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Pipelay with Residual Curvature

Master Thesis
Marine and Subsea Technology

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ABSTRACT

Offshore pipelines under operating loads, i.e. under high temperature and pressure, are exposed to expansion and compressive forces, which may cause the pipeline to buckle globally. If significant lateral motion and excessive feed-in occurs at a specific location, the pipeline may form a sharp twist of high curvature where the resulting strain may be very large to initiate structural failure.

Commonly used mitigation measures in the offshore industry are by continuous burial or rock damping to avoid buckling of the pipeline completely; and by using various methods to trigger lateral buckling in a controlled and effective manner at a relatively low axial compressive force, for example snake lay, artificial vertical imperfections & buoyancy modules. These mitigation measures require the implementation of additional methods on the seabed, which often appear with significant cost.

Recent developments have shown how the use of intermittent residual curvature sections during reel-lay installation of pipelines can be used to control global pipeline thermal buckling in the operational phase. The method was first implemented in Statoil's Skuld project in the Norwegian sea in 2012. Results have shown that every section of the residual curvature is triggered as expected and ensured the sharing of thermal expansion. No additional methods were required to ensure the utilization within acceptable criteria. The method was found to be rewarding and cost effective than the above mentioned conventional mitigation methods.

The residual curvature sections are created as under-straightened sections in the vertical plane at the straightener of the reel-lay vessel. These convex upward residual sections create an additional imperfection in the pipeline and lead to pipe roll as it moves through the under-bend due to reversed bending. If the RCM is to be used effectively as a means for lateral buckling control, the residual curvature sections should acquire a position of stable equilibrium by ending the roll in the horizontal plane at the seabed. The tendency of the pipeline to bend and roll due to the residual curvature sections introduced on the reel ship can be estimated by energy approach. The total work done from the water surface to the seabed TDP is the sum of the bending and roll contribution. After initiating roll, the pipeline ends up in an equilibrium position when the total estimated work done is minimum and the corresponding angle gives the roll angle.

Considering the aspects discussed above, the current work focuses on an analytical energy approach method for the estimation of the total work done to bend and twist the pipeline from the surface to the seabed; and estimate pipeline roll at the seabed TDP. Sensitivity studies of various parameters are carried out based on single pipe sections of 12” ID & 14” ID as well as 18” OD pipe-in-pipe in water depth of 360m, 800m and 1200m. The thesis also includes a brief model of pipeline installation by introducing pre-bent curvature section using global analysis tool OrcaFlex. The purpose is to compare the results against the analytical method.

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Abraham Aimut Tewolde

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NOMENCLATURE

Symbols

Latin characters

A	Ratio of horizontal lay tension to pipe's submerged weight, [m]
c	External radius of pipeline cross section, [m]
d, D_0	Diameter of pipeline OD, unless specified, [m]
E	Modulus of elasticity of the steel pipe, Young's Modulus, [N/m^2]
g	Gravitational acceleration, [m/s]
G	Shear/Modulus of rigidity, [N/m^2]
h	Water depth, [m]
H	Horizontal component of the tension, [N]
I	Second moment of area, [m^4]
I_t	Polar second moment of area, [m^4]
L	Horizontal distance from the point the tension applied to seafloor, [m]
L_{curv}	Residual curvature length, [m]
M_B	Moment due to bending, [Nm]
M_ϕ, M_R	Moment due to roll, [Nm]
M_p	Plastic moment capacity of a section, [Nm]
M_{pip}	Plastic moment capacity of a pipe-in-pipe, [Nm]
r	Outer pipeline radius, [m]
R	Radius of curvature unless specified, [m]
R_{reel}	Minimum reel hub radius, [m]
s	distance from TDP, length of the catenary line to the seafloor, [m]
t	Nominal wall thickness, [m]
t_c	Cladding thickness, [m]
T	Tension, [N]
V	Vertical component of the tension, [N]
W_B	Work done due to bending, [J]
W_R	Work done due to roll, [J]
W_s	Submerged weight of the catenary line, [N/m]
W_{tot}	Total work done, [J]

Greek characters

γ A symbol defined by the square root of the ratio of pipe stiffness to tension, [m]

δ Residual out-of-straightness, [m]

ε_b Maximum allowable bending strain, [-]

ε_F Nominal functional strain during reeling, [-]

ε_{res} Residual strain, [-]

θ Angle measure, [rad]

κ Nominal curvature, [m^{-1}]

κ_{res}, κ_r Residual curvature, [m^{-1}]

κ_{tot} Total curvature, [m^{-1}]

ρ_{clad} Density of cladding, [kg/m^3]

ρ_{sea} Density of sea water, [kg/m^3]

ρ_{steel} Density of steel, [kg/m^3]

σ_y Yield stress, [N/m^2]

ϕ Roll angle along the suspended section, [rad]

ϕ_0 Roll angle at TDP, [rad]

ABBREVIATIONS

API	American Petroleum Institute
CCW	Counter clockwise
CW	Clockwise
DNV	Det Norske Veritas
DP	Dynamic positioning
FE	Finite Element
ID	In side diameter
NDT	Non-destructive testing
OD	Outside diameter
OOR	Out-of-roundness
OOS	Out-of-straightness
PiP	Pipe-in-pipe
RCM	Residual Curvature Method
SMTS	Specified Minimum Tensile Strength
SMYS	Specified Minimum Yield Strength
TDP	Touch down point

1. INTRODUCTION

1.1 Background

Offshore pipelines are pipelines that are laid on the seafloor or beneath the seabed inside a trench. The primary purpose of marine pipelines is to carry oil and gas under high temperature and pressure from one place to another. A pipeline on the sea bed is exposed to expansion and lateral buckling due to the buildup of compressive forces induced by the high operating temperature and pressure. If significant lateral movement and excessive feed-in occurs at a specific location, the pipeline may form a sharp twist of high curvature where the resulting strain may be very large to initiate structural failure or operational cyclic fatigue failure can take place, Ref [19] [27] [28]. The integrity of pipelines is always at risk if lateral buckling is not properly managed.

Pipeline lateral buckling is one of the design issues that has to be addressed properly before the installation of pipelines. The offshore industry employs several techniques to initiate buckle for a controlled lateral movement. The deployment of these methods brings the installation process to a halt, and these off course comes at a significant cost and delay. Recent developments in the industry has brought a technique of great significance in the area of lateral buckling.

A very simple and cost-effective method of lateral buckling is by the use of the straightener system during reel-lay installation in order to create residual curvature sections in the pipeline. The concept is that residual curvatures are created at constant intervals thereby pipeline buckling can be initiated at these locations at lower axial force. Figure 1 shows Subsea7's reel-lay vessel "Seven Oceans" which has been used for the successful implementation of the residual curvature method (RCM).

Figure 1: Subsea 7's reel-lay vessel "Seven Oceans", Ref [34]

The residual curvature method for lateral buckling control is exclusively carried out by the reel-lay installation. The straightener of the reel-lay vessel introduces the residual curvatures in the vertical plane. As a result, the convex upward residual curvature sections have tendency to roll or rotate as it passes the sagbend in which it bends in the opposite direction as the pipeline is paid out, Ref [13]. As the pipeline is installed, work is done to bend and roll the pipeline from the surface to the sea bottom and this work done can be used to estimate the pipeline roll at the seabed.

This thesis work primarily deals with the analytical study of the total work done to bend and roll pipelines installed with the residual curvatures method in reel-laying and to predict pipe roll at the seabed TDP when the pipeline acquires stable equilibrium position.

1.2 Problem Description

The thesis emphasizes on the use of residual curvature method in reel-lay installation for lateral buckling control. The main challenge of using the RCM method is because it involves pipe rotation at the seabed. There is always tendency of the pipeline to roll as the residual curvature moves past the sag bend. This happens since the residual curvatures are created in the vertical plane at the straightener of the reel-lay vessel. The pipeline changes bending direction at the sagbend and consequently, the under-straightened imperfections created on the pipeline are forced to rollover to reach an equilibrium position. Work is done to bend and twist the pipeline from the surface to the seabed, and using this total work done pipeline rotation can be estimated at the seabed. The pipe line obtains its equilibrium position by ending rotation and the total work done at this point is minimum.

The thesis focuses primarily on predicting pipe roll based on the total work done to bend and roll the pipeline from the surface to the touch down point. The reasons for giving importance for pipe roll are:

- If residual curvatures are used for lateral buckling control, the under-straightened sections need to end rotation in the horizontal plane of the sea bed;
- Pipeline at the seabed can be connected to an in-line Tee connection, and hence it is crucial to predict the roll in the pipeline as a result of the use of residual curvature method;
- Pipe roll due to the use of residual curvature method can potentially expose subsea units such as templates, PLET & PLEM to overturning moment.
- Pipe roll due to the method of residual curvature can be utilized to adapt seabed topography in areas where free spans exist.

Therefore, it is important to study and predict pipe line roll when using residual curvature method as it can potentially have many applications in the offshore industry.

1.3 Purpose and Scope

The main purpose of this thesis is to briefly study and analyze the analytical energy approach method for the estimation of the total work done to bend and twist a pipeline from the surface to the seabed; and to estimate pipe roll at TDP during installation.

The scope of the thesis:

- To discuss the commonly used pipeline installation methods in the offshore industry;
- To review the conventional buckle initiation techniques that are used to date for controlled lateral buckling of marine pipelines and compare them against the method of residual curvature;
- To briefly review the catenary analysis in pipeline installation;
- To study and understand the methodology of Residual Curvature Methods in pipeline installation;
- To estimate pipe roll by the energy approach method and to be able to show steps in the derivation of work done by bending and roll based on Endal's equations;
- To model and perform pipeline installation to estimate pipe roll using OrcaFlex and compare the results with analytical approach;
- Sensitivity study for single pipe sections of 12" ID & 14" ID as well as 18" OD pipe-in-pipe at water depths of 360m, 800m and 1200m for different parameters.

