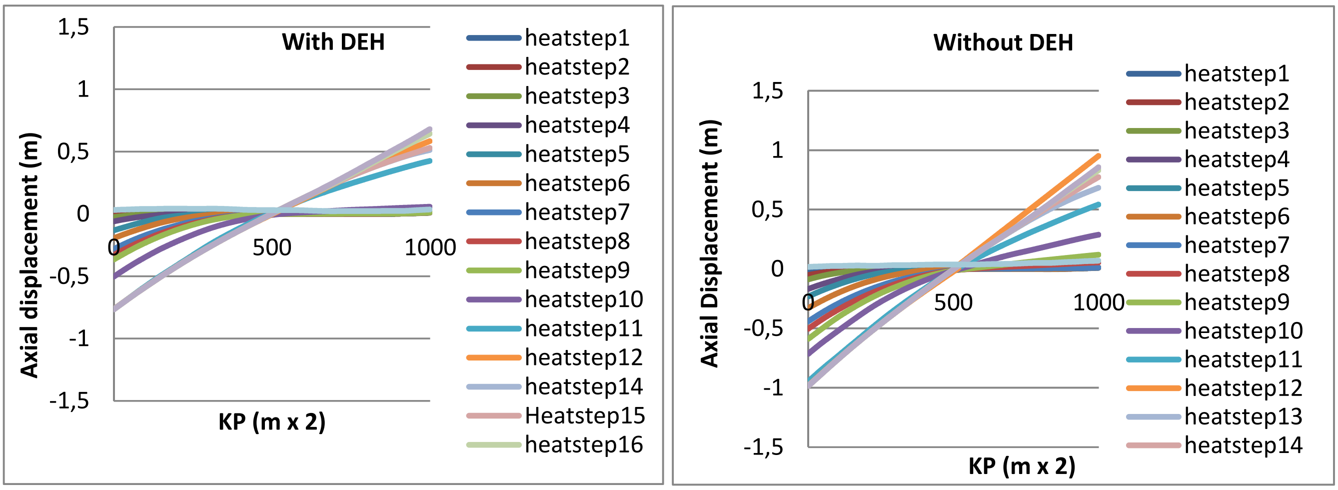


Figure 8-26: Axial displacement for heating with DEH and without DEH

It is evident from Figure 8-26, that the heating steps with DEH after full mobilization are almost the same values as compared to the one without DEH. This shows that walking happens at the heat-up sections and not after full mobilization. Hence, DEH reduces the walking by gradual warming to uniform temperature of 20^{o}C and the results are presented in Table 8-14:

Table 8-14: Results for both cases

	With DEH	Without DEH
Rate of walking (mm)	40	59.2
Thermal gradient (^{o}C/km)	35	35

8.4.6 Challenges facing the use of DEH

There are challenges with welcome development in the use of direct electric heating method as a means of reducing the effect of walking in short pipelines.

Advantages in the use of DEH:

Direct electric heating system (DEH) has been utilized in subsea operations largely in the control of flow assurance in multiphase flows in the pipeline. The use of the DEH in short flowline where pipeline walking are mostly encountered will be of good help in reducing walking and at the same using the mechanism to reduce hydrate formation within the pipeline.

The heating required from the DEH is only during the start-up and shutdown section and hence it does not yield much operational cost once installed.

There will be need of installing the conventional heavy anchors if it could be designed to reduce the walking as low as possible.

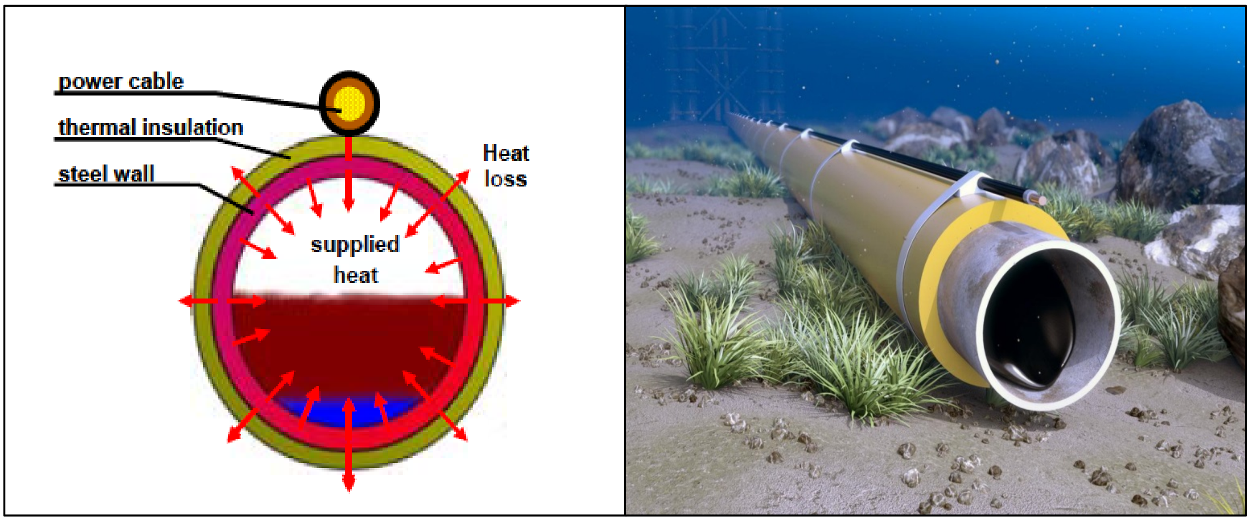


Figure 8-27: Direct Electric heating – DEH (Harald, 2008)

Possible Negative impact :

Trawls gear/pulling on the cable. The DEH system can be expensive to install or operate.

9. Conclusions, Recommendations and Further Work

9.1 Summary and Conclusions

Lateral Buckling and Snake Lay Configuration

The design of 10km rigid pipeline for lateral buckling was carried out in accordance with the design standards, DNV-RP-F110 and SAFEBUCK guidelines. The pipeline was assessed to be susceptible to lateral buckling based on the calculations from Hobbs Analytical method and out-of-straightness force. Based on these calculations, the region prone to buckle was identified and the maximum allowable feed-in was deduced based on allowable design strain from the local buckling criterion for displacement controlled condition. The results were checked such that the predicted feed-in lengths are within the maximum allowable limits.

Having obtained the allowable design strain of 0.4% and post buckling force from the FE analyses for a given lay radius, the number of snakes required for sharing the expansion under thermal and pressure loading were established based on expansion sharing methodology given in DNV-RP-F110. The feed-in is distributed among **seven** snakes such that the predicted feed-in lengths are not exceeded the allowable values and expansion at the ends are reduced.

Table 9-1: Expansion Result

End Expansion- 10km Pipeline		
	Hot-end	**Cold-end**
Before Snake lay	1.96m	0.96m
After snake-lay	0.80	0.6

The combination of snake lay and rock dumping in expansion sharing is a way of building up effective force such that the critical buckling force will not be exceeded for any pipeline to laterally buckle under the action thermal and pressure loading.

From the sensitivity analyses, it is deduced that the axial friction, initial imperfection, lay radius and the buckle wavelength are important factors that influence the amount feed-in into a buckle.

Reducing the initial imperfection is a function of the available corridor of operation for the project and increases the lay radius required for expansion sharing. The cost of laying several snakes with longer radius and rock dumping is relatively less compared to laying more snakes with smaller radius without rock dumping.

This is because lay barge takes longer time for negotiating a smaller bend radius than for a larger radius.

Increasing the buckle length from 160m (R1500m) to 200m (R2500m) resulted in less initial imperfection. From the analyses for the selected pipeline, this radius (R2500m) gives less feed-in compared to the initial radius ((R1500m) but with rock dumping at only the hot-end.

Pipeline Walking

Pipeline walking has been studied in greater depth by SAFEBUCK JIP and a number of deductions were generated. In the present thesis work, the influence of thermal gradient on pipeline axial walking has been studied. FE analyses were performed for the selected pipeline considering the two cases of thermal gradients. The predictions from the two cases are compared and discussed with respect to the rate of pipeline walking toward cold end.

The calculations using the analytical method based on SAFEBUCK guidelines were performed and compared against the predictions from FE analyses. Based on the results, it can be confirmed that analytical relations do not give an accurate estimation of rate of walking, but can be used as basis for preliminary assessment whether to perform an FE analysis.

Reason for discrepancy between analytical and FE results being that the analytical relations are based on certain assumptions which cannot be generalized for all pipeline operation cases.

Findings:

- The critical buckling force at lower bound friction has been seen as better basis for pipeline buckling design such that where the pipe-soil interaction are not properly estimated, the system will still be able to withstand the worst case effect in any failure mode.
- Use of post-lay rock dumping with large lay radius for expansion sharing has been seen as a better means of lateral buckling control measure. This is especially where the operational corridor is smaller such that the distance between successive buckles are less than the total buckle length.
- Pre-warming the pipeline system is a greater way of reducing the effect of thermal gradient on short pipeline before reaching full mobilization.
- Use of di-electric heating (DEH) of the short pipeline before operational start could assist in reducing thermal gradient along the pipeline.

9.2 Recommendations

As a result of the uncertainties surrounding pipe-soil interactions, most long pipelines are found to be susceptible to lateral buckling. Excessive build-up of effective axial force by the frictional force from the soils and the extreme high pressure and high temperature (XHPHT) have been a major driving factor as we drill deep for more oil and gas.

Moreover, the need to maintain the temperature and pressure of the well effluent in order to avoid the flow assurance issues has made the solution more critical. Hence, pipelines are allowed to move laterally at will provided that the integrity of the pipe is not jeopardized.

Allowing the pipeline to move laterally without restriction by the use of snake lay configuration is a great way of sharing expansion such that the total allowable feed-in is distributed among the snakes generated by the configuration applied.

In order to reduce the cost of lay barge which cost more in negotiating a smaller bend radius, longer lay radius with post-lay rock dumping can be applied thereby reducing the operational corridor which could act adversely in case of unforeseen lateral movement of the pipeline.

Axial accumulation at the cold end can be so disastrous if allowed to go on till the life of the system and it should be mitigated. Pre-warming the pipeline system is a greater way of reducing the effect of thermal gradient on short pipeline before reaching full mobilization.

The thermal gradient of pipeline installation should always be determined and the effect calculated based on the axial frictional forces so that the effect can be reduced or the pipeline re-routed to ensure safety of the connecting ends.

9.3 Further Work

As mentioned above, there are uncertainties hidden on the pipe-soil interaction which was evident on the results from the post buckling force at different soil frictions. A study should be carried out to generate a better way of deducing a better approximation of the pipe-soil movement with respect to temperature profile at extreme well pressures.

The use of di-electric heating (DEH) with pipe-in-pipe system c considered as a way of reducing the effect of thermal gradient along short pipeline such that the accumulation of the axial displacement is greatly reduced over the life of the field.

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APPENDIX A: CALCULATION RESULTS

APPENDIX A

APPENDIX A1

PIPELINE END EXPANSION

Pipeline End Expansion Calculations

Master Thesis: Lateral Buckling and Axial Walking of Surface Laid Subsea Pipeline
MSc Subsea Technology, University of Stavanger, Norway

Date : 8 March, 2013
Author : Obele Ifenna

Description :
The Mathcad analysis worksheet presented in this report is used for Pipeline end expansion calculation of a rigid pipeline under thermal and pressure loading. The purpose is to deduce the maximum expansion that an end connection can take during maximum loading. The Calculations are based on Subsea 7 Pipeline expansion guideline: CEO1PD-P-GU-126 and DNV-OS-F101

Limitation:
Pipeline Susceptibility to lateral buckling and walking are not considered at this stage.

Units: $MPa \equiv 1N \cdot mm^{-2}$ $g \equiv 9.81 \cdot m \cdot s^{-2}$ $MN \equiv 1 \times 10^6 N$

Pipeline Data:

Pipeline Outside Diamter $D_o := 559mm$

Wall Thickness $t_{wall} := 19.1mm$

External Coating Thickness $t_{ext.coat} := 5mm$

Concrete Coating Thickness $t_{conc} := 55mm$

Length of Pipeline $L := 2000m$

Material Properties:
Pipeline:

Pipe Steel Density $\rho_{st} := 7850kg \cdot m^{-3}$

SMYS Steel Pipe $SMYS := 450MPa$

Steel young's Modulus $E := 2.07 \cdot 10^5 MPa$

Steel Pipe Thermal Expansion Coefficient $\alpha := 1.17 \cdot 10^{-5} \cdot C^{-1}$

Steel Poisson Ratio $\nu := 0.3$

Insulation or Coating:

Insulation or Coating Density $\rho_{inscoat} := 910kg \cdot m^{-3}$

Concrete Coating Density $\rho_{conc} := 2400.kg \cdot m^{-3}$

Operating Parameters:

Sea Water Density $\rho_{water} := 1027kg \cdot m^{-3}$

Max Content Density $\rho_{cont} := 900kg \cdot m^{-3}$

Design Pressure $P_d := 15MPa$

Operating Pressure $P_{op} := 15MPa$

Hydrotest Pressure $P_{hyd} := 0MPa$

Sea water Ambient Temperature $T_{amb} := 5 \cdot C$

Operating Temperature $T_{op} := 95 \cdot C$

External Loads:

Bending moment $M_b := 0kN \cdot m$

Axial Force $N_a := 0kN$

Residual Lay Tension $N_{lay} := 0kN$

Soil Properties:

Axial Friction Factor $\mu_{axial} := 0.5$

Lateral Friction Factor $\mu_{lateral} := 0.8$

Safety Factors:

Usage Factor for Hoop stress $\beta_h := 0.72$

Usage Factor for Longitudinal stress $\beta_L := 0.8$

Parameter Calculations:

Internal Diameter $D_{in} := D_o - 2 \cdot t_{wall}$

Effective Pipe Diameter $D_{eff} := D_o + 2 \cdot \left(t_{ext.coat} + t_{conc}\right)$

Cross-sectional Area of Steel Pipe $A_s := \frac{\pi}{4} \cdot \left(\left(D_o^2 - D_{in}^2\right)\right)$

Cross-sectional Area of external coating $A_{ext} := \frac{\pi}{4} \cdot \left[\left[\left(D_o + 2 \cdot t_{ext.coat}\right)^2 - D_o^2\right]\right]$

Cross-sectional Area of Concrete coating $A_{conc} := \frac{\pi}{4} \cdot \left[\left[\left(D_o + 2 \cdot t_{ext.coat} + 2 \cdot t_{conc}\right)^2 - \left(D_o + 2 \cdot t_{ext.coat}\right)^2\right]\right]$

Mass of Steel Pipe $M_{st} := A_s \cdot \rho_{st}$

Mass of External coating $M_{ext.coat} := A_{ext} \cdot \rho_{inscoat}$

Mass of concrete coating $M_{conc} := A_{conc} \cdot \rho_{conc}$

Mass of Content $M_{cont} := \frac{\pi}{4} \cdot D_{in}^2 \cdot \rho_{cont}$

Mass of water Content $M_{water} := \frac{\pi}{4} \cdot D_{in}^2 \cdot \rho_{water}$

Mass in water (Bouyancy Mass) $M_{bouyancy} := \frac{\pi}{4} \cdot D_{eff}^2 \cdot \rho_{water}$