1.4 Thesis Organization

The thesis is divided into six chapters. Following this introductory Chapter 1, the remaining chapters of the text are organized as follows:

Chapter 2 - Pipeline Basic Theory: This chapter discusses basic theories about pipeline installation methods, catenary shape and pipeline lateral buckle initiation techniques. Steps are shown for the derivation of the catenary equation for calculating the distance from the point of installation to the touch down point. This chapter introduces the method of residual curvature (RCM) as a robust and cost-effective way of buckle initiation technique.

Chapter 3 - Residual Curvature and pipe roll: This chapter talks about the use, application and advantages of the residual curvature method for pipeline lateral thermal buckling control. The chapter focuses on the use of the energy methods to estimate piperoll due to the introduction of under-straightened section in the straightener of the reel-lay vessel. Some of the steps in the derivation of the work done to bend and roll a pipeline from the surface to the seabed TDP at is presented.

Chapter 4 - Methodology and Analysis data: This chapter deals with the methodology applied in the thesis work, including input data for analysis such as material grades, pipe types, data about environmental issues and data about residual curvature. The method of modeling pipeline installation using a global analysis tool, OrcaFlex, is also discussed.

Chapter 5 - Results and Discussions: This chapter presents the results and assessments of the energy method approach to predict piperoll at TDP. The results and interpretation are based on sensitivity studies of: pipe outer diameter OD, diameter to thickness D_0/t ratio, horizontal lay tension, residual strain and water depth. The analysis is carried out using single pipe sections of 12” ID & 14” ID, and 18” OD Pipe-in-pipe in water depth of 360m, 800m and 1200m. Moreover, comparisons between the results of the analytical approach method and mean gamma measurements that are obtained from OrcaFlex are discussed.

Chapter 6 - Conclusions and Recommendations: presents the conclusions to the study made in this thesis and stipulates recommendations for further studies.

2. PIPELINE BASIC THEORY

2.1 Pipeline installation

2.1.1 Introduction

The implementation of the residual curvature method (RCM) involves the use of reel-lay method of pipe installation where residual curvatures are introduced at the straightener of the reel vessel. It is also possible to create residual curvatures using the S-lay method by exposing the pipeline to plastic strains as it passes over a stinger by exceeding a certain curvature. The offshore industry uses several methods of pipeline installation, but a brief introduction is given to the commonly used methods.

Some of the basic terminologies that are commonly used in the installation analysis are defined below in table 1. Graphical representation of the installation terminologies is also given in figure 2.

Axial Stress / Strain:	The Axial Stress / Strain are defined as the direct contribution of the Tensile stress / strain (due to wall tension) and Bending Stress / Strain.
Bottom Tension:	Pipeline tension at TDP, generally horizontal for following seabed slope.
Displacement Controlled:	Part of the pipeline where pipeline shape is imposed by a pure displacement (typically when a pipe is spooled on a reel, its displacement is imposed by the diameter of the reel)
Gain / Projection Growth:	Generally noted S(x)-x. It denotes the difference between a pipeline length and the horizontal distance between the two extremity points of this pipeline section. Physically it represents the horizontal distance from the pipeline top end extremity on the vessel and the point on the seabed where this extremity will rest once installed.
Layback:	Horizontal distance between a reference point on the barge (stern, J-lay tower…) and pipeline TDP.
Load Controlled:	Part of the pipeline where pipeline shape is imposed by pure loading (tension, moments…).
Longitudinal Strain:	It corresponds to the total longitudinal strain of the pipeline in the pipeline main direction. As per Hook’s law, it is the contribution of the axial strain (due to tensile strain and bending strain) and the poison’s effects (pressure effects).
Overbend:	Part of the pipeline which makes a bend on the opposite side to the sagbend, i.e. a convex bend which is low at the end and high in the middle. This is located on the barge or on the stinger (by means of supports, reel…).

Sagbend:	Part of the pipeline which makes a bend on the opposite side to the overbend, i.e. a concave bend which is high at the ends and low in the middle. It deals with freespan section from the end of the overbend to the seabed.
Stinger	Steel structure protruding at the end of a laybarge, used in S-lay to support the pipeline and provide to it the required declination to avoid buckling.
Top Tension:	Pipeline tension at the barge hang-off point (tensioners, clamps, bushings…)
Touch Down Point (TDP):	Point where the pipeline is touching the seabed floor.

Table 1: Definition of basic installation terminologies, Ref [30]

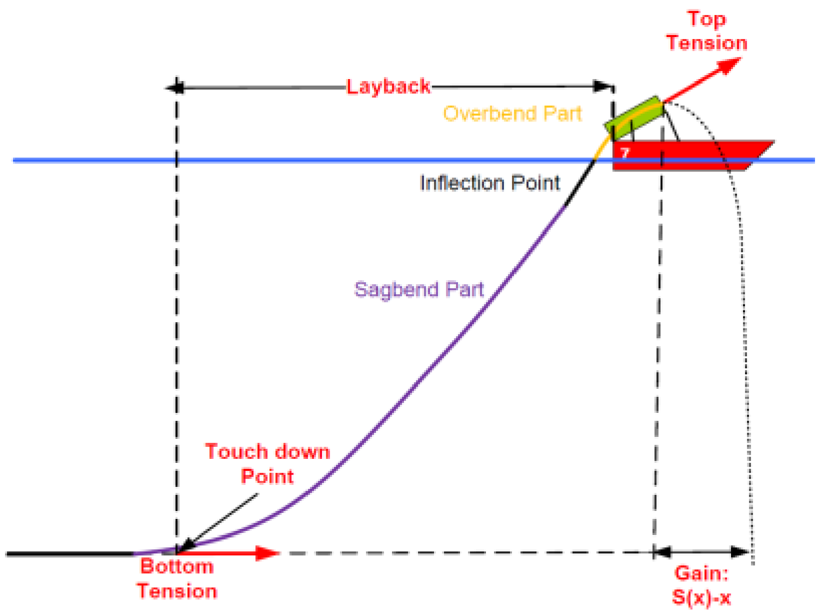


Figure 2: Graphical representation of the installation terminologies, Ref [30]

Generally, pipeline installation involves the use of either a lay-barge or a reel ship for construction. The most common method of pipeline installation is by lay-barge, where the pipeline is produced offshore by welding individual pipe joints into a pipe string, and is laid out from the lay-vessel to the seabed. The individual coated and anoded pipe joints are delivered to the laybarge by a supply vessel. It is also possible to fabricate smaller size pipe strings onshore at a spool base and reeled onto a reel ship, which is then unreeled and installed offshore, Ref [3].

This section outlines three common methods used to install pipelines, namely:

- ’S’ lay Method
- ’J’ lay method
- Reeled lay method

2.1.2 'S' Lay Method

The 'S' lay method is the most common and frequently used technique of pipeline installation. During laying the suspended pipeline forms an 'S' shaped curve as it extends from the vessel to the seabed. Individual coated and anoded line pipes are supplied to the laybarge and are lined up at the upper end of the ramp and pass through a series of welding stations as the laybarge moves forward, paying the line into the sea, Ref [27].

The pipe leaves through the sloping ramp at the stern of the laybarge (refer to ***Figure 3***). The stinger, an open steel structure, is located at the end of the ramp and is used to support the pipe and control its shape. Stinger length is determined by the water depth and the submerged weight of the pipeline, while its shape is decided by the choice of angles of the segments. A short stinger can expose the pipeline to huge bending stresses at the end of the stinger and this can lead to pipeline buckling. Tensioners, generally located at the ramp of the vessel, are used to keep the suspended length of the pipeline, Ref [23].

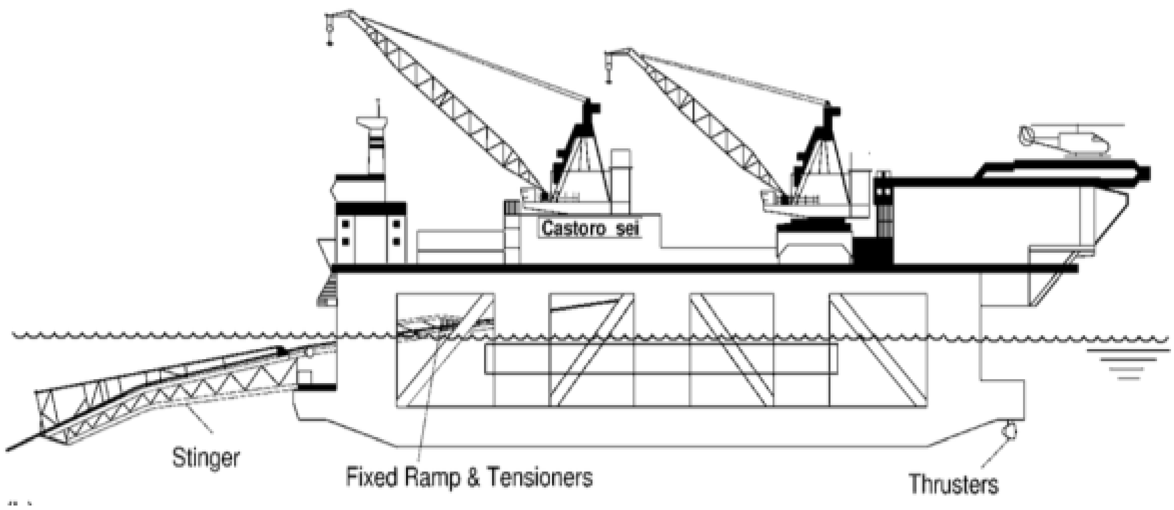


Figure 3: Schematic diagram of Saipem Semi-Submersible S-lay vessel, Ref [23]

The upper curved part of the suspended pipeline is called the overbend (convex upward) and the lower curved part is called the sagbend (concave upward). During installation, the overbend curvature is controlled by the lay-vessel stinger. The curvature in the sagbend is controlled by the lay tension transferred to the pipeline by tension machines gripping the pipe string on the laybarge, Ref [3]. ***Figure 4*** shows a typical 'S' lay configuration illustrating the overbend and sagbend of the pipeline.

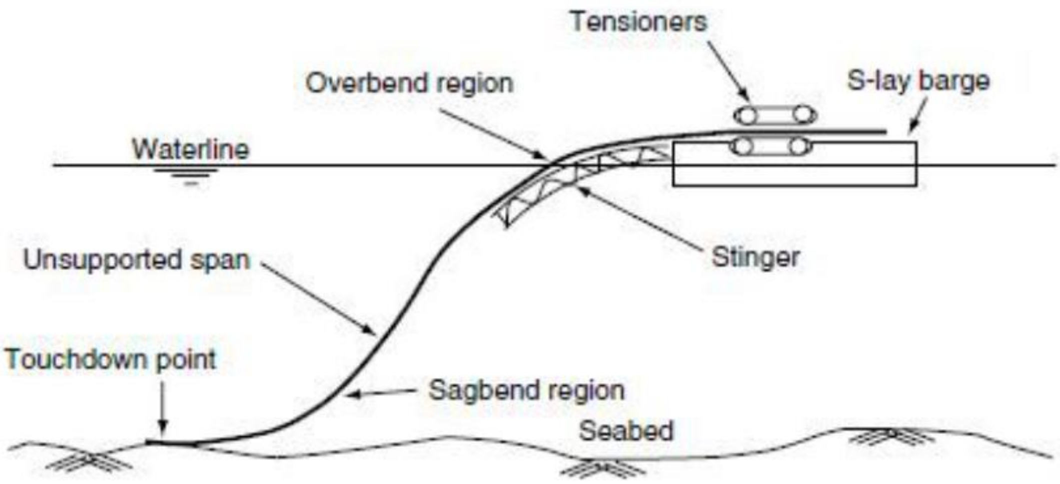


Figure 4: S-lay configuration, Ref [18]

The maximum curvature usually occurs at the sagbend area near the seabed, which is at the maximum water depth and hence we need to ensure the safety of the pipe against the combined bending and pressure loads. Once the pipeline reaches the seabed past the sagbend, it is relieved from the installation loading and remains under hydrostatic pressure when empty as shown in figure 5.

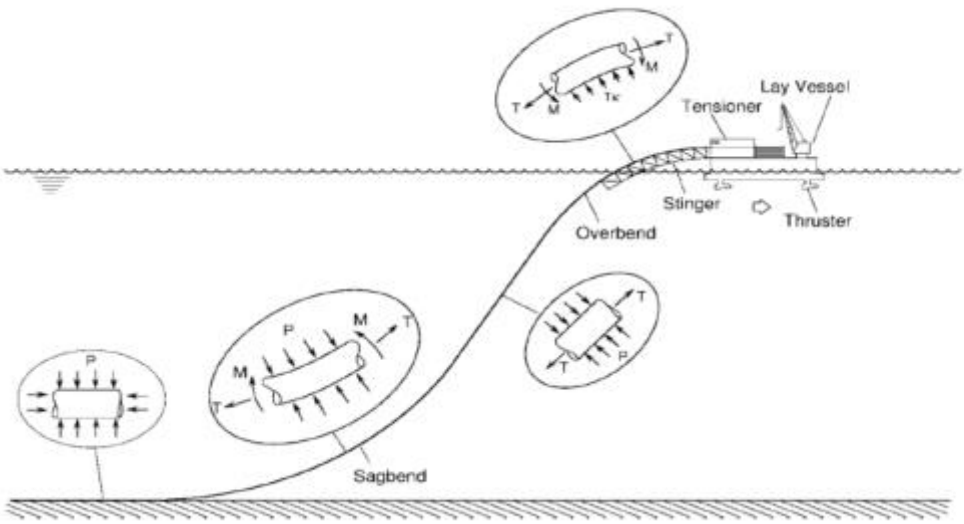


Figure 5: Schematic representation of S-lay pipeline installation and associated pipeline loadings, Ref [23]

It is to be noted that any loss of tension or uncontrolled movement of the vessel for any reason can lead to excessive bending, local buckling and collapse of the pipeline. The local buckling in turn has the capability of initiating a propagating buckle as shown in figure 6, Ref [23].

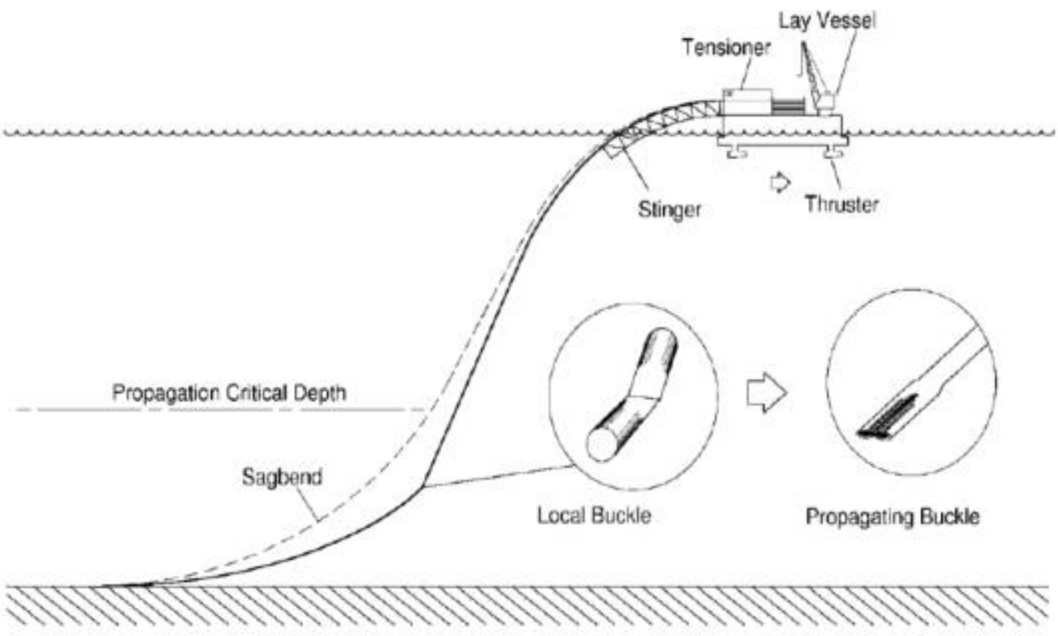


Figure 6: Initiation of propagating buckle from a local buckle in S-lay, Ref [23]

The lay-vessel primary task is to provide the tension in order to keep the suspended line and control its shape. The long-suspended pipe acts more like a cable rather than a rigid beam. The water depth, the submerged weight of the line and the tension applied at the barge define the length of the line as well as the sagbend curvature. Generally, the tensile force controls the curvature in the sagbend, however the section over the stinger can be exposed beyond its elastic limits if excessive tension is applied. As a result, most pipelines are installed empty to reduce the applied tension.

Thus, the main purpose of installation design is to avoid buckling failures in the overbend and the sagbend, and to keep the pipeline in the elastic regime. If plastic deformation occurs on the overbend or sagbend, it can lead to section ovalization and twisting of the pipeline on the seabed. Generally, the installation parameters are maximized by considering these points and the material and installation costs as well, Ref [23]

The conventional S-lay can be used for installation of pipelines for water depths up to 1,000 m. However, with the use of a longer articulated stingers on dynamically positioned vessels of high tensile force, the water depth is significantly increased.

The construction procedure in the S-lay method of installation is:

- The barge is first set in position by a mooring system or is dynamically positioned.
- The pipes pass through a series of welding stations as the barge moves forward and lengths of pipes are lined up at the upper end of the ramp
- Tensioners apply a force to the pipe near the stern end of the ramp

- The welded pipes supported by the stinger structure, leave the barge at the stern. The pipeline

- The shape of the pipeline in the sagbend is controlled by the interaction between the applied tension and the submerged weight of the pipeline.

In this method, single lengths of steel pipe are welded, inspected and field coated in a horizontal working plane (firing line) on board a pipelay vessel. As the vessel moves forward, the pipe gradually exits the firing line, curving downward through the water until it reaches the touch down point on the seabed. As more pipe is welded in the line and eased off the vessel, the pipe forms the shape of an 'S' in the water under its own weight.

Stingers, measuring up to 91 meters long, extend from the stern to support the pipe as it is moved into the water, as well as to control the curvature of the installation. Some pipelay barges have adjustable stingers, which can be lengthened or shortened depending on the water length.

The pipe tension force is an integral part during the S-lay process, which is maintained via tensioning rollers and a controlled forward thrust, keeping the pipe from buckling. S-lay method can be performed in water depths up to 2000 meters deep and about 6 kilometers a day of pipe can be installed in this manner.

Advantages and Disadvantages of S-lay

As an offshore pipeline installation method, the S-lay has some benefits and drawbacks compared to other methods. Below is list of some advantages and disadvantages of the method:

Advantages

- It is the best method for installing large diameter single pipelines.

- It is possible to install pipelines with various diameters. Hence, there is no limitation to pipeline diameter and length.

- Suitable for installation in shallow and intermediate waters.

- Multiple tasks such as welding, NDT and field joint coatings can be done simultaneously.

- Minimum modification is required to its system to suit varying diameter pipe (As an example, a barge can lay a 48" pipeline in a certain project and shortly it can lay a 6" pipe on another project with a minimum modification to its system)

- Once the lay vessel is mobilized, it can operate efficiently with minimum shore support.