Total Mass in air $M_{air} := M_{st} + M_{conc} + M_{ext.coat}$

Submerged Mass $M_{submerged} := M_{air} - M_{bouyancy}$

Weight of Dry Pipe $W_{dry} := M_{air} \cdot g$

Weight of Content $W_{cont} := M_{cont} \cdot g$

Weight of Submerged Pipe $W_{submerged} := M_{cont} \cdot g + M_{ext.coat} \cdot g + M_{st} \cdot g + M_{conc} \cdot g - M_{bouyancy} \cdot g$

$$W_{submerged} = 3.345 \frac{1}{m} \cdot kN$$

Temperature Difference $\Delta T := T_{op} - T_{amb}$

Moment of Inertia of Steel Pipe cross section $I_s := \frac{\pi}{4} \cdot \left(D_o^{\,4} - D_{in}^{\,4}\right)$

Sectional Modulus of Steel Pipe $Z_s := \frac{I_s}{\frac{D_o}{2}}$

EFFECTIVE AXIAL FORCE CALCULATION

1. 559 x 19.1mm PIPE OF 2km Pipe Length

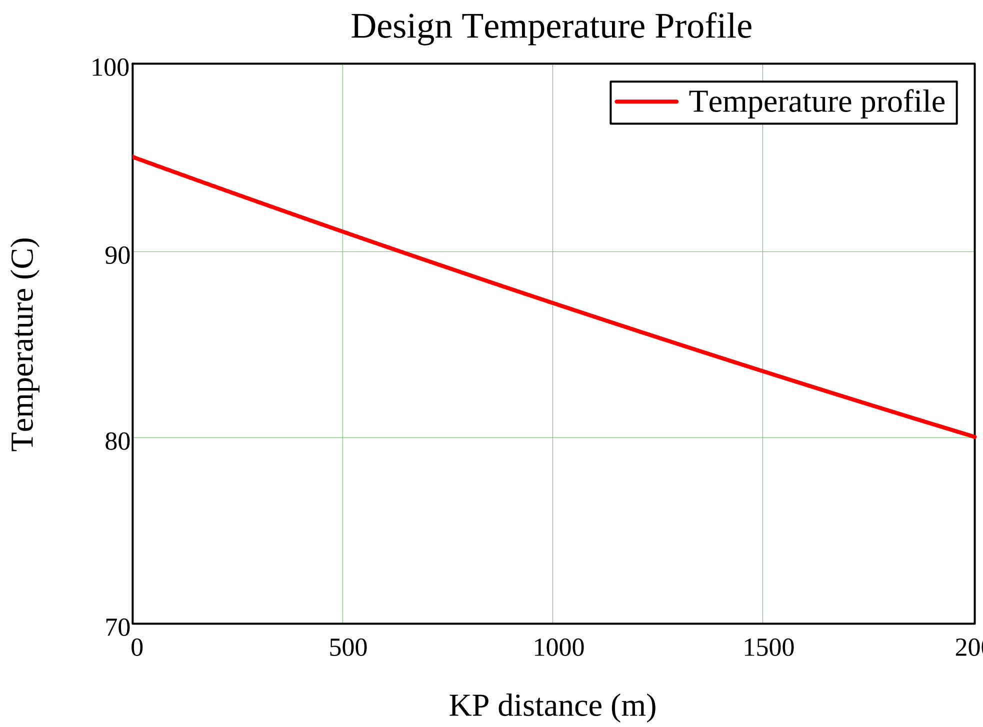
$n := 6$ $Kp_0 := 0m$ $KP_{step} := 100m$ $k := 0..2000$

$Kp_{n-1} := 2000m$

$T_k := (5C) + (90C) \cdot e^{-0.0000911607 \cdot k}$

$x := Kp_0, KP_{step}..Kp_{n-1}$

$x_k := k \cdot 1m$



Water depth

$$WD := \begin{pmatrix} 800m \\ 800m \end{pmatrix}$$

$$KPw := \begin{pmatrix} 0km \\ 2km \end{pmatrix}$$

$$WD(k) := \mathrm{linterp}(KPw, WD, x_k)$$

External Pressure $$P_o(k) := \rho_{water} \cdot g \cdot WD(k)$$

Internal Pressure $$P_{in}(k) := P_{op} + \rho_{cont} \cdot g \cdot WD(k)$$

Pressure Difference with KP $$\Delta P(k) := P_{in}(k) - P_o(k)$$

Thermal Force $$N_{thermal}(k) := -E \cdot A_s \cdot \alpha \cdot T_k$$

Poisson Effect Force $$N_{poisson}(k) := \left[\nu \cdot \Delta P(k) \cdot A_s \cdot \frac{(D_o - t_{wall})}{2t_{wall}}\right]$$

End Cap Force $$N_{Endcap}(k) := \frac{\pi}{4} \cdot \left[(P_{in}(k)) \cdot D_{in}^2 - (P_o(k)) \cdot D_o^2\right]$$

Effective Axial Force with KP $$N_{eff}(k) := N_{lay} - N_{Endcap}(k) + N_{poisson}(k) + N_{thermal}(k)$$

$$F_{anchor} := \pi \cdot D_{in} \cdot t_{wall} \cdot \alpha \cdot E \cdot (T_{op} - T_{amb}) + \left[(1 - 2\nu) \frac{P_{op} \cdot \pi \cdot D_{in}^2}{4}\right]$$ $$F_{anchor} = 8.09 \cdot MN$$

Restraining Force: $$F_{friction} := \mu_{axial} \cdot (W_{submerged}) \cdot 1m$$

$$W_{submerged} = 3.345 \times 10^3 \frac{1}{m} \cdot N$$ $$F_{friction} = 1.673 \times 10^3 N$$

$$L_{anchor} := \frac{F_{anchor}}{\left[\mu_{axial} \cdot (W_{submerged})\right]}$$ $$L_{anchor} = 4.837 \cdot km$$

Since the Restraining Force (Friction Force) cannot attain the Fully constraint Axial Force (Anchoring Force), then pipeline is termed a **Short Pipeline (fully mobilised)**

Short Pipeline: Pipeline which will never develop the full constrain force

Effective Axial Force - Fully mobilized Pipeline

Maximum Friction Force at the mid-line:

$$F_{MAXfriction} := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot \frac{L}{2}$$

$$F_{MAXfriction} = 2.613 \times 10^6 N$$

Friction Force with Length at the hot end:

$F_{HOTfriction}(k) := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot x_k \cdot (-1)$

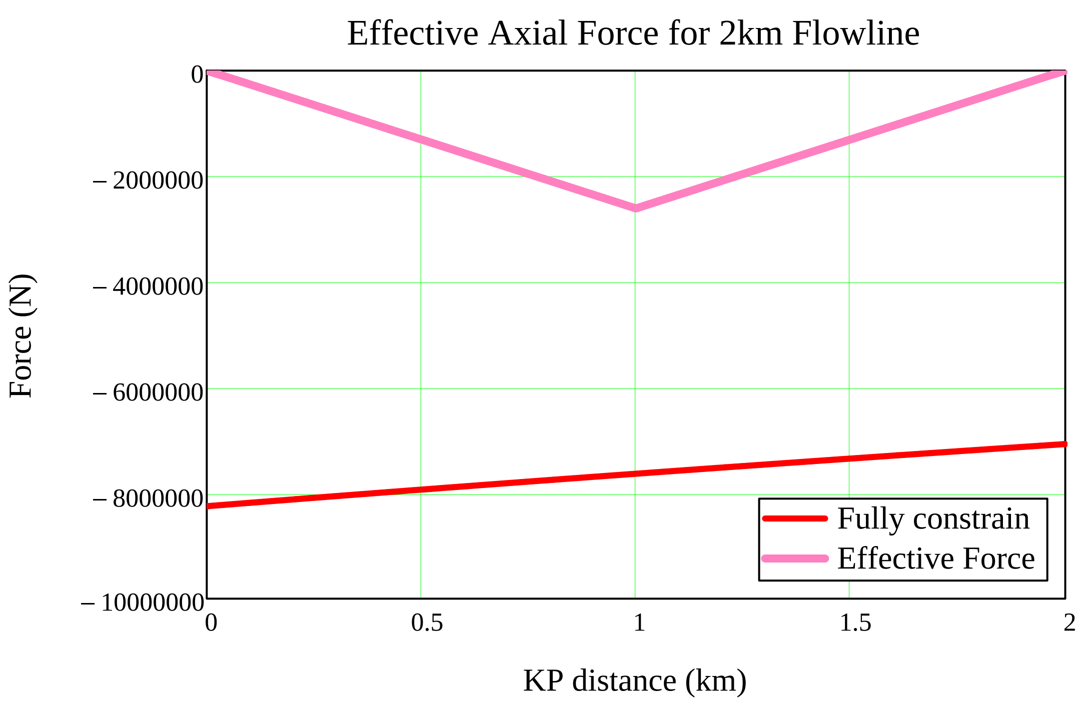
Friction Force with Length at the cold end:

$F_{COLDfriction}(k) := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot (x_k - L)$

The Frictional Restrained Force along the Pipeline full Length:

$$F_{Restfriction}(k) := \text{if}(F_{HOTfriction}(k) > F_{COLDfriction}(k), F_{HOTfriction}(k), F_{COLDfriction}(k))$$

$$N_{effSHORT}(k) := \text{if}(N_{eff}(k) < F_{Restfriction}(k), F_{Restfriction}(k), N_{eff}(k))$$



EFFECTIVE FORCE FOR A 559 x 19.1mm Pipe of 10km Pipelength

$n := 6$

$KP_{Lstep} := 0.001km$

$i := 0 .. n - 1$

$L_{longKpL_{n-1}} := 10km$

$Kp_0 = 0m$

$j := 0, 1 .. 10000$

$x_i := Kp_0, KP_{Lstep} .. L_{longKpL_{n-1}}$

$T_j := (5C) + (90C) \cdot e^{-0.0000492476 \cdot j}$

$x_j := j \cdot 1m$

Water depth

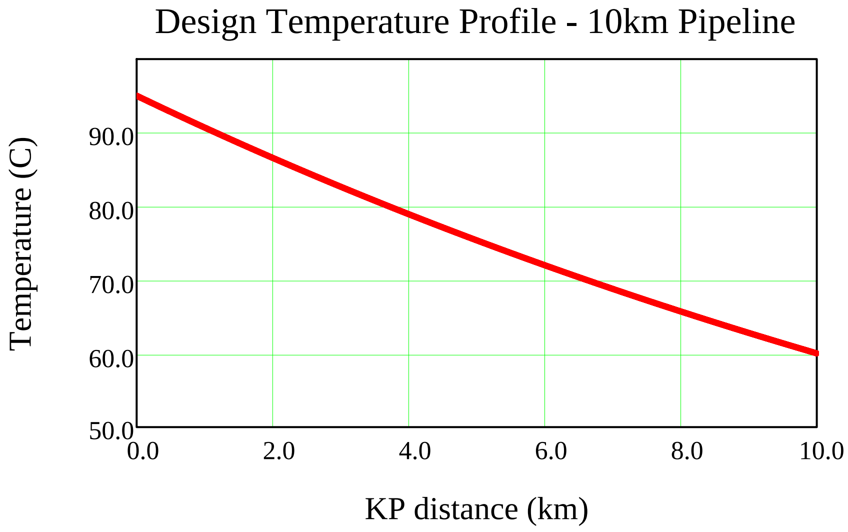
$nw := 2$

$iw := 0 .. nw - 1$

$WDL := \begin{pmatrix} 800m \\ 800m \end{pmatrix}$

$KPLw := \begin{pmatrix} 0km \\ 10km \end{pmatrix}$

$WDL(j) := \text{linterp}(KPLw, WDL, x_j)$



$N_{critical} := -3.010MN$

External Pressure $\quad P_{oL}(j) := \rho_{water} \cdot g \cdot WDL(j)$

Internal Pressure $\quad P_{inL}(j) := P_{op} + \rho_{cont} \cdot g \cdot WDL(j)$

Pressure Difference with KP $\quad \Delta PL(j) := P_{inL}(j) - P_{oL}(j)$

Thermal Force $\quad N_{thermalL_j} := -E \cdot A_s \cdot \alpha \cdot T_j$

Poisson Effect Force

$$N_{poissonL}(j) := \left[\nu \cdot \Delta PL(j) \cdot A_s \cdot \frac{(D_o - t_{wall})}{2t_{wall}}\right]$$

End Cap Force

$$N_{EndcapL}(j) := \frac{\pi}{4} \cdot \left[(P_{inL}(j)) \cdot D_{in}^{\;2} - (P_{oL}(j)) \cdot D_o^{\;2}\right]$$

Effective Axial Force with KP

$$N_{FULL}(j) := N_{lay} - N_{EndcapL}(j) + N_{poissonL}(j) + N_{thermalL_j}$$

Friction Force with Length at the hot end:

$$F_{HOTfrictionL}(j) := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot x_j \cdot (-1)$$

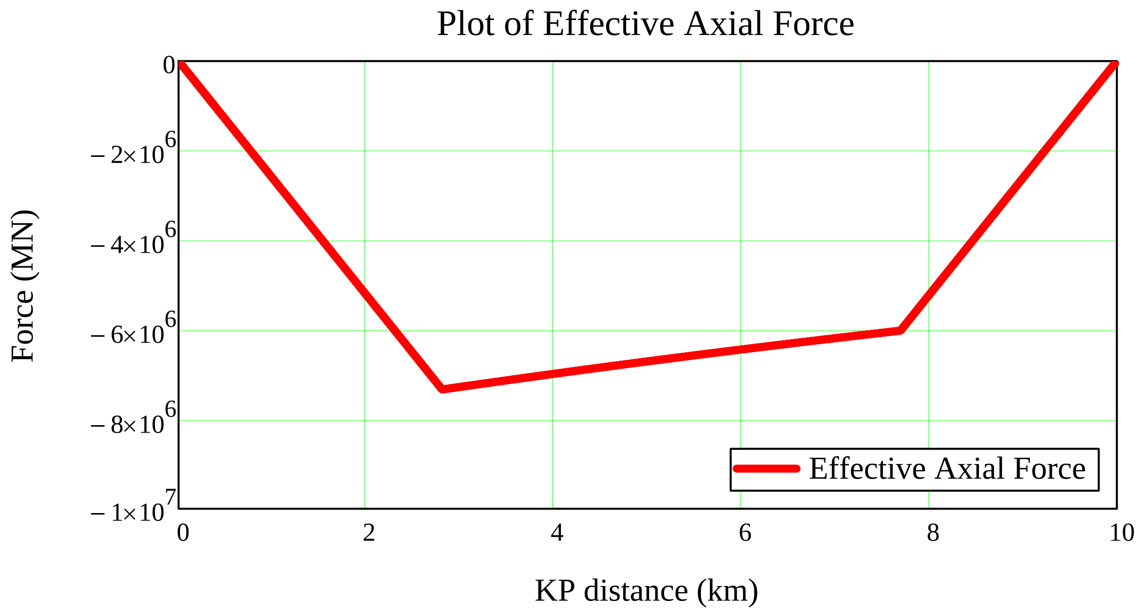
Friction Force with Length at the cold end:

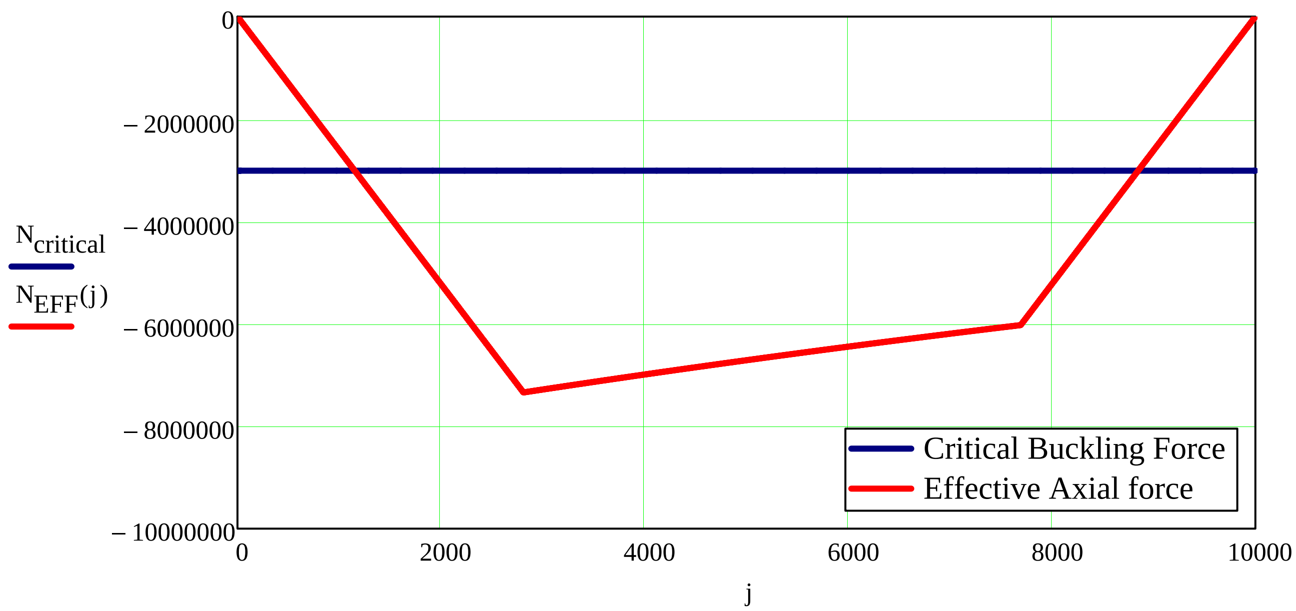
$$F_{COLDfrictionL}(j) := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot (x_j - x_{10000})$$

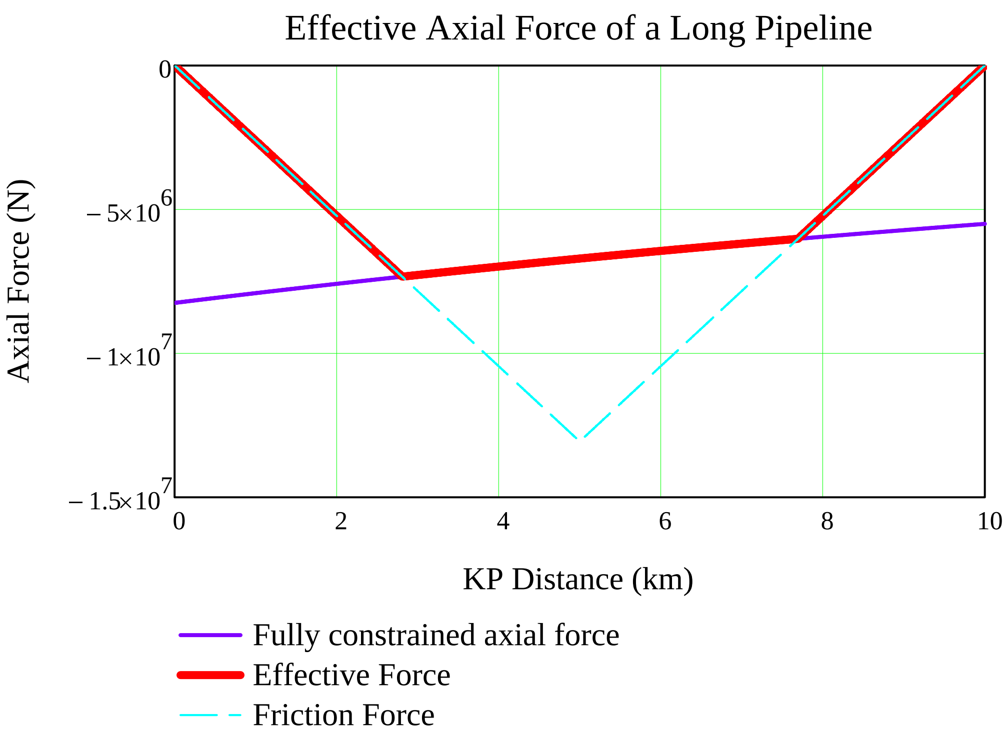
The Frictional Restrained Force along the Pipeline full Length:

$$F_{RestfrictionL}(j) := if(F_{HOTfrictionL}(j) > F_{COLDfrictionL}(j), F_{HOTfrictionL}(j), F_{COLDfrictionL}(j))$$

$$N_{EFF}(j) := \begin{array}{|l} out \leftarrow N_{FULL}(j) \quad if \quad F_{RestfrictionL}(j) < N_{FULL}(j) \\ F_{RestfrictionL}(j) \quad otherwise \end{array}$$







$N_{FULL}(3028) = -7.274 \cdot MN$

$F_{RestfrictionL}(3028) = -7.912 \times 10^{6} N$

$N_{FULL}(7469) = -6.079 \cdot MN$

$F_{RestfrictionL}(7469) = -6.613 \times 10^{6} N$

$VAP_1 := 3272m$

$VAP_2 := 7210m$

VIRTUAL ANCHOR POINT

From the Tables and datas above, it can deduced that the virtual Anchor Point for the Long pipeline where - *Fully Constrained Axial Force Equals the Frictional Force are:*

- **VAP_1 = KP 3.272**
- **VAP_2 = KP 7.210**

Therefore, the anchor Length for the long pipeline are now:

L_anchor (1) = The distance betwen KP_0 and VAP_1

L_anchor (2) = The distance betwen KP_{n-1} and VAP_2

For the Long Pipeline

$L_{anchorHotEnd} := VAP_1 - Kp_0$

Anchor Length at the hot end:

$L_{anchorHotEnd} = 3.272 \cdot km$

$L_{anchorColdEnd} := L_{longKpL_{n-1}} - VAP_2$

Anchor Length at the cold End:

$L_{anchorColdEnd} = 2.79 \cdot km$

For the Short Pipeline

$$F_{anchor} := \pi \cdot D_{in} \cdot t_{wall} \cdot \alpha \cdot E \cdot \left(T_{op} - T_{amb}\right) + \left[(1 - 2\nu) \frac{P_{op} \cdot \pi \cdot D_{in}^{2}}{4}\right] \quad * \qquad F_{anchor} = 8.09 \cdot MN$$

$$F_{friction} := \mu_{axial} \cdot W_{submerged} \qquad F_{friction} = 1.673 \frac{1}{m} \cdot kN$$

$$L_{anchor} := \frac{F_{anchor}}{F_{friction}} \qquad L_{anchor} = 4.837 \cdot km$$

Since the anchor length 6.417km is greater than the length of the pipeline (2km), this is a prove that this is a short Pipeline having insufficient friction to attain the full constrain Axial Force. Hence, it is Fully mobilised.

Total Frictional Force $F_{frictional} := F_{friction} \cdot 1m \qquad F_{frictional} = 1.673 \times 10^{-3} \cdot MN$

END EXPANSION CALCULATION

Based on the **Long Pipeline** analysis, the end expansion can be deduce as the following for each ends:

The Expansion at the Hot end: $$\Delta_{expansionHOT} := \sum_{j=3028}^{0} \frac{\left(N_{FULL}(j) - F_{RestfrictionL}(j)\right) \cdot -1m}{E \cdot A_s}$$

$$\Delta_{expansionHOT} = 1.714\,m$$

The Expansion at the Cold end: $$\Delta_{expansionCOLD} := \sum_{j=10000}^{7469} \frac{\left(N_{FULL}(j) - F_{RestfrictionL}(j)\right) \cdot 1m}{E \cdot A_s}$$

$$\Delta_{expansionCOLD} = -0.936\,m$$

For **Short Pipeline** analysis, the end expansion can be deduce as the following for each ends:

$$\Delta_{expansionHOTshort} := \sum_{k=1000}^{0} \frac{\left(N_{eff}(k) - F_{Restfriction}(k)\right) \cdot -1m}{E \cdot A_s}$$

$$\Delta_{expansionHOTshort} = 0.99\,m$$

$$\Delta_{expansionCOLDshort} := \sum_{k=2000}^{1000} \frac{\left(N_{eff}(k) - F_{Restfriction}(k)\right) \cdot -1m}{E \cdot A_s}$$

$$\Delta_{expansionCOLDshort} = 0.902\,m$$

EXPANSION OFFSET DESIGN

The expansion offset is configured to transfer the expansion displacement into a bending stress, below the code allowable. Typical offset configurations include "L", "U" or "Z" shaped spools.

For an L-shaped spool the bending is idealised as a pinned / fixed cantilever and the allowable stress is taken from the combination of hoop, end-cap and longitudinal (incl. temperature stress):

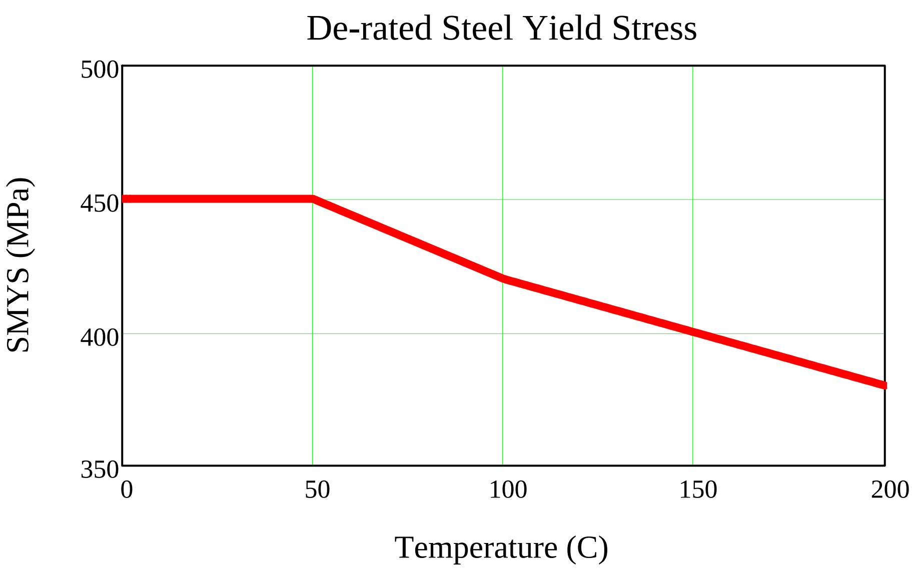
Maximum allowable bending stress: $\delta_{Bending} := \dfrac{F_{anchor}}{A_s}$

The minimum Spool length for an L shaped spool according Subsea7 guideline is given as:

$$L_{min} := \sqrt{\frac{2.25 \cdot E \cdot D_o \cdot \Delta_{expansionHOT}}{\delta_{Bending}}} \qquad L_{min} = 42.275\,m$$

Temperature de-rated steel Yield Stress

$$T_d := 0C, 1C .. 200C \qquad SMYS(T_d) := \begin{cases} SMYS & \text{if } T_d \le 50C \\ SMYS - \left[\left[3\dfrac{(T_d - 50C)}{5}\right] \cdot \dfrac{MPa}{C}\right] & \text{if } 50C < T_d \le 100C \\ SMYS - \left[\left[\dfrac{(T_d - 100C)}{2.5}\right] \cdot \dfrac{MPa}{C} + 30MPa\right] & \text{otherwise} \end{cases}$$



$SMYS(T_{op}) = 423 \cdot MPa$

APPENDIX A2

HOBBS CRITICAL BUCKLING FORCE

Susceptibility of Pipeline to Lateral Buckling
Hobbs Critical Buckling

Description :
The Mathcad analysis worksheet presented here is used to calculate the Pipeline susceptibility to lateral buckling due to axial loading from temperature, pressure and frictional resistance.
The Calculations are based on SAFEBUCK DESIGN GUIDELINE which integrated the DNV-RP-F110 using Hobbs Critical Buckling Force.

Assumptions:
The Steel yield stress is only temperature de-rated
Straight Pipeline is considered
Initially perfect Pipe buckles at an indefinte series of half waves.
Lateral Frictional force is fully mobilized

Limitation:
The concrete coating is not applicable in this case.
The Lateral restrain applicable here is only the friction resistance forces

References:

1. Hobbs, R. E., 'In Service Buckling of heated pipelines', Journal of Transport Engineering, Vol 110, No. 2, March 1984
2. Carr, M., Bruton, D., & Baxter, D., 'Safe Design of Pipeline with Lateral Buckling', SAFEBUCK III, DESIGN GUIDELINE. July, 2011

Units: $MPa \equiv 1N \cdot mm^{-2}$ $g \equiv 9.81 \cdot m \cdot s^{-2}$ $MN \equiv 1 \times 10^{6} N$

Pipeline Data:

Pipeline Outside Diamter	$D_o := 559mm$
Wall Thickness	$t_{wall} := 19.1mm$
External Coating Thickness	$t_{ext.coat} := 5mm$
Concrete Coating Thickness	$t_{conc} := 55mm$
Length of Pipeline	$L := 2000m$

Material Properties:
Pipeline:

Pipe Steel Density	$\rho_{st} := 7850 kg \cdot m^{-3}$
SMYS Steel Pipe	$SMYS := 450MPa$
Steel young's Modulus	$E := 2.07 \cdot 10^{5} MPa$
Steel Pipe Thermal Expansion Coefficient	$\alpha := 1.17 \cdot 10^{-5} \cdot C^{-1}$
Steel Poisson Ratio	$\nu := 0.3$

Insulation or Coating:

Insulation or Coating Density	$\rho_{inscoat} := 910 kg \cdot m^{-3}$
Concrete Coating Density	$\rho_{conc} := 2400. kg \cdot m^{-3}$

Operating Parameters:

Sea Water Density $\rho_{water} := 1027kg\cdot m^{-3}$

Max Content Density $\rho_{cont} := 900kg\cdot m^{-3}$

Design Pressure $P_d := 15MPa$

Operating Pressure $P_{op} := 15MPa$

Hydrotest Pressure $P_{hyd} := 0MPa$

Sea water Ambient Temperature $T_{amb} := 5\cdot C$

Operating Temperature $T_{op} := 95\cdot C$

External Loads:

Bending moment $M_b := 0kN\cdot m$

Axial Force $N_a := 0kN$

Residual Lay Tension $N_{lay} := 0kN$

Soil Properties:

Axial Friction Factor $\mu_{axial} := 0.5$

Lateral Friction Factor $\mu_{lateral} := 0.8$

Safety Factors:

Usage Factor for Hoop stress $\beta_h := 0.72$

Usage Factor for Longitudinal stress $\beta_L := 0.8$

Parameter Calculations:

Internal Diameter $D_{in} := D_o - 2\cdot t_{wall}$

Effective Pipe Diameter $D_{eff} := D_o + 2\cdot\left(t_{ext.coat} + t_{conc}\right)$

Cross-sectional Area of Steel Pipe

$$A_s := \frac{\pi}{4}\cdot\left(\left(D_o^{\,2} - D_{in}^{\,2}\right)\right)$$

Cross-sectional Area of external coating

$$A_{ext} := \frac{\pi}{4}\cdot\left[\left[\left(D_o + 2\cdot t_{ext.coat}\right)^2 - D_o^{\,2}\right]\right]$$

Cross-sectional Area of Concrete coating

$$A_{conc} := \frac{\pi}{4}\cdot\left[\left[\left(D_o + 2\cdot t_{ext.coat} + 2\cdot t_{conc}\right)^2 - \left(D_o + 2\cdot t_{ext.coat}\right)^2\right]\right]$$

Mass of Steel Pipe $M_{st} := A_s\cdot\rho_{st}$

Mass of External coating $M_{ext.coat} := A_{ext}\cdot\rho_{inscoat}$

Mass of concrete coating $M_{conc} := A_{conc}\cdot\rho_{conc}$

Mass of Content

$$M_{cont} := \frac{\pi}{4}\cdot D_{in}^{\,2}\cdot\rho_{cont}$$

Mass of water Content

$$M_{water} := \frac{\pi}{4}\cdot D_{in}^{\,2}\cdot\rho_{water}$$

Mass in water (Bouyancy Mass) $M_{bouyancy} := \frac{\pi}{4} \cdot D_{eff}^2 \cdot \rho_{water}$

Total Mass in air $M_{air} := M_{st} + M_{conc} + M_{ext.coat}$

Submerged Mass $M_{submerged} := M_{air} - M_{bouyancy}$

Weight of Dry Pipe $W_{dry} := M_{air} \cdot g$

Weight of Content $W_{cont} := M_{cont} \cdot g$

Weight of Submerged Pipe $W_{submerged} := M_{cont} \cdot g + M_{ext.coat} \cdot g + M_{st} \cdot g + M_{conc} \cdot g - M_{bouyancy} \cdot g$

$$W_{submerged} = 3.345 \frac{1}{m} \cdot kN$$

Temperature Difference $\Delta T := T_{op} - T_{amb}$

Moment of Inertia of Steel Pipe cross section $I_s := \pi \cdot \frac{\left(D_o^4 - D_{in}^4\right)}{64}$

Sectional Modulus of Steel Pipe $Z_s := \frac{I_s}{\frac{D_o}{2}}$

EFFECTIVE AXIAL FORCE CALCULATION

1. 559 x 19.1mm PIPE OF 2km Pipe Length

$n := 6$ $Kp_0 := 0m$ $KP_{step} := 100m$ $k := 0..2000$

$Kp_{n-1} := 2000m$

$x := Kp_0, KP_{step} .. Kp_{n-1}$ $T_k := (5C) + (90C) \cdot e^{-0.0000911607 \cdot k}$

$x_k := k \cdot 1m$

Water depth

$$WD := \begin{pmatrix} 800m \\ 800m \end{pmatrix}$$

$$KPw := \begin{pmatrix} 0km \\ 2km \end{pmatrix}$$

$$WD(k) := linterp\left(KPw, WD, x_k\right)$$

External Pressure $P_o(k) := \rho_{water} \cdot g \cdot WD(k)$

Internal Pressure $P_{in}(k) := P_{op} + \rho_{cont} \cdot g \cdot WD(k)$

Pressure Difference with KP $\Delta P(k) := P_{in}(k) - P_o(k)$

Thermal Force $N_{thermal}(k) := -E \cdot A_s \cdot \alpha \cdot T_k$

Poisson Effect Force
$$N_{poisson}(k) := \left[\nu \cdot \Delta P(k) \cdot A_s \cdot \frac{(D_o - t_{wall})}{2t_{wall}}\right]$$

End Cap Force
$$N_{Endcap}(k) := \frac{\pi}{4} \cdot \left[\left(P_{in}(k)\right) \cdot D_{in}{}^2 - \left(P_o(k)\right) \cdot D_o{}^2\right]$$

Effective Axial Force with KP
$$N_{eff}(k) := N_{lay} - N_{Endcap}(k) + N_{poisson}(k) + N_{thermal}(k)$$

$$F_{anchor} := \pi \cdot D_{in} \cdot t_{wall} \cdot \alpha \cdot E \cdot (T_{op} - T_{amb}) + \left[(1 - 2\nu)\frac{P_{op} \cdot \pi \cdot D_{in}{}^2}{4}\right] \qquad F_{anchor} = 8.09 \cdot MN$$

Restraining Force: $F_{friction} := \mu_{axial} \cdot (W_{submerged}) \cdot 1m$

$$W_{submerged} = 3.345 \times 10^3 \frac{1}{m} \cdot N \qquad F_{friction} = 1.673 \times 10^3 N$$

$$L_{anchor} := \frac{F_{anchor}}{\left[\mu_{axial} \cdot (W_{submerged})\right]} \qquad L_{anchor} = 4.837 \cdot km$$

Since the Restraining Force (Friction Force) cannot attain the Fully constraint Axial Force (Anchoring Force), then pipeline is termed a **Short Pipeline (fully mobilised)**

Short Pipeline: Pipeline which will never develop the full constrain force

<u>Effective Axial Force - Fully mobilized Pipeline</u>

Maximum Friction Force at the mid-line:
$$F_{MAXfriction} := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot \frac{L}{2}$$

$$F_{MAXfriction} = 2.613 \times 10^6 N$$

Friction Force with Length at the hot end:
$$F_{HOTfriction}(k) := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot x_k \cdot (-1)$$

Friction Force with Length at the cold end:
$$F_{COLDfriction}(k) := \mu_{axial} \cdot (W_{submerged} + W_{cont}) \cdot (x_k - L)$$

The Frictional Restrained Force along the Pipeline full Length:

$$F_{Restfriction}(k) := \text{if}\left(F_{HOTfriction}(k) > F_{COLDfriction}(k), F_{HOTfriction}(k), F_{COLDfriction}(k)\right)$$

$$N_{effSHORT}(k) := \text{if}\left(N_{eff}(k) < F_{Restfriction}(k), F_{Restfriction}(k), N_{eff}(k)\right)$$

EFFECTIVE FORCE FOR A 559 x 19.1mm Pipe of 10km Pipelength

$n := 6$ $\quad KP_{Lstep} := 0.001km$

$i := 0..n-1$ $\quad L_{longKpL_{n-1}} := 10km$

$Kp_0 = 0m$ $\quad j := 0, 1..10000$

$x_i := Kp_0, KP_{Lstep}..L_{longKpL_{n-1}}$ $\quad T_j := (5C) + (90C)\cdot e^{-0.0000492476\cdot j}$

$x_j := j\cdot 1m$

Water depth

$nw := 2$ $\quad WDL := \begin{pmatrix} 800m \\ 800m \end{pmatrix}$

$iw := 0..nw-1$ $\quad KPLw := \begin{pmatrix} 0km \\ 10km \end{pmatrix}$

$WDL(j) := \text{linterp}(KPLw, WDL, x_j)$

$N_{critical} := -2.017MN$

External Pressure $\quad P_{oL}(j) := \rho_{water}\cdot g\cdot WDL(j)$

Internal Pressure $\quad P_{inL}(j) := P_{op} + \rho_{cont}\cdot g\cdot WDL(j)$

Pressure Difference with KP $\quad \Delta PL(j) := P_{inL}(j) - P_{oL}(j)$

Thermal Force $\quad N_{thermalL_j} := -E\cdot A_s\cdot \alpha\cdot T_j$

Poisson Effect Force $\quad N_{poissonL}(j) := \left[\nu\cdot \Delta PL(j)\cdot A_s\cdot \frac{(D_o - t_{wall})}{2t_{wall}}\right]$

End Cap Force $\quad N_{EndcapL}(j) := \frac{\pi}{4}\cdot\left[\left(P_{inL}(j)\right)\cdot D_{in}^2 - \left(P_{oL}(j)\right)\cdot D_o^2\right]$

Effective Axial Force with KP $\quad N_{FULL}(j) := N_{lay} - N_{EndcapL}(j) + N_{poissonL}(j) + N_{thermalL_j}$

Friction Force with Length at the hot end: $\quad F_{HOTfrictionL}(j) := \mu_{axial}\cdot\left(W_{submerged} + W_{cont}\right)\cdot x_j\cdot(-1)$

Friction Force with Length at the cold end:

$$F_{COLDfrictionL}(j) := \mu_{axial}\cdot\left(W_{submerged} + W_{cont}\right)\cdot\left(x_j - x_{10000}\right)$$

The Frictional Restrained Force along the Pipeline full Length:

$$F_{RestfrictionL}(j) := \text{if}\left(F_{HOTfrictionL}(j) > F_{COLDfrictionL}(j), F_{HOTfrictionL}(j), F_{COLDfrictionL}(j)\right)$$

$$N_{EFF}(j) := \begin{array}{|l} \text{out} \leftarrow N_{FULL}(j) \quad \text{if} \quad F_{RestfrictionL}(j) < N_{FULL}(j) \\ F_{RestfrictionL}(j) \quad \text{otherwise} \end{array}$$

$N_{FULL}(3028) = -7.274 \cdot MN$ $\qquad$ $F_{RestfrictionL}(3028) = -7.912 \times 10^{6}\,N$

$N_{FULL}(7469) = -6.079 \cdot MN$ $\qquad$ $F_{RestfrictionL}(7469) = -6.613 \times 10^{6}\,N$

$VAP_1 := 3272m$ $\qquad$ $VAP_2 := 7210m$

BUCKLING PROGRAMMING

$\phi :=$

	0	1	2	3
0	"Direction"	"Minimum"	"Median"	"Maximum"
1	"Axial"	0.3	0.45	0.5
2	"Static Lateral"	0.6	0.7	0.8
3	ynamic Lateral"	0.43	0.85	1.28

REF_2

HOBBS LATERAL BUCKLING ANALYSIS

Inserting the Constants for lateral Buckling modes

$K :=$

	0	1	2	3	4	5
0	"Mode"	"K1"	"K2"	"K3"	"K4"	"K5"
1	1	80.76	$6.391 \cdot 10^{-5}$	0.5	$2.407 \cdot 10^{-3}$	$6.938 \cdot 10^{-2}$
2	2	39.478	$1.743 \cdot 10^{-4}$	1	$5.532 \cdot 10^{-3}$	0.109
3	3	34.06	$1.668 \cdot 10^{-4}$	1.294	$1.032 \cdot 10^{-2}$	0.143
4	4	28.2	$2.144 \cdot 10^{-4}$	1.608	$1.047 \cdot 10^{-3}$	0.148
5	"infinity"	39.478	$4.705 \cdot 10^{-5}$	$4.705 \cdot 10^{-5}$	$4.495 \cdot 10^{-3}$	$5.066 \cdot 10^{-2}$

REF_1

***Case 1*: Infinite mode Lateral buckling with lateral friction of ϕ = 0.8_**

Lateral Friction

Buckle Wave Length

$$L_{buckle} := \left[\frac{2.7969\cdot 10^{5}\cdot (E\cdot I_s)^3}{(\phi_{2,3}\cdot W_{submerged})^2\cdot A_s\cdot E}\right]^{0.125}$$

Ref 1, Equat. 22

$L_{buckle} = 55\cdot m$ $\quad L_{buckle}\cdot 0.5 = 28\,m$ $\quad L_{buckle}\cdot 1.5 = 83\,m$

$n_x := 0.5$ $\quad m_x := 2.5$

Accordning Hobbs recommendation the Buckle wave length will be manipulated within a range of 20 values between 0.5 of buckle wave length to 1.5 of the wavelength

$$L_{bw} := n_x\cdot L_{buckle}, \left[\left[\frac{(m_x\cdot L_{buckle} - n_x\cdot L_{buckle})}{20}\right] + n_x\cdot L_{buckle}\right] .. m_x\cdot L_{buckle}$$

$$P_{buckle}(L_{bw}) := K_{5,1}\cdot \frac{E\cdot I_s}{L_{bw}^2}$$

Ref 1, Equat. 20

Reduced Axial Force within Buckle

Axial force due to Thermal expansion Ref 1, Equat. 21

$$P_{o\_infinity}(L_{bw}) := P_{buckle}(L_{bw}) + 4.705\cdot 10^{-5}\cdot A_s\cdot E\cdot \left(\frac{\phi_{2,3}\cdot W_{submerged}}{E\cdot I_s}\right)^2\cdot L_{bw}^6$$

The Buckle Amplitude

$$y_{max}(L_{bw}) := K_{5,4}\cdot \frac{\phi_{2,3}\cdot W_{submerged}}{E\cdot I_s}\cdot L_{bw}^4$$

Case 2: All Buckling modes of mode 1 - 4

Mode 1

The Reduced force within the Buckle in mode 1: $P_{bucklemode1}(L_{bw}) := K_{1,1}\cdot \frac{E\cdot I_s}{L_{bw}^2}$

The Axial Force for mode:

$$P_{omode1}(L_{bw}) := P_{bucklemode1}(L_{bw}) \ldots + K_{1,3}\cdot \phi_{2,3}\cdot W_{submerged}\cdot L_{bw}\cdot \left[\left[1 + K_{1,2}\cdot A_s\cdot E\cdot (\phi_{2,3})\cdot W_{submerged}\cdot \frac{L_{bw}^5}{(E\cdot I_s)^2}\right]^{0.5} - 1.0\right]$$

The Buckle Amplitude

$$y_{maxmode1}(L_{bw}) := K_{1,4} \cdot \frac{\phi_{2,3} \cdot W_{submerged}}{E \cdot I_s} \cdot L_{bw}^{4}$$

Mode 2

The Reduced force within the Buckle in mode 2:

$$P_{bucklemode2}(L_{bw}) := K_{2,1} \cdot \frac{E \cdot I_s}{L_{bw}^{2}}$$

The Axial Force for mode:

$$P_{omode2}(L_{bw}) := P_{bucklemode2}(L_{bw}) \ldots + K_{2,3} \cdot \phi_{2,3} \cdot W_{submerged} \cdot L_{bw} \cdot \left[\left[1 + K_{2,2} \cdot A_s \cdot E \cdot (\phi_{2,3}) \cdot W_{submerged} \cdot \frac{L_{bw}^{5}}{(E \cdot I_s)^2} \right]^{0.5} - 1.0 \right]$$

The Buckle Amplitude

$$y_{maxmode2}(L_{bucklewave}) := K_{2,4} \cdot \frac{\phi_{2,3} \cdot W_{submerged}}{E \cdot I_s} \cdot L_{bucklewave}^{4}$$