- The method is beneficial for routing and minimizing spans.

Disadvantages

- Limited installation depth due to limited tension capacity.
- The size and shape complexity of the stinger increases with an increase in water depth.
- The pipeline and the stinger are exposed to large hydrodynamic loads as it enters the water.

2.1.3 'J' Lay Method

As water depth of S-lay installation increases, the suspended length of the pipeline increases resulting in a significant rise in tension force applied by the lay vessel. Moreover, deeper water installations need a longer stinger size, which increases in complexity and cost, to control and support the overbend curvature of the suspended pipe.

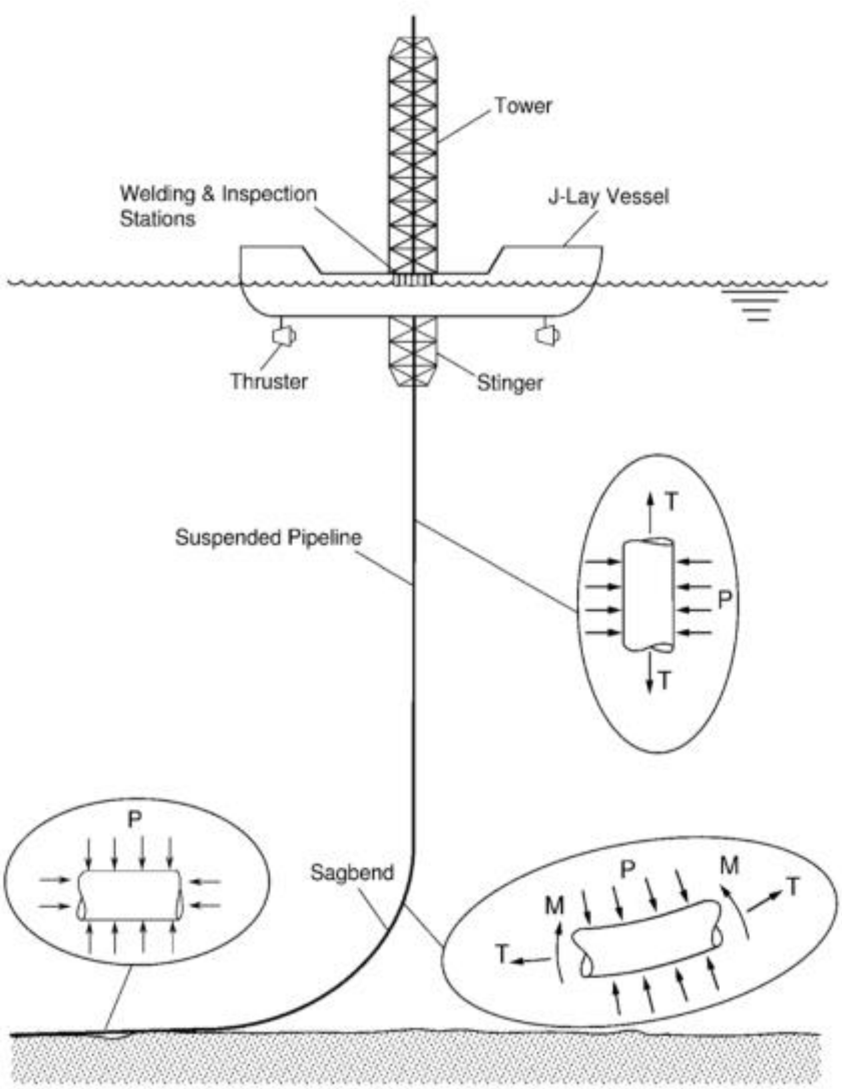


Figure 7: Schematic representation of J-lay pipeline installation & associate pipe loading, Ref [23]

However, these issues are solved if we can avoid the notion that the pipe leaves the lay vessel horizontally and the solution comes in the J-lay method. The J-lay method of installation allows the pipe to leave the vessel in a nearly vertical position i.e. the actual tower angles vary between 0^0 and 15^0 from the vertical. In this method, the pipeline forms a J shape on the way down to the seabed as shown in figure 7.

Compared to the S-lay, the suspended length of the pipe in the J-lay method is remarkably reduced. As a result, the tension force required is smaller and its main function is to support the shorter suspended pipe length and to control the line curvature in the sagbend close to the sea bed. In addition, since the vessel in J-lay method applier a smaller tensile force the requirement of thruster power is significantly reduced, Ref [23].

The fact that the pipe leaves the vessel in a vertical position, the J-lay method is usually equipped with one welding and one inspection station for NDT. Therefore, to increase the efficiency and expedite the operation of the installation longer pipe sections are used. These pipes usually consist of four to six sections of 12m long and are welded onshore. Each multiple section pipes are lifted to the tower, fully aligned with the suspended pipe, welded, inspected and coated (Figure 8). The pipe is then lowered and installed to the seabed as the lay vessel moves forward. A short stinger just below the pipe holding point is used to guide the direction of the line near the water surface. The positioning and alignment of the pipe is done very precisely due to the fact that the touch down point is very close from the lay vessel.

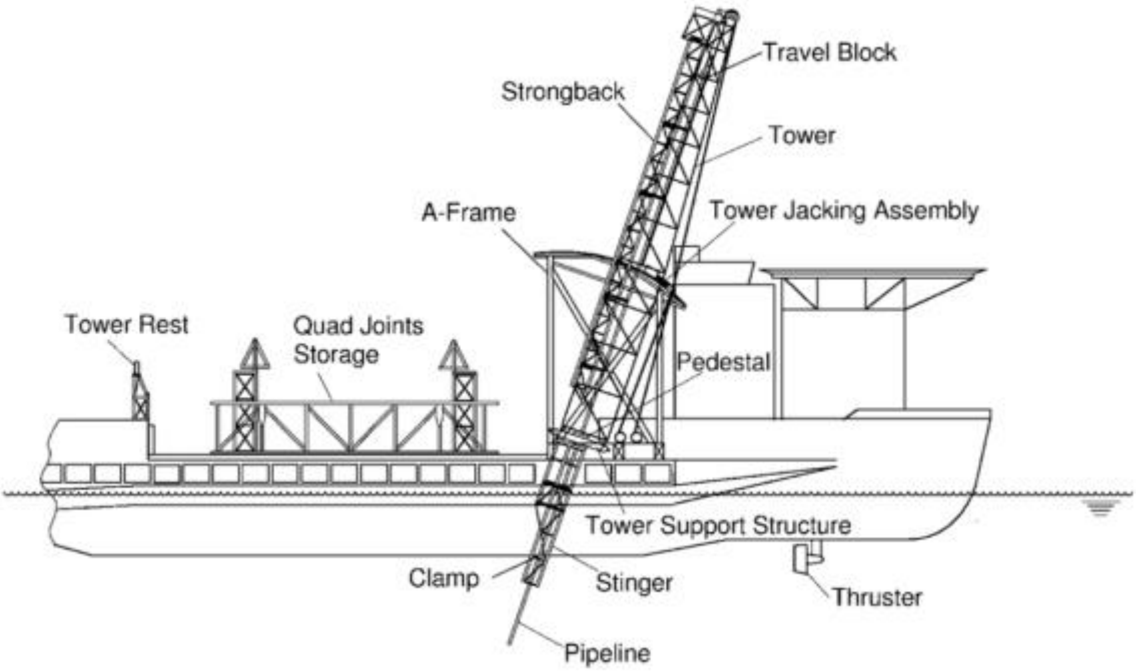


Figure 8: Schematic showing DP 50 and its J-lay tower, Ref [23]

The J-lay method is comparatively slower than the S-lay method, but it is a preferred method of installation in deep water of up to 3,350 m depth. In the case of the deep water, the pipeline is exposed to different load conditions as illustrated schematically in figure 7. The loads acting on the pipeline are:

- High tension and relatively small external pressure close to the surface of the sea;
- Progressively increasing pressure and decreasing tension down the long-suspended section;
- High external pressure and bending in the sagbend and
- Hydrostatic pressure on the flat seabed.

Hence, the pipeline should be designed to resist each of the above loadings. Furthermore, the initiation of propagation buckle should also be addressed properly and it is compulsory to install buckle arrestors to mitigate and control the buckle propagation.

Advantages and Disadvantages of J-lay

Some of the advantages and disadvantages of the J-lay method are, Ref [27]:

Advantages

- Since the pipe leaves the vessel in a vertical position, the required tension force is determined by the limit in the sagbend. Hence, the required tension force is less.
- The pipeline is not exposed to significant hydrodynamic forces since it is positioned nearly vertical into the water.
- No overbend and stingers are required, as a result the limit criteria for overbend region is eliminated.
- Compared to the S-lay, the J-lay method of pipelaying is precise because of the location of the TDP is close to the vessel and the lay tension is less. This also enables the lay vessel to operate in congested area.
- Free spans get reduced due to the fact that a smaller lay tension result in reduced bottom tension in the pipeline.

Disadvantages

- The pipe lengths are restricted by the height of the tower.
- The height of the tower and the added weight at the top has a significant effect in the stability of the laying vessel.
- The number of stations for welding and inspection is usually not more than one, which leads to a slow welding and installation time compared to the S-lay method.
- If the barge operates in shallow waters, the ramp has to be lowered to a less steep angle, else the pipe bends with a small radium to reach the seabed horizontally.

2.1.4 Reel Lay Method

The reel lay method is a very efficient installation method for offshore pipelines. The method involves onshore reeling of a long pipeline into a large diameter reel mounted on a reel vessel. The vessel moves to the installation site and installs the pipeline slowly by unreeling the pipes offshore. The installation time and cost of the reel lay method is remarkably reduced due to the continuity of the system and the relocation of the fabrication process to onshore i.e. assembly, welding, NDT and coating.

The first offshore pipelines that were laid from a reel were wrapped onto a floating spool and towed by tug vessels before being unspooled. The pipelines were not straightened as it leaves the barge. Reeling was used subsequently to install small diameter pipelines. One of the reeling vessels capable of laying 12.75inch pipe was the Chickasaw, refer to figure 9, a flatbed barge constructed with a horizontal reel of 6.1m radius and a system for straightening of the pipe as it leaves the vessel. The vessel was upgraded to equip it with dynamic positioning, increasing tension capacity and longer stinger, Ref [23].

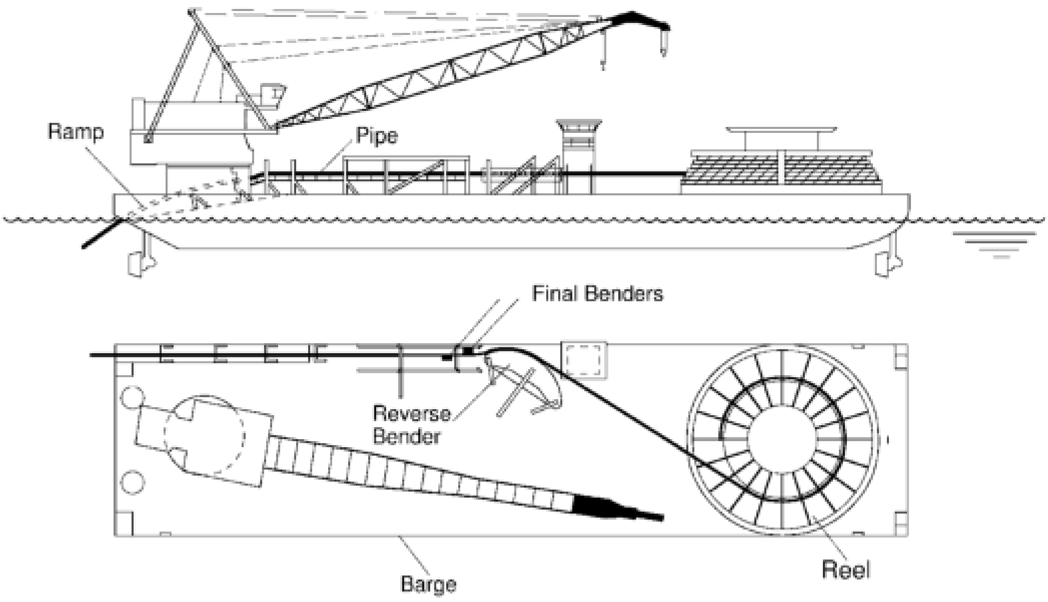


Figure 9: Schematic of Chickasaw reel pipelay barges, Ref [23]

However, subsequent developments in the reeling industry brought the construction of a vertically oriented sea-going ships like the Apache. The vessel is capable of installing pipelines of diameter up to 16-inch and it can straighten the pipeline as it is paid into the sea supported by sloping ramp, refer to figure 10, Ref [13]. The pipe bends over the overbend of the ramp, straightens and is reverse-bent by a special straightener. The size of the ramp is 32x9m structure with a level wind mounted on it. The level wing carries all pipe-handling equipment like overbend track, straightener and tensioner. The ramp inclination angle is adjustable and can be set between 18^0 and 60^0 (72^0 with special additions) to the horizontal, which allows installation in different water depths.

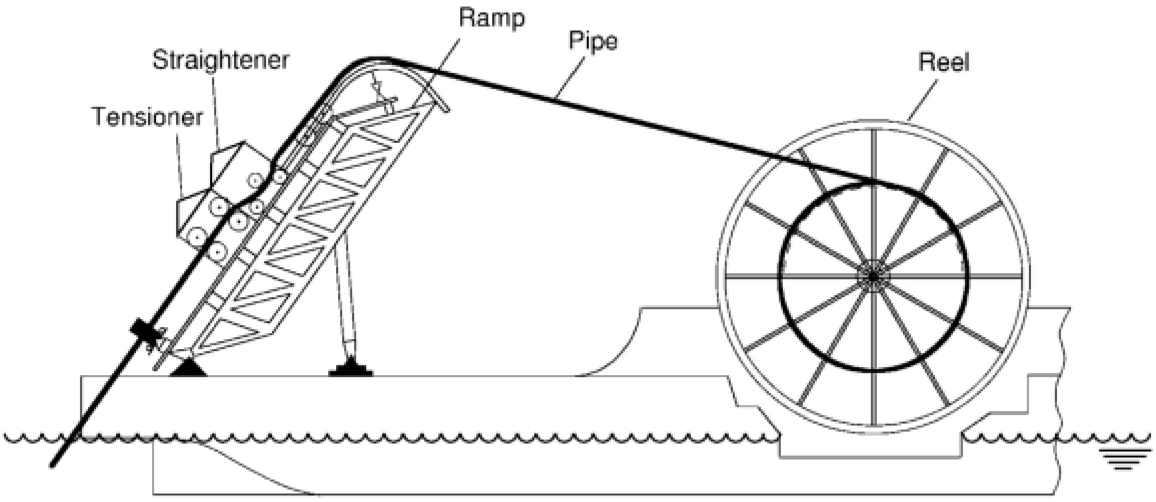


Figure 10: Schematic of Technip's Apache reel ship, Ref [23]

The spooling and unspooling of the reel installation induce bending curvature to the pipe well into the plastic curvature. As an example, it can be noted that a 12inch pipe bends a maximum strain of around 1.93%, while a 16inch pipe bends to 2.41% strain. Hence the local buckling due to bending should be avoided by selecting the right wall thickness and mechanical properties of the material. In addition, the local buckling of the materials can be reduced by applying the tension during the reeling and unreeling of the pipe on the reel. It is to be noted that the operational characteristics of the vessel can induce extra plastic bending cycles in the pipeline. Figure 11 illustrates the schematic drawing of the moment-curvature history experienced by the pipe during installation.

The pipe is initially plastically deformed to a curvature k_1 during the spooling onto the reel vessel (from point 0 to 1). During the unspooling, the pipeline straightens (from point 1 to 2) due to the tension applied on the pipeline, and bends again to curvature k_3 as it goes over the overbend on the ramp. The pipe straightens once more at the downstream of the overbend (from point 3 to 4) and in the end, it is reverse bent in the straightener (from point 4 to 5), and it ends up to an approximate zero moment and curvature during the unloading.

It should be noted that such bending loading histories have an effect on the pipe geometry and its fatigue life. Although the process is meant to avoid bending buckles, the repeated exposure into the plastic range initiates ovalization of the pipe cross section, causes some permanent elongation, and changes in its mechanical properties of the material.

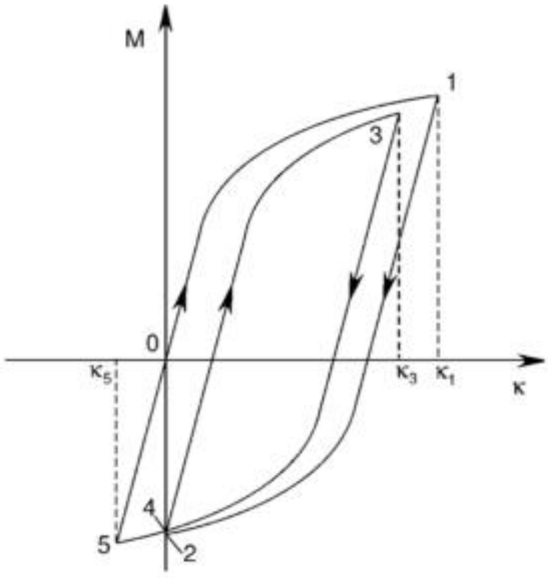


Figure 11:Moment-curvature history seen by pipe during reeling and unreeling on the Apache, Ref [23]

Spoolbase

The use of reel lay method for offshore pipeline installation requires an onshore fabrication facility known as 'spool base'. The major works that are conducted at the spool base are welding and coating of pipelines, onshore inspection and non-destructive testing (NDT), prepare stalks – a very long strings of pipelines & wound the stocks onto the reel of the reel-lay vessel.

Figure 12 shows Subsea7's North Sea spool base at Vigra, Norway. The facility handles single and double joint pipes, providing a very flexible set of fabrication; the facility includes a fully automatic pipe handling system, with a stalk rack length of 1,520 meters.

The key features of the facility are, Ref [33]:

- 110m Long quay
- 1520m Long pipe stalk rack
- 375m fabrication building
- 22 station fabrication line
- Single joint, pipe in pipe and auxiliary fabrication
- Fully automatic pipe handling system

Figure 12: Subsea7 North Sea spoolbase Vigra, Norway, Ref [22]

Advantages and Disadvantages of Reel-lay

Some of the advantages and disadvantages of the reel-lay method are:

Advantages

- The pipelines are welded onshore and this speeds up offshore installation and minimizes vessel costs and improves the fabrication quality.
- The method is suitable to the use of corrosion resistant materials and the use of plastic lined pipe for water injection.
- The method is suitable for various coatings such as FBE and solid polypropylene.

Disadvantages

- The method is not suitable to concrete coating.
- There is limitation on pipe diameter and the existing limitation to reeling pipes is 18'' OD.
- There could be inconsistency in section stiffness between adjacent joints and this results in discontinuity and strain concentration.
- The section stiffness varies due to changes in material property (i.e. yield stress) and geometrical properties i.e. wall thickness.
- Possibility of strain concentration which can result in local buckle near the pipe joint.
- Stiff coatings with gaps across field joints will amplify strain concentration at the joints.

2.2 Catenary Analysis

2.2.1 Introduction

The installation of pipelines with residual curvature assumes a catenary shape. The top tension, the nominal curvature, end conditions and the length of the pipeline from the surface to the seabed TDP are all dependent on the suspended catenary shape. Therefore, it is necessary to introduce catenary equations in order to validate the models used in the thesis.