Mode 3

The Reduced force within the Buckle in mode 3:

$$P_{bucklemode3}(L_{bw}) := K_{3,1} \cdot \frac{E \cdot I_s}{L_{bw}^{2}}$$

$$P_{omode3}(L_{bw}) := P_{bucklemode3}(L_{bw}) \ldots + K_{3,3} \cdot \phi_{2,3} \cdot W_{submerged} \cdot L_{bw} \cdot \left[\left[1 + K_{3,2} \cdot A_s \cdot E \cdot (\phi_{2,3}) \cdot W_{submerged} \cdot \frac{L_{bw}^{5}}{(E \cdot I_s)^2} \right]^{0.5} - 1.0 \right]$$

$$y_{maxmode3}(L_{bw}) := K_{3,4} \cdot \frac{\phi_{2,3} \cdot W_{submerged}}{E \cdot I_s} \cdot L_{bw}^{4}$$

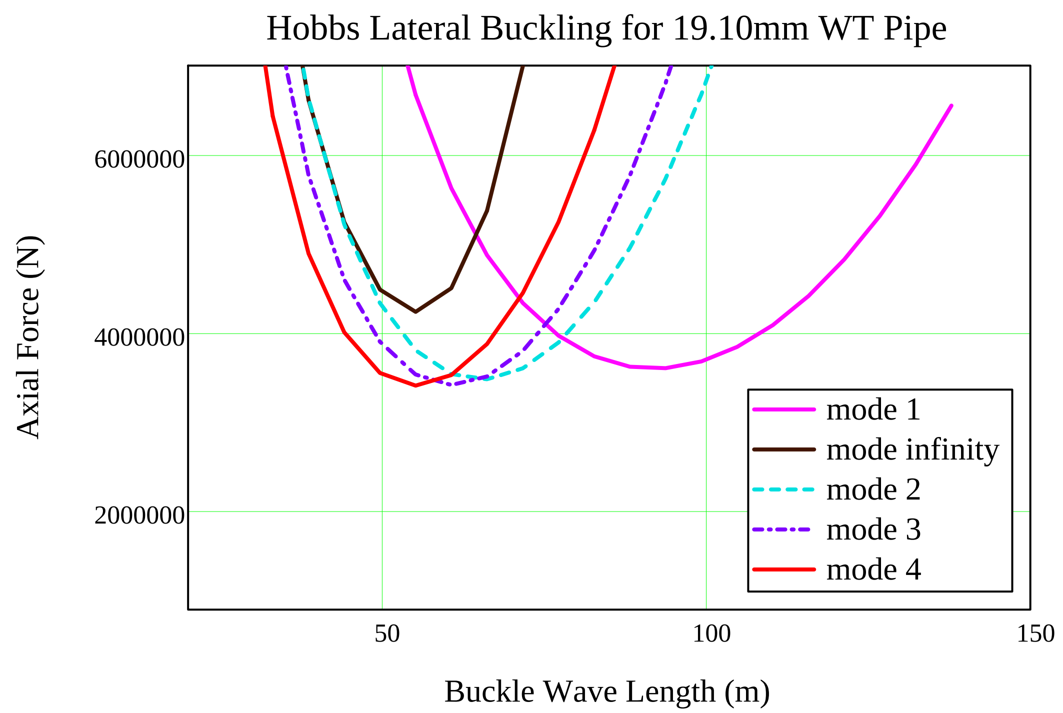
Mode 4

The Reduced force within the Buckle in mode 4:

$$P_{bucklemode4}(L_{bw}) := K_{4,1} \cdot \frac{E \cdot I_s}{L_{bw}^{2}}$$

$$P_{omode4}(L_{bw}) := P_{bucklemode4}(L_{bw}) \ldots + K_{4,3} \cdot \phi_{2,3} \cdot W_{submerged} \cdot L_{bw} \cdot \left[\left[1 + K_{4,2} \cdot A_s \cdot E \cdot (\phi_{2,3}) \cdot W_{submerged} \cdot \frac{L_{bw}^{5}}{(E \cdot I_s)^2} \right]^{0.5} - 1.0 \right]$$

$$y_{maxmode4}(L_{bw}) := K_{3,4} \cdot \frac{\phi_{2,3} \cdot W_{submerged}}{E \cdot I_s} \cdot L_{bw}^{4}$$



$min\_mode\_1 := 3.605MN$ $min\_mode\_2 := 3.48MN$

$min\_mode\_3 := 3.417MN$ $min\_mode\_4 := 3.4107MN$

$min\_mode\_infy := 4.238MN$

$$MinCritivcalBuckleForce := \min(min\_mode\_1, min\_mode\_2, min\_mode\_3, min\_mode\_4, min\_mode\_infy)$$

$$MinCritivcalBuckleForce = 3.411 \cdot MN$$

Therefore the minimum force for which a buckle can exist in a straight line is given by the Hobbs Force:

$$N_{Hobbs} := MinCritivcalBuckleForce$$

$$N_{Hobbs} = 3.411 \cdot MN$$

Based on SAFEBUCK GUIDELINE: A pipeline is is not susceptible to buckling if the inequality below can be established

$N_{max} \le N_{critical}$ ....REF 2

$\mu_{max.axial} := \phi_{1,3}$

$$N_{fmax} := \mu_{max.axial} \cdot W_{submerged} \cdot \frac{L}{2}$$

$$N_{FULL} := F_{anchor}$$

For short Pipeline, the maximum for in the system: $N_{maxshort} := \min(N_{FULL}, N_{fmax})$

For Long Pipeline, the maximum for in the system is the fully constrain force : $N_{maxlong} := N_{FULL}$

Considering only the Long Pipeline of KP 10

$N_{max} := N_{maxlong}$ $\quad N_{max} = 8.09 \cdot MN$

Given the critical buckling force associated with Pipeline out of straightness (OOS) as:

$\mu_{minlateral} := \phi_{2,1}$

Minimum Radius of Curvature of Nominally Straight Pipe: $R := 1000m$

$$N_{OOS} := \mu_{minlateral} \cdot W_{submerged} \cdot R$$

The critical buckling force is defined according to SAFEBUCK GUIDELINE as:

$N_{critical} := \min(N_{OOS}, N_{Hobbs})$ $\quad N_{critical} = 2.007 \cdot MN$

$N_{max} = 8.09 \cdot MN$

Since $\quad N_{max} \geq N_{critical}$

<u>The Long Pipeline of 559 X 19.1mm is Susceptible to Lateral Buckling</u>

For the Short Pipeline of 2km Length:

$N_{maxshort} = 1.673 \cdot MN$ $\quad N_{critical} = 2.007 \cdot MN$

$$N_{maxshort} \leq N_{critical}$$

Hence, the short Pipeline is not Susceptible to Lateral Buckling

APPENDIX A3

PIPELINE WALKING

Pipeline Walking

SUSCEPTIBILITY TO PIPELINE WALKING

References:

Description :

The Mathcad analysis worksheet presented in this report is used for Pipeline end expansion calculation of a rigid pipeline under thermal and pressure loading. The purpose is to deduce the maximum expansion that an end connection can take during maximum loading. The Calculations are based on Subsea 7 Pipeline expansion guideline: CEO1PD-P-GU-126 and DNV-OS-F101

Assumtions:

Linear thermal profile with constant gradient throughout the heat-up
Pressure is assumed to be zero

References:

Hobbs, R. E., 'In Service Buckling of heated pipelines', Journal of Transport Engineering, Vol 110, No. 2, March 1984
Carr, M., Bruton, D., & Baxter, D., 'Safe Design of Pipeline with Lateral Buckling', SAFEBUCK III, DESIGN GUIDELINE. July, 2011

Units: $MPa \equiv 1N \cdot mm^{-2}$ $g \equiv 9.81 \cdot m \cdot s^{-2}$ $MN \equiv 1 \times 10^{6} N$

Pipeline Data:

Pipeline Outside Diamter	$D_o := 559mm$
Wall Thickness	$t_{wall} := 19.1mm$
External Coating Thickness	$t_{ext.coat} := 5mm$
Concrete Coating Thickness	$t_{conc} := 55mm$
Length of Pipeline	$L := 2000m$

Material Properties:

Pipeline:

Pipe Steel Density	$\rho_{st} := 7850kg \cdot m^{-3}$
SMYS Steel Pipe	$SMYS := 450MPa$
Steel young's Modulus	$E := 2.07 \cdot 10^{5} MPa$
Steel Pipe Thermal Expansion Coefficient	$\alpha := 1.17 \cdot 10^{-5} \cdot C^{-1}$
Steel Poisson Ratio	$\nu := 0.3$

Insulation or Coating:

Insulation or Coating Density	$\rho_{inscoat} := 910kg \cdot m^{-3}$
Concrete Coating Density	$\rho_{conc} := 2400.kg \cdot m^{-3}$

Operating Parameters:

Sea Water Density	$\rho_{water} := 1027kg \cdot m^{-3}$
Max Content Density	$\rho_{cont} := 900kg \cdot m^{-3}$
Design Pressure	$P_d := 15MPa$
Operating Pressure	$P_{op} := 15MPa$
Hydrotest Pressure	$P_{hyd} := 0MPa$

Sea water Ambient Temperature $T_{amb} := 5 \cdot C$

Operating Temperature $T_{op} := 95 \cdot C$

Residual Lay Tension $N_{lay} := 0kN$

Soil Properties:

Axial Friction Factor $\mu_{axial} := 0.5$

Lateral Friction Factor $\mu_{lateral} := 0.8$

Parameter Calculations:

Internal Diameter $D_{in} := D_o - 2 \cdot t_{wall}$

Effective Pipe Diameter $D_{eff} := D_o + 2 \cdot (t_{ext.coat} + t_{conc})$

Cross-sectional Area of Steel Pipe $A_s := \frac{\pi}{4} \cdot \left(\left(D_o^{\ 2} - D_{in}^{\ 2} \right) \right)$

Cross-sectional Area of external coating $A_{ext} := \frac{\pi}{4} \cdot \left[\left[\left(D_o + 2 \cdot t_{ext.coat} \right)^2 - D_o^{\ 2} \right] \right]$

Cross-sectional Area of Concrete coating $A_{conc} := \frac{\pi}{4} \cdot \left[\left[\left(D_o + 2 \cdot t_{ext.coat} + 2 \cdot t_{conc} \right)^2 - \left(D_o + 2 \cdot t_{ext.coat} \right)^2 \right] \right]$

Mass of Steel Pipe $M_{st} := A_s \cdot \rho_{st}$

Mass of External coating $M_{ext.coat} := A_{ext} \cdot \rho_{inscoat}$

Mass of concrete coating $M_{conc} := A_{conc} \cdot \rho_{conc}$

Mass of Content $M_{cont} := \frac{\pi}{4} \cdot D_{in}^{\ 2} \cdot \rho_{cont}$

Mass of water Content $M_{water} := \frac{\pi}{4} \cdot D_{in}^{\ 2} \cdot \rho_{water}$

Mass in water (Bouyancy Mass) $M_{bouyancy} := \frac{\pi}{4} \cdot D_{eff}^{\ 2} \cdot \rho_{water}$

Total Mass in air $M_{air} := M_{st} + M_{conc} + M_{ext.coat}$

Submerged Mass $M_{submerged} := M_{air} - M_{bouyancy}$

Weight of Dry Pipe $W_{dry} := M_{air} \cdot g$

Weight of Content $W_{cont} := M_{cont} \cdot g$

Weight of Submerged Pipe $W_{submerged} := M_{cont} \cdot g + M_{ext.coat} \cdot g + M_{st} \cdot g + M_{conc} \cdot g - M_{bouyancy} \cdot g$

$$W_{submerged} = 3.345 \frac{1}{m} \cdot kN$$

Temperature Difference $\Delta T := T_{op} - T_{amb}$

Effective Area $A_{eff} := \frac{\pi}{4} \cdot \left(D_{eff} \right)^2$

SUSCEPTIBILITY TO PIPELINE WALKING

Thermal Transient

Using SAFEBUCK guideline, the pipeline is not susceptible to walking if the axial friction force exceeds the following value:-

$$f > \beta \cdot \frac{(E \cdot A_{eff} \cdot \alpha \cdot \Delta T)}{L}$$ ....REF 2

f = Axial Friction force

The constant β = Parameter for walking due to thermal transient equation

The parameter can be obtained from the relation below:

$$2\beta^3 - 8\beta^2 + 6 \cdot \beta + \frac{q_\theta \cdot L}{\Delta T} = 0$$

If the system is susceptible, the walking displacement per cycle can be estimated from the relations below:

$$\left(\Delta_\theta = \frac{f \cdot L^2}{8 \cdot E \cdot A_s}\right)$$ .... when $f \le \frac{f_\theta}{6}$

$$\left[\Delta_\theta = \frac{L^2}{16E \cdot A_s} \cdot \left(\sqrt{24 \cdot f_\theta \cdot f} - f_\theta - 4 \cdot f\right)\right]$$ .... when $f > \frac{f_\theta}{6}$

The axial friction due to the temperature gradient

$$f_\theta = E \cdot A_s \cdot \alpha \cdot q_\theta$$

$$q_\theta = \text{constant} - \text{Heatup} - \text{gradient}\left(\frac{C}{km}\right)$$

According to SAFEBUCK guideline, the maximum level of walking occurs when:

$$f = \frac{3}{8} \cdot f_\theta$$ .... REF....2

Susceptibility Check

$i := 1 .. 3$

Given $q := \begin{pmatrix} 35 \\ 20 \end{pmatrix} \frac{C}{km}$ $q_\theta := 35 \frac{C}{km}$

We can obtain the corresponding β parameter as follows:

$$2\beta^3 - 8\beta^2 + 6 \cdot \beta + \frac{q_1 \cdot L}{\Delta T} = 0 \qquad \frac{q_0 \cdot L}{\Delta T} = 0.778 \qquad y := \frac{q_0 \cdot L}{\Delta T}$$

$$k := \begin{pmatrix} y \\ 6 \\ -8 \\ 2 \end{pmatrix} \qquad \beta := \text{polyroots}(k) \qquad \beta = \begin{pmatrix} -0.112 \\ 1.181 \\ 2.931 \end{pmatrix}$$

$$\beta \cdot \frac{(E \cdot A_{eff} \cdot \alpha \cdot \Delta T)}{L} = \begin{pmatrix} -4.433 \\ 46.608 \\ 115.68 \end{pmatrix} \frac{1}{m} \cdot kN$$

$$f := \mu_{axial} \cdot W_{submerged} \qquad f = 1.673 \frac{1}{m} \cdot kN$$

Using SAFEBUCK guideline, the pipeline is not susceptible to walking if the axial friction force exceeds the following value:-

$$f > \beta \cdot \frac{(E \cdot A_s \cdot \alpha \cdot \Delta T)}{L}$$

Hence, the 2km flowline will be susceptible to walking with an axial friction coefficient of 0.5
We can also see that the length of the pipeline has a strong factor in determining the susceptibility of pipeline.

The axial friction due to the temperature gradient

$$f_\theta = E \cdot A_s \cdot \alpha \cdot q_\theta$$

$$f_\theta := E \cdot A_s \cdot \alpha \cdot q \qquad f_\theta = \begin{pmatrix} 2.746 \\ 1.569 \end{pmatrix} \frac{1}{m} \cdot kN$$

$$\frac{f_\theta}{6} = \begin{pmatrix} 0.458 \\ 0.262 \end{pmatrix} \frac{1}{m} \cdot kN \qquad f = 1.673 \frac{1}{m} \cdot kN$$

Since

$$f > \frac{f_\theta}{6}$$

The walking displacement per cycle can be estimated from the relations below:

$$\Delta_\theta := \frac{L^2}{16E \cdot A_s} \cdot \left(\sqrt{24 \cdot f_\theta \cdot f} - f_\theta - 4 \cdot f\right)$$

$$A_s = 0.032\, m^2$$

The walking displacement per cycle can for different thermal gradient considered are as follows:

$$q = \begin{pmatrix} 35 \\ 20 \end{pmatrix} \cdot \frac{C}{km} \qquad \Delta_\theta = \begin{pmatrix} 39.623 \\ -12.032 \end{pmatrix} \cdot mm$$

APPENDIX A4

LOCAL BUCKLING CHECK

DNV-OS-F101

DNV-OS-F101 and DNV-RP-F110 Structural checks of pipeline

1 - Input

Design moment	$M_{sd} := 0.15kN \cdot m$	
Design effective axial force	$S_{sd} := -15kN$	
Internal pressure	$p_{ip} := 345bar$	
External pressure	$p_{ep} := 0bar$	
Minimum internal pressure	$p_{min} := 0bar$	
Yield strength	$R_{t05} := 450MPa$	
Tensile strength	$R_m := 535MPa$	
Strain at yield strength point	$\varepsilon_{rt05} := 0.005$	
Strain at tensile strength limit	$\varepsilon_{rm} := 0.180$	
Outer diameter of pipe	$D := 559mm$	
Wall thickness of pipe	$t_w := 19.1mm$	
Corrosion allowance	$t_{corr} := 5mm$	
Specified minimum yield strength	$SMYS := 450.0MPa$	at 100degC derarting
Specified minimum tensile strength	$SMTS := 700.0MPa$	at 100degC derarting
Young's modulus	$E := 207000MPa$	
Functional load factor	$\gamma_f := 1.1$	
Safety class resistance factors	$\gamma_{sc} := 1.14$	
Seabed condition factor	$\gamma_c := 0.9$	
Pressure load factor (OS-F101 - 2000)	$\gamma_{pr} := 1.05$	
Material resistance factor	$\gamma_m := 1.15$	
Material reduction factor	$\alpha_u := 0.96$	
Resistance strain factor	$\gamma_e := 2.5$	
Axial strain resistance factor	$\gamma_{ax} := 3.5$	
Concrete strain intention factor	$\gamma_{cc} := 1.25$	

2 - Load controlled combined buckling check in accordance with DNV-OS-F101 - 2007

Design wall thickness

$t := t_w - t_{corr} = 14.1 \cdot mm$

Design internal pressure

$p_i := p_{ip} = 345 \cdot bar$

$p_e := p_{ep} = 0 \cdot bar$

$$\text{cloadcheck} := \begin{cases} \text{"The combined loading buckling criterion is applicable"} & \text{if } \frac{D}{t} \le 45 \wedge p_{ip} > p_{ep} \\ \text{"The combined loading buckling criterion is not applicable"} & \text{otherwise} \end{cases}$$

cloadcheck = "The combined loading buckling criterion is applicable"

Design yield stress:

$$f_y := SMYS \cdot \alpha_u = 432 \cdot MPa$$

Design tensile stress:

$$f_u := SMTS \cdot \alpha_u = 672 \cdot MPa$$

The pressure containment resistance

$$f_{cb} := \min\left(f_y, \frac{f_u}{1.15}\right) = 432 \cdot MPa$$

$$p_b := \frac{2 \cdot t}{D - t} \cdot f_{cb} \cdot \frac{2}{\sqrt{3}} = 25.8 \cdot MPa$$

Plastic capacities for a pipe

$$S_p := f_y \cdot \pi \cdot (D - t) \cdot t = 10427.2 \cdot kN$$

$$M_p := f_y \cdot (D - t)^2 \cdot t = 1808.6 \cdot kN \cdot m$$

Normalised moment

$$M_{sdn} := \frac{M_{sd} \cdot \gamma_f \cdot \gamma_c}{M_p} = 0.0001$$

Normalised effective force

$$S_{dn} := \frac{S_{sd} \cdot \gamma_f \cdot \gamma_c}{S_p} = -0.0014$$

Normalised pressure

$$q_h := \frac{p_i}{p_b \cdot \frac{2}{\sqrt{3}}} = 1.157$$

$$\beta := \begin{cases} 0.5 & \text{if } \frac{D}{t} < 15 \\ \frac{60 - \frac{D}{t}}{90} & \text{if } 15 \le \frac{D}{t} \le 60 \\ 0 & \text{if } \frac{D}{t} > 60 \end{cases} = 0.23$$

$$\alpha_p := \begin{cases} 1 - \beta & \text{if } \frac{p_i - p_e}{p_b} < \frac{2}{3} \\ 1 - 3 \cdot \beta \cdot \left(1 - \frac{p_i - p_e}{p_b}\right) & \text{if } \frac{p_i - p_e}{p_b} \ge \frac{2}{3} \end{cases} = 1.228$$

$$\alpha_c := (1 - \beta) + \beta \cdot \frac{f_u}{f_y} = 1.126$$

Utilisation in accordance with DNV-OS-F101 - 2007

$$UF1 := \left[\gamma_m \cdot \gamma_{sc} \cdot \frac{|M_{sd} \cdot \gamma_f \cdot \gamma_c|}{\alpha_c \cdot M_p} + \left(\frac{\gamma_m \cdot \gamma_{sc} \cdot \gamma_f \cdot \gamma_c \cdot S_{sd}}{\alpha_c \cdot S_p}\right)^2\right]^2 + \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b}\right)^2 = 2.126$$

$$UF2 := \left[\gamma_m \cdot \gamma_{sc} \cdot \frac{|M_{sdn}|}{\alpha_c} + \left(\frac{\gamma_m \cdot \gamma_{sc} \cdot S_{dn}}{\alpha_c}\right)^2\right]^2 + \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b}\right)^2 = 2.126$$

Maximum allowable moment:

$$M_{bsmax} := \left[\frac{\alpha_c}{\gamma_m \cdot \gamma_{sc}} \cdot \sqrt{1 - \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b}\right)^2} - \frac{\gamma_m \cdot \gamma_{sc} \cdot S_{dn}^{\ 2}}{\alpha_c}\right] \cdot M_p \cdot \frac{1}{\gamma_f \cdot \gamma_c} = (-0 + 1664.7i) \cdot kN \cdot m$$

2 - Displacement controlled combined buckling check in accordance with DNV-OS-F101

$$cloaddischeck := \begin{cases} \text{"The displ. contr. buckling criterion is applicable"} & \text{if } \frac{D}{t} \le 45 \wedge p_{ip} > p_{ep} \\ \text{"The displ. contr. buckling criterion is not applicable"} & \text{otherwise} \end{cases}$$

cloaddischeck = "The displ. contr. buckling criterion is applicable"

Yield strength / tensile strength ratio:

$$\alpha_h := \frac{R_{t05}}{R_m} = 0.841$$

Girth weld factor:

$$\alpha_{gw} := \begin{cases} 1 & \text{if } \frac{D}{t} \le 20 \\ 1 - \left(\frac{D}{t} - 20\right) \cdot 0.01 & \text{if } 20 < \frac{D}{t} < 60 \\ 0.6 & \text{otherwise} \end{cases} = 0.804$$

Design compressive strain - pi > pe:

$$\varepsilon_c := 0.78 \cdot \left(\frac{t}{D} - 0.01\right) \cdot \left(1 + 5.75 \cdot \frac{p_{min} - p_e}{p_b}\right) \cdot \alpha_h^{-1.5} \cdot \alpha_{gw} = 0.0124$$

$$\varepsilon_{sd} := \frac{\varepsilon_c}{\gamma_e \cdot \gamma_{cc}} = 0.004$$

3 - Axial strain limit - DNV-RP-F110

Ramberg-Osgood hardening parameter:

$$n_{ro} := \frac{\log\left(\frac{\varepsilon_{rm} - \frac{R_m}{E}}{\varepsilon_{rt05} - \frac{R_{t05}}{E}}\right)}{\log\left(\frac{R_m}{R_{t05}}\right)} = 23.926$$

Compressive axial strain limit:

$$\varepsilon_{cr} := \frac{4}{3}\cdot\sqrt{\frac{1}{n_{ro}}}\cdot\frac{t}{D} = 0.007$$

$$\varepsilon_d := \frac{\varepsilon_{cr}}{\gamma_{ax}} = 0.002$$

4 - Ratcheting criterion in accordance with Klever et. al.

Hoop stress (Barlow's formula):

$$\sigma_h := \frac{\left(p_i - p_e\right)\cdot D}{2\cdot t} = 683.9\cdot MPa$$

Ratcheting design factor:

$$f_3 := 0.7$$

Limit strain wrt. ratcheting:

$$m_{ra} := \frac{\sigma_h}{SMYS} = 1.52$$

$$\varepsilon_{rl} := \frac{SMYS\left(\sqrt{1 - 0.75\cdot m_{ra}^2} + \sqrt{f_3^2 - 0.75\cdot m_{ra}^2}\right)}{E} = 0.00428i$$