The installation of marine pipelines in deep water is achieved by allowing the pipe to leave the lay vessel at a certain angle and maintaining it under high tensile action, while lowering it to the bottom of the seabed. The applied axial force is selected in such a way that there will be no overstressing and buckling of the pipeline at the touch down point with the seabed. Moreover, the upper end of the pipeline should be infinitely fixed to the lay vessel during installation of each section of pipeline. The choice of the angle at the upper end is to avoid a large bending moment imposed at the clamp position, Ref [9].

In the following section of the chapter, equations for determining the end conditions are derived by assuming the pipeline to take a shape of a natural catenary and a stiffened catenary. This will be the basis to the models developed in the analysis of pipe installation and pipe roll.

2.2.2 Natural Catenary

A natural catenary can be defined as the shape formed due a free hanging line under the action of the gravity. A typical natural catenary shape can be described as shown in figure 13, Ref [17]. A detailed natural catenary system is defined and we will reach to the basic equation of catenary along with the derivation of the formulas.

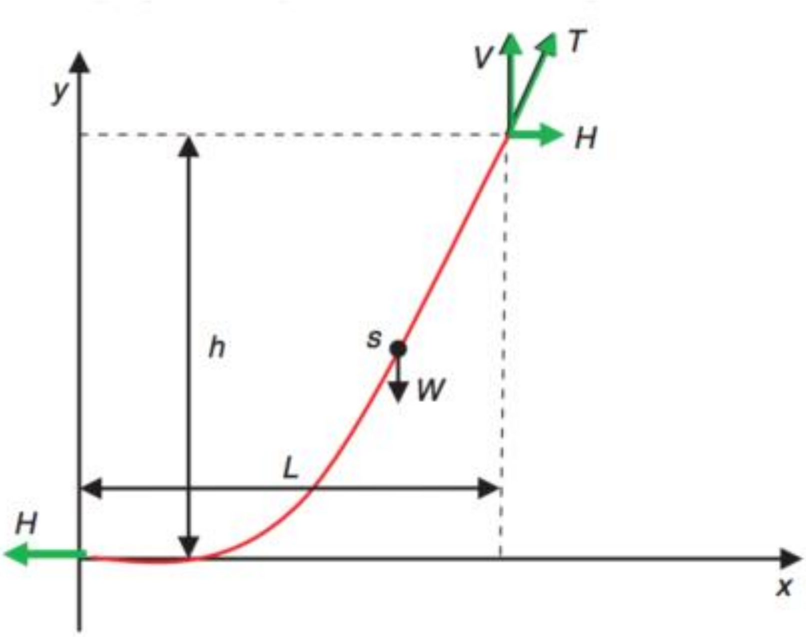


Figure 13: The hanging chain, the catenary, Ref [17]

Where,
T - Tension in the catenary line
V - Vertical component of the tension
H - Horizontal component of the tension
s - length of the catenary line to the seafloor
L - Horizontal distance from the point the tension applied to the seafloor
h - Water depth
W_s - Submerged weight of the catenary line

It is to be noted that pipe stiffness (i.e. resistance to deflection) plays an important role in the analysis of short pipelines, but long sections of unsupported pipe lengths are similar to a chord or cable; which implies that the shear is almost non existant and the curvature appears without a considerable moment. In this case, the pipeline can be approximated as a natural catenary over the majority of its length. However, on both sides of the ends the geometry turns aside from the natural catenary because of the bending stiffness and boundary conditions which are not well matching to the natural catenary.

If a marine pipeline is assumed to take a natural catenary geometry throughout its unsupported length, the maximum curvature occurs at the touch down point with the sea floor assuming the sea floor is flat. The shape of the pipeline and the required minimum tension at the lay vessel are selected to minimize the curvature at the touch down point and, thereby, to control the maximum stress due to bending, Ref [9].

I. Length of natural catenary

To analyze the different parameters involved in the natural catenary, consider a small section from the geometry, figure 14, and the relationship between the distance from the vessel to the touch down point, L, and forces acting on the catenary are derived as follows:

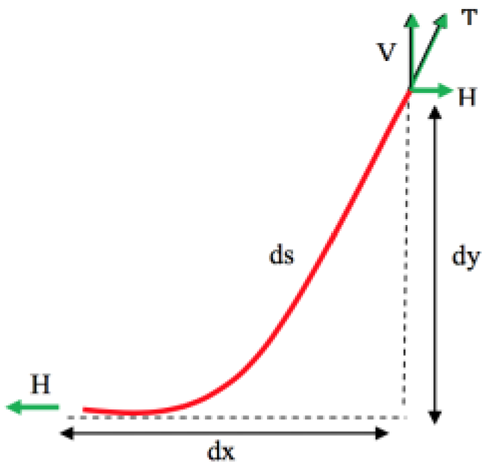


Figure 14: A section of the catenary, Ref [20]

Let us consider the relationship between the vertical and horizontal force components of the catenary:

$$ds = \sqrt{dx^2 + dy^2} \quad (2.1)$$

$$\frac{dy}{dx} = \frac{V}{H}$$

$$V = H\frac{dy}{dx} = Hy'$$

$$\frac{dV}{dx} = H\frac{d^2y}{dx^2} = Hy''$$

but over a distance dx, $dV = W_s ds$ (2.2)

$$W_s ds = Hy'' = H\frac{d^2y}{dx^2} \quad \text{where, } ds = \sqrt{dx^2 + dy^2}$$

$$w_s\sqrt{dx^2 + dy^2} = H\frac{d^2y}{dx^2}dx$$

$$w_s dx\sqrt{1 + \left(\frac{dy}{dx}\right)^2} = H\frac{d^2y}{dx^2}dx$$

$$\frac{W_s}{H}dx = \frac{\frac{d^2y}{dx^2}}{\sqrt{1+\left(\frac{dy}{dx}\right)^2}}dx$$

$$\frac{W_s}{H}dx = \frac{\frac{d}{dx}\left(\frac{dy}{dx}\right)}{\sqrt{1+\left(\frac{dy}{dx}\right)^2}}dx \qquad let\ \frac{dy}{dx} = y'$$

$$\int_0^x \frac{W_s}{H}dx = \int_0^{y'} \frac{dy\prime}{\sqrt{1+y\prime^2}}dx \qquad at\ x = 0,\ y' = 0$$

$$\frac{W_s}{H}x = arcsinh(y') = sinh^{-1}y'$$

$$y' = sinh\left(\frac{W_s}{H}x\right)$$

Hence, the formula for the catenary is:

$$y = \frac{H}{W_s}\left(cosh\left(\frac{W_s}{H}x\right) - 1\right) \quad (2.3)$$

In terms of x = L and y = water depth h, we have:

$$h = \frac{H}{W_s}\left(cosh(\frac{W_s}{H}L) - 1\right) \tag{2.4}$$

$$h\frac{W_s}{H} + 1 = cosh\left(\frac{W_s}{H}L\right)$$

$$\frac{W_s}{H}L = arccosh\left(\frac{hW_s}{H} + 1\right)$$

Therefore, the distance, L, to the touch down point is:

$$L = \frac{H}{W_s} arccosh\left[\frac{hW_s}{H} + 1\right] \tag{2.5}$$

From equation (1), we know that:

$$W_s\frac{ds}{dx} = H\frac{d^2y}{dx^2}$$

$$\frac{ds}{dx} = \frac{H}{W_s}\frac{d^2y}{dx^2}$$

$$s = \frac{H}{W_s}\frac{d(y)}{dx}$$

$$s = \frac{H}{W_s}\frac{d}{dx}\left[\frac{H}{W_s}\left(cosh\left(\frac{W_s}{H}x\right) - 1\right)\right]$$

$$s = \frac{H}{W_s}\left(sinh\frac{W_s}{H}L\right) \tag{2.6}$$

Using equations (2.4) and (2.6), the relation between the line tension, H, the length of the catenary line, S, and the water depth, h, can be obtained as follows:

$$s^2 - h^2 = \left(\frac{H}{W_s}\right)^2\left\{sinh^2\left(\frac{W_s}{H}L\right) - \left[\cosh\left(\frac{W_s}{H}L\right) - 1\right]^2\right\}$$

$$s^2 - h^2 = \left(\frac{H}{W_s}\right)^2\left\{sinh^2\left(\frac{W_s}{H}L\right) - \left[cosh^2\left(\frac{W_s}{H}L\right) - 2\cosh\left(\frac{W_s}{H}L\right) + 1\right]\right\}$$

$$s^2 - h^2 = \left(\frac{H}{W_s}\right)^2\left\{sinh^2\left(\frac{W_s}{H}L\right) - cosh^2\left(\frac{W_s}{H}L\right) - 1 + 2\cosh\left(\frac{W_s}{H}L\right)\right\}$$

We know that:

$$sinh^2\alpha - cosh^2 = -1 \qquad (2.7)$$

Hence:

$$s^2 - h^2 = \left(\frac{H}{W_s}\right)^2 \left\{-1 - 1 + 2\cosh\left(\frac{W_s}{H}L\right)\right\}$$

$$s^2 - h^2 = \left(\frac{H}{W_s}\right)^2 \left\{2\cosh\left(\frac{W_s}{H}L\right) - 2\right\}$$

$$s^2 - h^2 = 2\left(\frac{H}{W_s}\right)^2 \left\{\cosh\left(\frac{W_s}{H}L\right) - 1\right\}$$

$$s^2 - h^2 = 2\frac{H}{W_s}\frac{H}{W_s}\left\{\cosh\left(\frac{W_s}{H}L\right) - 1\right\}$$

$$s^2 - h^2 = 2\frac{H}{W_s}h$$

$$\frac{W_s}{2h} * (s^2 - h^2) = \frac{W_s}{2h}2\frac{H}{W_s}h$$

Therefore, the relation between the three parameters is given by:

$$H = \frac{W_s}{2h}(s^2 - h^2) \qquad (2.8)$$

II. Estimation of horizontal component of tension

One main reason why the natural catenary is an attractive method for laying pipeline is that the horizontal component of tension at the lay vessel H is independent of the water depth h, and can be estimated as, Ref [9]:

$$H = \frac{cW}{\epsilon_b} \qquad (2.9)$$

Where, H - Horizontal component of the tension

W - the buoyant unit weight of the pipeline

c - the external radius of pipeline cross section $D_0/2$

ϵ_b - maximum allowable bending strain.