APPENDIX B: ANSYS SCRIPT

APPENDIX B1

LATERAL BUCKLING ANSYS SCRIPT

```
!##############################################################################################
!#                                                                                            #
!#    Title     :   Lateral Buckling and Axial Walking of Surface Laid Subsea Pipeline        #

!#                                                                                            #
!#    Company   :   Subsea 7 Norway                                                           #
!#    Date      :   March 2013                                                                #
!#    Originator:   Ifenna Obele                                                              #
!#                  Master Student in Offshore Tech. University of Stavanger, Norway          #
!##############################################################################################
!                                                                                             #
!Filename: Lateral_Buckling_model                                                             #
!Description: The response analysis of lateral buckling on HT/HP subsea pipeline              #
!triggered by horizontal out-of-straightness on a flat seabed.                                #
!##############################################################################################

*SET,model_id,'Lateral_Buckling_model'

/TITLE,%model_id%
/FILNAM,%model_id%
/ESHAPE,1                    !Display elements as solids
/TRIAD,rbot                  !Display XYZ triad in right bottom corner
/PSYMB,NDIR,1                !Display nodal coord. system if other than global

/UNITS,MKS                   !MKS system (m, kg, s, deg C).
!###############################################################################################
!Defining parameters
!Units are [m] [N]  [KG] [S] [deg]
!###############################################################################################

pi=4*ATAN(1.0)               !Pi
g=9.81                       !Gravitational Acceleration (ms^-2)

WD=200                       !Water Depth (m)
RADc=100                     !RAdius of Curvature in a normally straight pipe

igap=0                       !Initial gap between pipeline and seabed
bgap=0                       !Gap between pipe to the peakseabed profile

/PREP7                       !Enter model creation preprocessor
!ANTYPE,0,NEW                !0=STATIC
ACEL,,g                      !Define gravity

ET,1,PIPE288                 !Pipe elements
SECTYPE,1,PIPE               !Define pipe Section type
SECDATA,559E-3,19.1E-3       !Define Pipe Section:Outer Dia. and Wall Thickness [M]

ET,2,TARGE170                !Seabed element
ET,3,CONTA175                !Contact elements
!###############################################################################################
!Defining PIPELINE DATA
!###############################################################################################
```

```
!#PHYSICAL DATA

OD=559E-3                    !Pipe Outer Diameter (m)
twall=19.1E-3                !Pipe Wall Thickness (m)
Din=OD-2*twall               !Pipe Internal Diameter (m)
L=2000                       !Pipe Model Length (m)
             !
t_ext=5E-3                   !External Coating Thickness (m)
t_conc=55E-3                 !Concrete Coating Thickness (m)

!#OPERATIONAL DATA

D_w=1027                     !WaterDensity (kgm^-3)
D_cont=900                   !Content Density (kgm^-3)
D_st=7850                    !Pipe steel Density (kgm^-3)

P_des=15E6                   !Design Pressure (Nm^-2)
P_op=15E6                    !Operational Pressure (Nm^-2)
P_hyd=0E6                    !Hydrotest Pressure

T_amb=5                      !Ambient Temperature
T_op=95                      !Operating Temperature

!N_Ray=0                     !Residual Lay Tension

!#MATERIAL PROPERTIES

MPTEMP,1,0,95                ! Define temperatures for Young's modulus
MP,EX,1,207E9                !Young's Modulus (Nm^-2)
MP,ALPX,1,1.17E-5            !Thermal expansion Coefficient (1/deg)
MP,PRXY,1,0.3                !Poisson Ratio
!MP,DENS,1,D_st

D_ext=910                   !Insulation or Coating Density (kgm^-3)
D_conc=2400                  !Concrete coating density (kgm^-3)

!---------------------------------------------------------------------------------------------------------------
!                                SEABED DATA
!---------------------------------------------------------------------------------------------------------------
!DEFINE SEABED  SOIL FRICTION
 FRICLAX=0.5                                        ! Soil friction coefficient in axial direction
 FRICLLAT=0.8                                       ! Soil friction coefficient in lateral direction

  TB,FRIC,2,,,ORTHO                                 ! Define orthotropic soil friction
  TBDATA,1,FRICLAX,FRICLLAT

!##############################################################################################################
!**RELEVANT CONNECTING EQUATION
!##############################################################################################################

D_eff=OD+2*(t_ext+t_conc)                                   ! Effective Pipe Diameter (m)
 Ast=pi*(OD**2-Din**2)/4                                    ! Cross-sectional Area of Pipe Steel (m^2)
```

```
 Ast_ext=pi*((OD+2*t_ext)**2-OD**2)/4                ! Cross-sectional Area of External Coating (m^2)
 Ast_conc=pi*((OD+2*t_ext+2*t_conc)**2-(OD+2*t_ext)**2)/4! Cross-sectional Area of Concrete Coating (m^2)
 M_st=Ast*D_st                                       ! Pipe Steel Mass (Kg/m)
 M_ext=Ast_ext*D_ext                                 ! External Coating Mass (Kg/m)
 M_conc=Ast_conc*D_conc                              ! Concrete Coating Mass (Kg/m)
 M_cont=pi*(Din**2)*D_cont/4                         ! Content Mass (Kg/m)
 M_water=pi*(Din**2)*D_w/4                           ! Water Mass (Kg/m)

 M_bouy=pi*(D_eff**2)*D_w/4                          ! Buoyancy Mass (Kg/m)
 M_air=M_st+M_ext+M_conc                             ! Pipeline Total Mass (Kg/m) (weight on air)
 M_sub=M_air-M_bouy                                  ! Submerged Mass (Kg/m) (weight in water)

 W_cont=M_cont*g                                     ! Content Weight (N/m)
 W_water=M_water*g                                   ! Flooded Weight (N/m)
 W_sub=M_sub*g                                       ! Empty Pipe Submerged Weight (N/m)
 DEN_equiv=M_sub/Ast                                 ! Submerged pipe Equivalent Density (kg/m^3)

 D_insul=((t_ext*D_ext)+(t_conc*D_conc))/(t_ext+t_conc) ! Insulation Eqv. Density (Corr. & Concr. Coat.)

(N/m)
 t_insul=t_ext+t_conc                                ! Insulation thickness (Corr. & Concr. Coat.) (m)
 A_insul=Ast_ext+Ast_conc                            ! Insulation Area (Corrosion coat.& Concrete

Coat.)(m^2)

!##############################################################################################
!**UPDATE WEIGHT ON PIPELINE !EQUIVALENT DENSITY APPLIED TO SUBMERGED WEIGHT
!##############################################################################################

 MP,DENS,1,DEN_equiv           ! Pipe Material density (Kg/m^3)
 SECCONTROLS,M_cont            ! overrides default section properties.added mass: Content(kg/m)

!##############################################################################################
!**STRESS-STRAIN CURVE** STRAIN HARDENING
!##############################################################################################
TB,KINH,1,2,4       !Activates a data table for nonlinear material properties
                    !KINH Multilinear kinematic hardening using von Mises or Hill plasticity.

TBTEMP,20.0         !Temperature = 20 deg
TBPT,,0.0,0.0       !Strain=0.00,Stress=0.00
TBPT,,0.002174,450E6   !Elastic: Strain = 0.0217%, Stress = 450E6 (Nm^-2)
TBPT,,0.020,450E6   !Yield Strain: strain = 2.0%, stress = 450E6 (Nm^-2)
TBPT,,0.060,535E6   !Plastic strain: strain = 6.0%, stress = 535E6 (Nm^-2)

TBTEMP,100.0        !Temperature = 100 deg for material data
TBPT,,0.0,0.0       !Strain=0.00,Stress=0.00
TBPT,,0.00203,420E6   !Elastic: Strain = 0.0203%, Stress = 420E6 (Nm^-2)
TBPT,,0.020,420E6   !Yield Strain: strain = 2.0%, stress = 420E6 (Nm^-2)
TBPT,,0.060,505E6   !Plastic strain: strain = 6.0%, stress = 535E6 (Nm^-2)

TBLIST,KINH,1       !Lists the material data tables.
/XRANGE,0,0.01      !Specifies a linear abscissa (X) scale range of TBPLOT
```

```
TBPLOT,KINH,1       !Displays the Data table

!##############################################################################################
!**ELEMENT REAL CONSTANT
!##############################################################################################
!# FOR PIPELINE !
!################!

 KEYOPT,1,1,0                             ! Temperature Through wall gradient
 !KEYOPT,1,3,0                            ! linear shape functions
 KEYOPT,1,4,1                             ! Thin Pipe Theory
 KEYOPT,1,6,0                             ! Internal and External pressure cause loads on end caps
 KEYOPT,1,7,0                             ! Output control for section forces/moments and strains/curvatures


 KEYOPT,1,8,0                             ! Output control at integration points (1=Maximum and minimum

stresses/strains)
 KEYOPT,1,9,2                             ! Maximum and minimum stresses/strains + plus stresses and strains

at each section node
 KEYOPT,1,15,0                            ! One result for each section integration point

!#################
!# SEABED       !
!#################
 !R,22,,,1,0.2                            ! Define Normal Contact Stiffness Factor and Penetration Tolerance

Factor
                                          ! (use ANSYS default)

 KEYOPT,3,10,2                            ! Set option 10 (Contact Stiffnes Update) for element type 3 to 2

(Each substep based on mean
                                          ! stress of underlying elements from the previous substep (pair

based))
                                          ! Update stiffness automaticly based on maximum penetration

 KEYOPT,3,2,1                             ! Penalty method, static stiffness of seabed
 !KEYOPT,3,3,1                            ! Contact MOdel: (0)Contact Force Based (1)Contact traction based
 KEYOPT,3,4,2                             ! Normal from contact nodes
  !KEYOPT,3,5,3                           ! Either Close the gap or reduces initial penetration
  !KEYOPT,3,9,4                           ! Include offset only (exclude initial geometrical penetration or

gap), but with ramped effects
 KEYOPT,3,10,2                            ! Applying the normal contact stiffness by a factor of 0.2 for each

bisection
 KEYOPT,3,12,0                            ! Behaviour of Contact Surface (0=standard)

!################################################################################################
```

```
!Generate nodes and pipe element:
!###########################################################################################################

nod1=  1                                    !first node number
nodn=  999                                  !last nodenumber
nelem=nodn-1                                !number of elements in pipe
midnode=(nodn+1)/2                          !midnode
elength=L/nelem                             !length of an element

n,nod1,0,0,0                                !position of first pipenode
n,nodn,L,0,0                                !position of last pipenode
fill,nod1,nodn                              !fill a row of nodes between nod1 and nodn

numstr,elem,1                               !element numbering from 1
e,1,2                                       !create pipeelement nod1 and nod2

*repeat,nelem,1,1                           !create the all the pipeelement

nsel,all                                    !select all nodes
nsel,s,node,,1,nodn                         !select the pipenodes
cm,pipenodes,node                           !make it a single component

nsel,all
esel,s,type,,1                              !select element by type
cm,pipeelem,elem                            !make it a pipeeleme

esel, all


!###########################################################################################################
!**MESHING SEABED ELEMENT
!###########################################################################################################

! Define nodes for seabed area
N,      3001    ,       -30.0   ,   -igap       , 30
N,      3002    ,       2030    ,   -igap       , 30
N,      3003    ,       2030    ,   -igap       , -30
N,      3004    ,       -30.0   ,   -igap       , -30

!#DEFINE TARGET ELEMENT##
!#########################

numstr,elem,2990
TYPE,2                                              ! Select material and properties for seabed
MAT,2
REAL,22
TSHAPE,QUAD                                         ! SET TARGET SHAPE
E,3001,3002,3003,3004                               ! Define Element

numstr,elem,3001
type,3
real,22
```

```
mat,2

NSEL,R,LOC,Y,0                                      ! Reselect nodes (DOF) in Y-direction
ESURF                                               ! Generate contact elements overlaid on the free faces of

existing selected elements

ALLSEL                                              ! - Seabed done

!############################################################################################################
!                                        DISPLAY MODEL
!############################################################################################################
/ESHAPE,1                                           ! Display elements as solids
/TRIAD,rbot                                         ! Display XYZ triad in right bottom corner
/PSYMB,NDIR,1                                       ! Display nodal coord. system if other than globa

WAVES                                               ! Initiates reordering for the solution phase
WSORT                                               ! Sorts elements based on geometric sort
!WMID,YES
SAVE                                                ! Save all current database information
PARSAV,ALL,Latbuck,txt                              ! Save parameters to latbuck.txt

FINISH                                              ! Exit the preprocessor
!/EOF


!############################################################################################################
!                                        SOLUTION
!############################################################################################################
/CONFIG,NRES,30000

/solu                                        !Enter solution processor
ANTYPE,TRANS                                 !NEW STATIC SOLUTION
solcontrol,on                                !solution control on activates optimized defaults
                                             !for a set of commands applicable to nonlinear solutions
nlgeom,on                                    !Includes large-deflection effects in a static or full transient

analysis.
autots,on                                    !automatic timestepping on
NROPT,UNSYM                                  ! Specifies the Newton-Raphson options in a static or full

transient analysis
                                             ! (FULL or UNSYM= the stiffness matrix is updated at every

equilibrium iteration)

!NSUBST,10,20,10                                     ! Specifies the number of substeps to be taken every

loadstep (nbr this step, maximum number of
                                             ! substeps to be taken (i.e. min. time step), minimum number of

step (i.e. max time step)
```

```
neqit,1000                                 !Specifies the maximum number of equilibrium iterations for

nonlinear analyses.

pstres,on                                  !Calculate (or include) prestress effects
lnsrch,on                                  !Activates a line search to be used with Newton-Raphson.
parres,,Latbuck,txt                        !Reads parameters from a latbuck.txt file.
tref,T_amb                                 !Defines the reference temperature for the thermal strain

calculations.
                                           !Thermal strains are given by  α *(T-TREF)
sfcum,pres,repl                            !cummulative surface load on
bfcum,temp,repl
cncheck,auto                               !Automatically sets certain real constants and key options to

recommended values


nsel,all
nsel,u,node,,465,535
D,all,UZ,0

allsel,all

!############################################################################################################
!                        LOAD STEPS AND BOUNDARY CONDITION
!############################################################################################################
!The word loads as used in ANSYS documentation includes boundary conditions
!(constraints, supports, or boundary field specifications) as well as other
!externally and internally applied loads
!------------------------------------------------------------------------------------------------------------
TIME,1
/stitle,1,Lay pipeline on seabed and Apply boundary condition,set imperfection on pipeline and apply

internal and external presure

d,nod1,all                                  !Initial state: Fix end 1
d,nodn,all                                  !Fix end 2

!f,480,fz,(100000)/(520-480),,520           ! apply a load between node 1490 and 1505
f,480,fz,7000,,520

sfe,pipeelem,1,pres,,P_op                   !Apply internal Pressure
sfe,pipeelem,2,pres,,D_w*g*(WD)             !The hydrostatic pressure @ 800m WD (N/m)

NSUBST,10,20,10

solve
!save
!fini
!/EOF
```

```
!-----------------------------------------------------------------------------------------------------------
TIME,2
/stitle,1,Remove lateral force and apply internal pressure


f,480,fz,0,,520                        ! apply a load between node 1490 and 1505

NSUBST,10,20,10

allsel
solve
!save
!fini
!/EOF

!-----------------------------------------------------------------------------------------------------------
TIME,3
/stitle,1,Appy operating pressure and temperature
sfcum,pres,repl
bfcum,temp,repl
sfe,pipeelem,1,pres,,P_op
bf,pipenodes,temp,90


NSUBST,50,100,50


allsel
solve
save
!/EOF
                                      !END OF LATERAL BUCKLING MODEL
!-----------------------------------------------------------------------------------------------------------
TIME,4
/stitle,1,FIRST COOLDOWN
sfcum,pres,repl
bfcum,temp,repl
sfe,pipeelem,1,pres,,D_cont*g*(WD+20)
bf,pipenodes,temp,T_amb

NSUBST,20

allsel
solve
!save
!/EOF

!-----------------------------------------------------------------------------------------------------------
TIME,5
/stitle,1,SECOND HEAT-UP
sfcum,pres,repl
bfcum,temp,repl
```

```
sfe,pipeelem,1,pres,,P_op
bf,pipenodes,temp,(T_op-T_amb)
NSUBST,20

allsel
solve
!save
!/EOF

!-------------------------------------------------------------------------------------------------------------
TIME,6
/stitle,1,SECOND COOLDOWN

sfe,pipeelem,1,pres,,D_cont*g*(WD+20)
bf,pipenodes,temp,T_amb
NSUBST,20,100,20

allsel
solve
!save
!/EOF

!-------------------------------------------------------------------------------------------------------------
TIME,7
/stitle,1,THIRD HEAT-UP

sfe,pipeelem,1,pres,,P_op
bf,pipenodes,temp,(T_op-T_amb)

NSUBST,25,100,25

allsel
solve
!save
!/EOF

!--------------------------------------------------------------------------------------------------------------
TIME,8
/stitle,1,THIRD COOLDOWN

sfe,pipeelem,1,pres,,D_cont*g*(WD+20)
bf,pipenodes,temp,T_amb

NSUBST,25,100,25

allsel
solve
!save
!/EOF
!-------------------------------------------------------------------------------------------------------------
```

APPENDIX B2

PIPELINE WALKING ANSYS SCRIPT

```
!##################################################################################################
#####
!#
   #
!#    Title     :   Lateral Buckling and Axial Walking of Surface Laid Subsea Pipeline
   #
!#    Company   :   Subsea 7 Norway
   #
!#    Date      :   March 2013
   #
!#    Originator:   Ifenna Obele
   #
!#                  Master Student in Offshore Tech. University of Stavanger, Norway
   #
!##################################################################################################
#####
!
   #
!Filename:Pipeline_Walking
   #
!Description: Axial response due to Pipeline walking
   #
!##################################################################################################
#####
*SET,model_id,'Pipeline_Walking'
/TITLE,%model_id%
/FILNAM,%model_id%
/ESHAPE,1                    !Display elements as solids
/TRIAD,rbot                  !Display XYZ triad in right bottom corner
/PSYMB,NDIR,1                !Display nodal coord. system if other than global
/UNITS,MKS                   !MKS system (m, kg, s, deg C).
!##################################################################################################
####
!Defining parameters
!Units are [m] [N]  [KG] [S] [deg]
!##################################################################################################
####
pi=4*ATAN(1.0)               !Pi
g=9.81                       !Gravitational Acceleration (ms^-2)
WD=800                       !Water Depth (m)
RADc=100                     !RAdius of Curvature in a normally straight pipe
igap=0                       !Initial gap between pipeline and seabed
bgap=0                       !Gap between pipe to the peakseabed profile
/PREP7                       !Enter model creation preprocessor
!ANTYPE,0,NEW                !0=STATIC
ACEL,,g                      !Define gravity
ET,1,PIPE288                 !Pipe elements
SECTYPE,1,PIPE               !Define pipe Section type
SECDATA,559E-3,19.1E-3       !Define Pipe Section:Outer Dia. and Wall Thickness [M]
ET,2,TARGE170                !Seabed element
ET,3,CONTA175                !Contact elements
!##################################################################################################
```

```
###
!Defining PIPELINE DATA
!##########################################################################################################################
###
!#PHYSICAL DATA
OD=559E-3                    !Pipe Outer Diameter (m)
twall=19.1E-3                !Pipe Wall Thickness (m)
Din=OD-2*twall               !Pipe Internal Diameter (m)
L=2000                       !Pipe Model Length (m)
             !
t_ext=5E-3                   !External Coating Thickness (m)
t_conc=55E-3                 !Concrete Coating Thickness (m)
!#OPERATIONAL DATA
D_w=1027                     !WaterDensity (kgm^-3)
D_cont=900                   !Content Density (kgm^-3)
D_st=7850                    !Pipe steel Density (kgm^-3)
P_des=15E6                   !Design Pressure (Nm^-2)
P_op=15E6                    !Operational Pressure (Nm^-2)
P_hyd=0E6                    !Hydrotest Pressure
T_amb=5                      !Ambient Temperature
T_op=95                      !Operating Temperature
!N_Ray=0                     !Residual Lay Tension
!#MATERIAL PROPERTIES
MPTEMP,1,0,95                ! Define temperatures for Young's modulus
MP,EX,1,207E9                !Young's Modulus (Nm^-2)
MP,ALPX,1,1.17E-5            !Thermal expansion Coefficient (1/deg)
MP,PRXY,1,0.3                !Poisson Ratio
MP,DENS,1,D_st
D_ext=910                   !Insulation or Coating Density (kgm^-3)
D_conc=2400                  !Concrete coating density (kgm^-3)
!--------------------------------------------------------------------------------------------------------------------------
--
!                                SEABED DATA
!--------------------------------------------------------------------------------------------------------------------------
-
!DEFINE SEABED  SOIL FRICTION
 FRICLAX=0.5                                          ! Soil friction coefficient in axial direction
 FRICLLAT=0.8                                         ! Soil friction coefficient in lateral direction
  TB,FRIC,2,,,ORTHO                                   ! Define orthotropic soil friction
  TBDATA,1,FRICLAX,FRICLLAT

!##########################################################################################################################
##
!**RELEVANT CONNECTING EQUATION
!##########################################################################################################################
##
D_eff=OD+2*(t_ext+t_conc)                                     ! Effective Pipe Diameter (m)
 Ast=pi*(OD**2-Din**2)/4                                      ! Cross-sectional Area of Pipe Steel (m^2)
 Ast_ext=pi*((OD+2*t_ext)**2-OD**2)/4                         ! Cross-sectional Area of External Coating (m^2)
 Ast_conc=pi*((OD+2*t_ext+2*t_conc)**2-(OD+2*t_ext)**2)/4! Cross-sectional Area of Concrete Coating (m^2)
 M_st=Ast*D_st                                                ! Pipe Steel Mass (Kg/m)
 M_ext=Ast_ext*D_ext                                          ! External Coating Mass (Kg/m)
```

```
 M_conc=Ast_conc*D_conc                                    ! Concrete Coating Mass (Kg/m)
 M_cont=pi*(Din**2)*D_cont/4                               ! Content Mass (Kg/m)
 M_water=pi*(Din**2)*D_w/4                                 ! Water Mass (Kg/m)
 M_bouy=pi*(D_eff**2)*D_w/4                                ! Buoyancy Mass (Kg/m)
 M_air=M_st+M_ext+M_conc                                   ! Pipeline Total Mass (Kg/m) (weight on air)
 M_sub=M_air-M_bouy                                        ! Submerged Mass (Kg/m) (weight in water)
 W_cont=M_cont*g                                           ! Content Weight (N/m)
 W_water=M_water*g                                         ! Flooded Weight (N/m)
 W_sub=((M_sub*g) + (M_cont*g))                                           ! Empty Pipe Submerged Weight (N/m)
 DEN_equiv=M_sub/Ast                                       ! Submerged pipe Equivalent Density (kg/m^3)
 D_insul=((t_ext*D_ext)+(t_conc*D_conc))/(t_ext+t_conc) ! Insulation Eqv. Density (Corr. & Concr. Coat.) (N/m)
 t_insul=t_ext+t_conc                                      ! Insulation thickness (Corr. & Concr. Coat.) (m)
 A_insul=Ast_ext+Ast_conc                                  ! Insulation Area (Corrosion coat.& Concrete Coat.) (m^2)
!###################################################################################################################
##
!**UPDATE WEIGHT ON PIPELINE !EQUIVALENT DENSITY APPLIED TO SUBMERGED WEIGHT
!###################################################################################################################
##
 !MP,DENS,1,DEN_equiv           ! Pipe Material density (Kg/m^3)
 !SECCONTROLS,M_cont            ! overrides default section properties.added mass: Content(kg/m)
!###################################################################################################################
###
!**ELEMENT REAL CONSTANT
!###################################################################################################################
###
!# FOR PIPELINE !
!###############!
 KEYOPT,1,1,0                             ! Temperature Through wall gradient
 !KEYOPT,1,3,0                            ! linear shape functions
 KEYOPT,1,4,1                             ! Thin Pipe Theory
 KEYOPT,1,6,0                             ! Internal and External pressure cause loads on end caps
 KEYOPT,1,7,0                             ! Output control for section forces/moments and strains/curvatures

 KEYOPT,1,8,0                             ! Output control at integration points (1=Maximum and minimum stresses/strains)
 KEYOPT,1,9,2                             ! Maximum and minimum stresses/strains + plus stresses and strains at each section node
 KEYOPT,1,15,0                            ! One result for each section integration point

!################
!# SEABED       !
!################
 !R,22,,,1,0.2                            ! Define Normal Contact Stiffness Factor and Penetration Tolerance Factor
                                          ! (use ANSYS default)
 KEYOPT,3,10,2                            ! Set option 10 (Contact Stiffnes Update) for element type 3 to 2 (Each substep based on
mean
                                          ! stress of underlying elements from the previous substep (pair based))
                                          ! Update stiffness automaticly based on maximum penetration

 KEYOPT,3,2,1                             ! Penalty method, static stiffness of seabed
 !KEYOPT,3,3,1                            ! Contact MOdel: (0)Contact Force Based (1)Contact traction based
 KEYOPT,3,4,2                             ! Normal from contact nodes
  !KEYOPT,3,5,3                           ! Either Close the gap or reduces initial penetration
  !KEYOPT,3,9,4                           ! Include offset only (exclude initial geometrical penetration or gap), but with ramped
```

```
effects
 KEYOPT,3,10,2                          ! Applying the normal contact stiffness by a factor of 0.2 for each bisection
 KEYOPT,3,12,0                          ! Behaviour of Contact Surface (0=standard)
!####################################################################################################
####
!Generate nodes and pipe element:
!####################################################################################################
####
nod1=  1                                !first node number
nodn=  999                              !last nodenumber
nelem=nodn-1                            !number of elements in pipe
midnode=(nodn+1)/2                      !midnode
elength=L/nelem                         !length of an element
n,nod1,0,0,0                            !position of first pipenode
n,nodn,L,0,0                            !position of last pipenode
fill,nod1,nodn                          !fill a row of nodes between nod1 and nodn
numstr,elem,1                           !element numbering from 1
e,1,2                                   !create pipeelement nod1 and nod2
*repeat,nelem,1,1                       !create the all the pipeelement

nsel,all                                !select all nodes
nsel,s,node,,1,nodn                     !select the pipenodes
cm,pipenodes,node                       !make it a single component

nsel,all                                !select all nodes
nsel,s,node,,500,nodn                   !select the pipenodes
cm,coldnodes,node                       !make it a single component

nsel,all
esel,s,type,,1                          !select element by type
cm,pipeelem,elem                        !make it a pipeeleme
esel, all
!####################################################################################################
#
!**MESHING SEABED ELEMENT
!####################################################################################################
#
! Define nodes for seabed area
N,      3001    ,       -30.0   ,   -igap       , 30
N,      3002    ,       2030    ,   -igap       , 30
N,      3003    ,       2030    ,   -igap       , -30
N,      3004    ,       -30.0   ,   -igap       , -30
!#DEFINE TARGET ELEMENT##
!#######################
numstr,elem,2990
TYPE,2                                          ! Select material and properties for seabed
MAT,2
REAL,22
TSHAPE,QUAD                                     ! SET TARGET SHAPE
E,3001,3002,3003,3004                           ! Define Element
numstr,elem,3001
type,3
```

```
real,22
mat,2
NSEL,R,LOC,Y,0                                    ! Reselect nodes (DOF) in Y-direction
ESURF                                             ! Generate contact elements overlaid on the free faces of existing selected
elements
ALLSEL                                            ! - Seabed done
!###########################################################################################################################
#####
!                                        DISPLAY MODEL
!###########################################################################################################################
#####
/ESHAPE,1                                         ! Display elements as solids
/TRIAD,rbot                                       ! Display XYZ triad in right bottom corner
/PSYMB,NDIR,1                                     ! Display nodal coord. system if other than globa
WAVES                                             ! Initiates reordering for the solution phase
WSORT                                             ! Sorts elements based on geometric sort
!WMID,YES
SAVE                                              ! Save all current database information
PARSAV,ALL,Latbuck,txt                            ! Save parameters to latbuck.txt
FINISH                                            ! Exit the preprocessor
!/EOF
!###########################################################################################################################
######
!                                        SOLUTION
!###########################################################################################################################
######
/CONFIG,NRES,30000
/solu                                     !Enter solution processor
ANTYPE,TRANS                              !NEW STATIC SOLUTION
solcontrol,on                             !solution control on activates optimized defaults
                                          !for a set of commands applicable to nonlinear solutions
nlgeom,on                                 !Includes large-deflection effects in a static or full transient analysis.
autots,on                                 !automatic timestepping on
NROPT,UNSYM                               ! Specifies the Newton-Raphson options in a static or full transient analysis
                                          ! (FULL or UNSYM= the stiffness matrix is updated at every equilibrium iteration)
!NSUBST,10,20,10                          ! Specifies the number of substeps to be taken every load step (nbr this step, maximum
number of
                                          ! substeps to be taken (i.e. min. time step), minimum number of step (i.e. max time step)
neqit,1000                                !Specifies the maximum number of equilibrium iterations for nonlinear analyses.
pstres,on                                 !Calculate (or include) prestress effects
lnsrch,on                                 !Activates a line search to be used with Newton-Raphson.
parres,,Latbuck,txt                       !Reads parameters from a latbuck.txt file.
tref,T_amb                                !Defines the reference temperature for the thermal strain calculations.
                                          !Thermal strains are given by  a *(T-TREF)
sfcum,pres,repl                            !cummulative surface load on
bfcum,temp,repl
cncheck,auto                              !Automatically sets certain real constants and key options to recommended values


nsel,all
nsel,u,node,,1,999
D,all,UZ,0
```

```
allsel,all
!##################################################################################################################
######
!                        LOAD STEPS AND BOUNDARY CONDITION
!##################################################################################################################
#####
!The word loads as used in ANSYS documentation includes boundary conditions
!(constraints, supports, or boundary field specifications) as well as other
!externally and internally applied loads

TIME,1
/stitle,1,Lay pipeline on seabed and Apply boundary condition,set imperfection on pipeline and apply internal and external presure

f,pipenodes,fy,-(W_sub*elength)
sfe,pipeelem,2,pres,,D_w*g*(WD)           !The hydrostatic pressure @ 800m WD (N/m)
NSUBST,15,20,10
solve
!save
!fini
!/EOF

!------------------------------------------------------------------------------------------------------------------
-
TIME,2
/stitle,1,Heatstep 2

heatstep2n.mac

NSUBST,15
allsel
solve
save
!/EOF
!------------------------------------------------------------------------------------------------------------------
----
TIME,3
/stitle,1,Heatstep 3

heatstep3n.mac

NSUBST,15
allsel
solve
save
!/EOF
!------------------------------------------------------------------------------------------------------------------
-------
TIME,4
/stitle,1,Heatstep 4

heatstep4n.mac
```

```
NSUBST,15
allsel
solve
save
!/EOF
!----------------------------------------------------------------------------------------------------------------------------------
------
TIME,5
/stitle,1,Heatstep 5

heatstep5n.mac

NSUBST,15
allsel
solve
save
!/EOF
!----------------------------------------------------------------------------------------------------------------------------------
--------
TIME,6
/stitle,1,Heatstep 6

heatstep6n.mac

NSUBST,15
allsel
solve
save
!/EOF
!----------------------------------------------------------------------------------------------------------------------------------
--------
TIME,7
/stitle,1,Heatstep 7

heatstep7n.mac

NSUBST,15
allsel
solve
save
!/EOF
!----------------------------------------------------------------------------------------------------------------------------------
---------
TIME,8
/stitle,1,Heatstep 8

heatstep8n.mac

NSUBST,15
allsel
solve
```

```
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------------
---------
TIME,9
/stitle,1,Heatstep 9

heatstep9n.mac
NSUBST,15
allsel
solve
save
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------------
------
TIME,10
/stitle,1,Heatstep 10

heatstep10n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------------
------

TIME,11
/stitle,1,Heatstep 11

heatstep11n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------------
-----

TIME,12
/stitle,1,Heatstep 12

heatstep12n.mac
NSUBST,15
allsel
solve
save
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------------
----
```

```
TIME,13
/stitle,1,Heatstep 13

heatstep13n.mac
NSUBST,15
allsel
solve
save
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------------
----
TIME,14
/stitle,1,Heatstep 14

heatstep14n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------------
--

TIME,15
/stitle,1,Heatstep 15

heatstep15n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------------
-
TIME,16
/stitle,1,Heatstep 16

heatstep16n.mac
NSUBST,15
allsel
solve
save
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------------
TIME,17
/stitle,1,Finalheatstep

finalheatstepn.mac
NSUBST,15
allsel
```

```
solve
save
!/EOF
!---------------------------------------------------------------------------------------------------------------------------------

TIME,18
/stitle,1,First cycle -cooldown

bf,pipenodes,temp,20
NSUBST,15
allsel
solve
save
!/EOF

!                                                    !Second Cycle
!#################################################################################################################################


TIME,19
/stitle,1,Heatstep 2

heatstep2n.mac

NSUBST,15
allsel
solve
save
!/EOF
!--------------------------------------------------------------------------------------------------------------------------------
TIME,20
/stitle,1,Heatstep 3

heatstep3n.mac

NSUBST,15
allsel
solve
save
!/EOF
!---------------------------------------------------------------------------------------------------------------------------------
TIME,21
/stitle,1,Heatstep 4

heatstep4n.mac

NSUBST,15
allsel
solve
save
!/EOF
!--------------------------------------------------------------------------------------------------------------------------------
```

```
TIME,22
/stitle,1,Heatstep 5

heatstep5n.mac

NSUBST,15
allsel
solve
save
!/EOF
!---------------------------------------------------------------------------------------------------------------------------------
TIME,23
/stitle,1,Heatstep 6

heatstep6n.mac

NSUBST,15
allsel
solve
save
!/EOF
!------------------------------------------------------------------------------------------------------------------------------
TIME,24
/stitle,1,Heatstep 7

heatstep7n.mac

NSUBST,15
allsel
solve
save
!/EOF
!---------------------------------------------------------------------------------------------------------------------------
TIME,25
/stitle,1,Heatstep 8

heatstep8n.mac

NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------
TIME,26
/stitle,1,Heatstep 9

heatstep9n.mac
NSUBST,15
allsel
solve
save
```

```
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------
TIME,27
/stitle,1,Heatstep 10

heatstep10n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------

TIME,28
/stitle,1,Heatstep 11

heatstep11n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-----------------------------------------------------------------------------------------------------------------------------

TIME,29
/stitle,1,Heatstep 12

heatstep12n.mac
NSUBST,15
allsel
solve
save
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------
TIME,30
/stitle,1,Heatstep 13

heatstep13n.mac
NSUBST,15
allsel
solve
save
!/EOF

!-----------------------------------------------------------------------------------------------------------------------------
TIME,31
/stitle,1,Heatstep 14

heatstep14n.mac
NSUBST,15
```

```
allsel
solve
save
!/EOF
!--------------------------------------------------------------------------------------------------------------------------------

TIME,32
/stitle,1,Heatstep 15

heatstep15n.mac
NSUBST,15
allsel
solve
save
!/EOF
!-------------------------------------------------------------------------------------------------------------------------------
TIME,33
/stitle,1,Heatstep 16

heatstep16n.mac
NSUBST,15
allsel
solve
save
!/EOF
!------------------------------------------------------------------------------------------------------------------------------

TIME,34
/stitle,1,Finalheatstep

finalheatstepn.mac
NSUBST,15
allsel
solve
save
!/EOF
!------------------------------------------------------------------------------------------------------------------------------

TIME,35
/stitle,1,First cycle -cooldown

bf,pipenodes,temp,20
NSUBST,15
allsel
solve
save
!/EOF
!-------------------------------------------------------------------------------------------------------------------------------
```