Hence, the horizontal tension applied by the lay vessel doesn't necessarily increase with water depth.

The maximum allowable bending strain ϵ_b in estimating the horizontal component of tension should be limited based on the corresponding bending stress, $\sigma_b = \epsilon_b E$, is a percentage or fraction of the yielding stress. It is to be noted that although the axial stress is very negligible, it does exist at the maximum curvature section and hence it is necessary to calculate in case the total stress does exceed its permissible range.

2.2.3 Stiffened Catenary

If a suspended pipeline is assumed to take a natural catenary shape, the end effects due to the pipeline bending stiffness are neglected when analyzing the different parameters of the catenary. However, if we adopt a stiffened catenary, then the catenary should be considered moment free at its touch down point and at the surface. Thus, the location of the maximum bending is at some distance above the sea bed and, it can be demonstrated that, the maximum bending stress is less than that estimated by the natural catenary analysis. It is to be noted that the curvature of the natural catenary is non-zero, thus the natural catenary is unable to satisfy the moment-free end condition at the lay barge.

Dixon and Rutledge have estimated the shape of a suspended marine pipeline and their study can be summarized in the following points, Ref [9]:

- In determining the shape of the stiffened catenary, it is assumed that the pipeline is tangent to the horizontal sea floor at the TDP and moment free at the laybarge end;
- The exact solution of an unsupported pipeline is not known, but by using Plunkett's asymptotic expansion a close approximation was obtained for the shape of the unsupported pipeline. The approximate solution also provides a way to measure the effect of bending stiffness;
- The shape of the pipeline is described by its angle (θ) with respect to the vertical line. In defining the shape angle, nondimensional quantities are used to measure the influence of bending stiffness and the vertical and horizontal components of axial force;
- The lay-barge end conditions of stiffened catenary are notably more complicated than the corresponding natural catenary. However, by using nondimenional curves the importance of the stiffened catenary is presented. Nondimentional curves for minimum tension and required angle at lay barge are illustrated in figure 15 and figure 16 respectively;
- A stiffness factor defined by $\frac{EI}{w}(\frac{\epsilon_b}{c})^3$ is introduced to measure the relative influence of bending stiffness on deflection in comparison to the influence of axial tension. For various standard oil and gas pipeline sizes the stiffness factor is found to be less than 0.015.

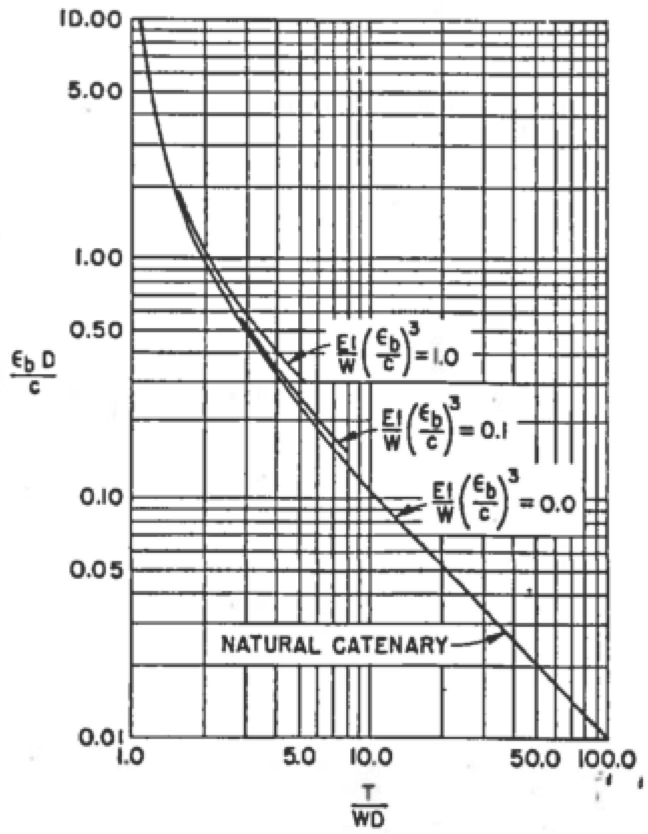


Figure 15: Nondimensional curves for minimum tension at laybarge, Ref [9]

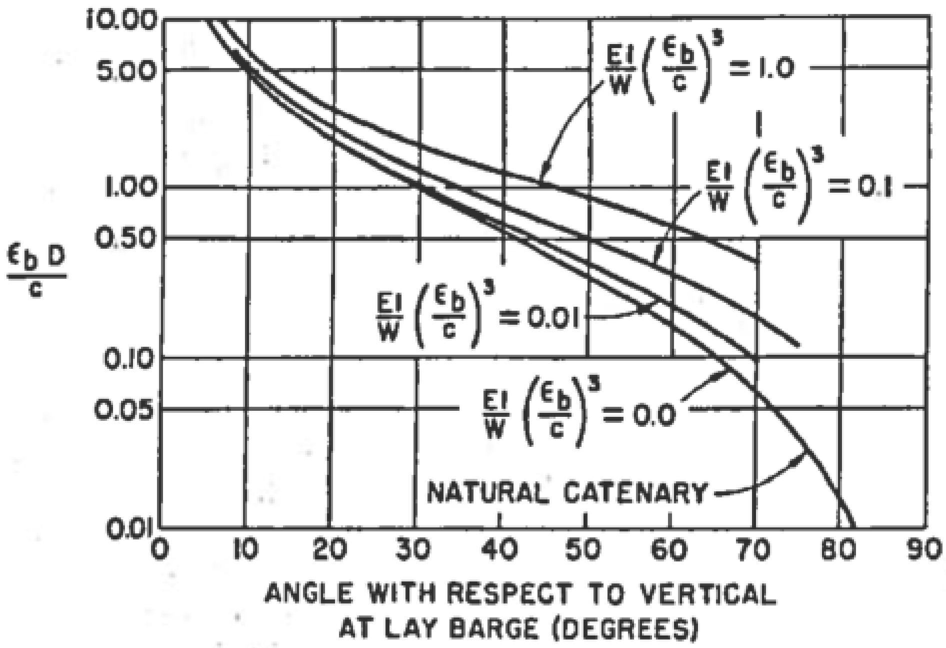


Figure 16: Nondimensional curves for required angle at lay barge, Ref [9]

Where, E – Modulus of Elasticity

I – Second moment of area

W – the buoyant unit weight of the pipeline

ϵ_b - Maximum allowable bending strain

c - the external radius of pipeline cross section $D_0/2$

D – Water depth

T – Minimum tension

- As shown in figure 15, the influence of bending stiffness on T/WD is very negligible and, in particular, the curve for stiffness factor 0.010 is superbly overlapping with that of the natural catenary (stiffness factor 0.00). As stated above, the stiffness factor of the commonly used pipelines was found to be less than 0.015. Hence, the minimum tension T given by the natural catenary is precise.

- In the case of the angle required at lay barge θ, refer to figure 16, the stiffness factor has a substantial influence on the angle at shallower water depths. However, with an increase in water depth (i.e. $\epsilon_b D/c$) the difference in the estimated angle between the stiffened and natural catenary diminishes to a point where the bending stiffness is insignificant at water depth for which $\epsilon_b D/c$ = 1.0.

As a conclusion, the natural catenary method is used when the influence of the stiffness on deflection is negligible in comparison to the influence of the axial force. By comparing the graphs prepared from both catenary methods, the minimum tension at the lay barge is not significantly influenced by the bending stiffness. Hence, the horizontal tension obtained from the natural catenary are precise and acceptable for all types of pipe sizes. But, the corresponding angle at the lay barge has considerable dependence on stiffness. And hence, the stiffened catenary approach for angle should be adopted over the natural catenary when laying pipelines at the common water depths.

It should be noted that in both methods the sea floor is assumed to be horizontal flat. Moreover, the dynamic stresses due to the motions of the lay vessel, wave forces and current forces acting on the suspended pipe line are excluded in both the natural and stiffened catenary methods of analysis, Ref [9].

2.3 Buckle Initiation techniques

2.3.1 Introduction

The recent development of residual curvature method for controlled lateral buckling of pipelines is due to the advantage it holds over the conventional buckle initiation techniques. To briefly explain the advantage of the residual curvature method, it is necessary to introduce a brief discussion to the commonly used buckle initiation techniques in the industry.

According to the experiments performed by Hobbs, Ref [21], a pipeline can deform into a number of different lateral mode shapes; the most common buckling shape configurations are presented in figure 17.

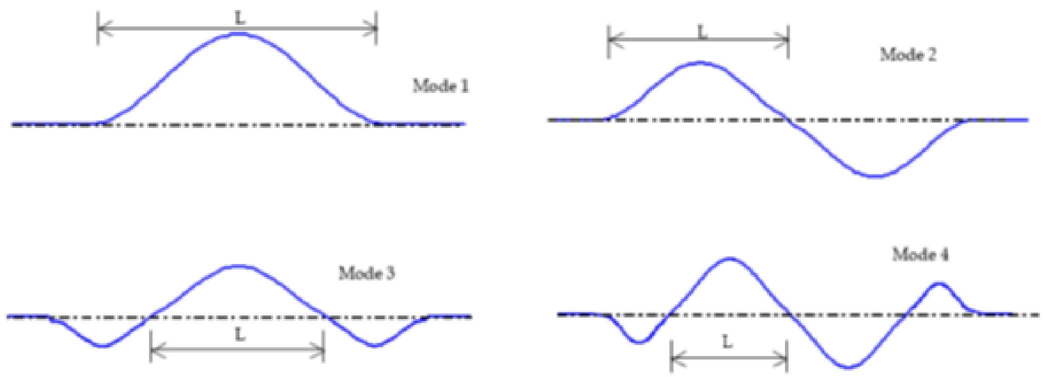


Figure 17: Pipeline Buckling, Ref [31]

Lateral buckling of pipelines can be controlled by generating lateral buckles at predetermined intervals along the length of the pipeline. The lateral buckling design strategy usually involves a buckle initiation technique, in order to guarantee the formation of regular buckles. All of the buckle initiation techniques that are in use sofar aim to impose relatively large OOS features at known locations. By initiating buckles at regular intervals along the pipeline, the loads are effectively shared between buckles sites, thus reducing and controlling the load in the pipe, Ref [31].

2.3.2 Common buckle initiation Techniques

A number of methods are available to initiate buckling at a controlled spacing. In this section, some of the conventional techniques the offshore industry employs to control and mitigate lateral buckling are discussed, Ref [19] [31].

I. Snake-Lay

The Snake-lay method is one of the buckle initiation techniques where the pipeline is laid in a series of gentle curves, as shown in figure 18. The key parameters in the snake lay configuration are snake pitch, offset and the bend radius. The bend radius is the average lay radius around the bend. The buckle response is influenced by the arc length which is defined by the offset and bend radius of the snake configuration. The purpose of the snake lay is to develop a lateral buckle at some point on the curve by aiming the bend radius to act as a buckle initiator, Ref [31].

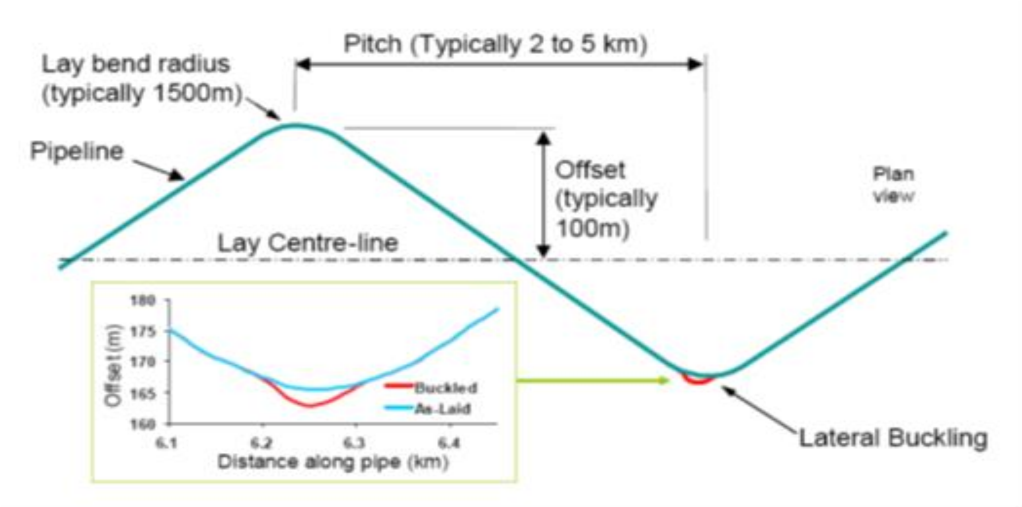


Figure 18: Typical Snake lay configuration, Ref [31]

II. Vertical upset

The vertical upset technique works by deliberate pre-installation of artificial vertical imperfections at a number of locations along the pipeline as shown in figure 19.

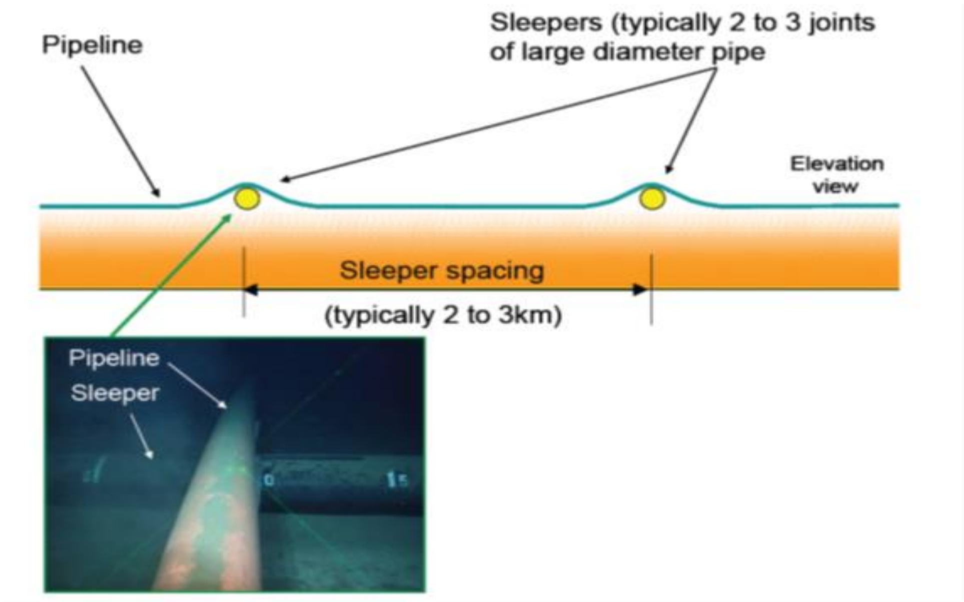


Figure 19: Buckle Initiator Using Sleepers, Ref [31]

The method is based on the fact that pipeline buckling can be initiated in either vertical or horizontal direction. Due to the irregularity at the seabed, the pipeline's initial vertical movement is likely to develop into a lateral buckle. Sleepers, concrete or rock berms can be used as a means to create the artificial irregularities at the seabed. Each imperfection locally raises the height of the pipe above the seabed and on either side the pipe forms a free-span, Ref [28] [31].

III. Distributed buoyancy

In the distributed buoyancy method, specific lengths of typically 60 to 200m of the pipeline are installed with additional buoyancy on them to reduce weight. These lengths of the pipeline are intended to act as buckle initiation sites as illustrated in figure 20. Typical buckle spacing that is used in this method is 2 to 3km. The aim of the buoyancy is to reduce the operational submerged weight of the pipeline to about 10% of the normal submerged weight. By installing distributed buoyance vertical imperfections coupled with the hydrodynamic forces produce a natural OOS at the chosen location. Moreover, since the submerged weight is very low, the lateral frictional restraint is reduced. As a result, the buckle initiation force is also reduced. These combined effect means that the pipe is likely to buckle at the location where the buoyance is applied, Ref [31].

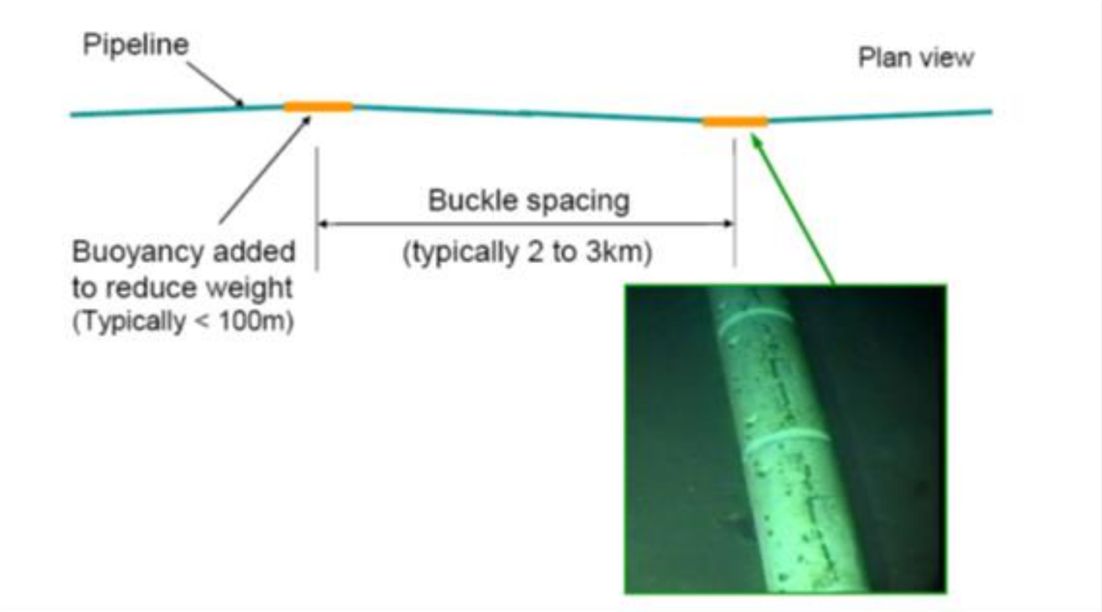


Figure 20: Buckle Initiator Using Distributed Buoyancy, Ref [31]

2.3.3 Residual Curvature Method

The residual curvature method (RCM) for lateral buckle initiator was developed and patented by Statoil, Ref [29]. The principle is based on creating intermittent residual curvature sections in the pipeline during reel-lay installation so that buckling can be initiated at these locations. By forming expansion loops, the residual curvatures share the expansion of the pipeline and thus a controlled lateral pipeline buckling is achieved under operating loads. The residual curvatures are introduced at the straightener of the reel-lay vessel during installation as presented in figure 21.

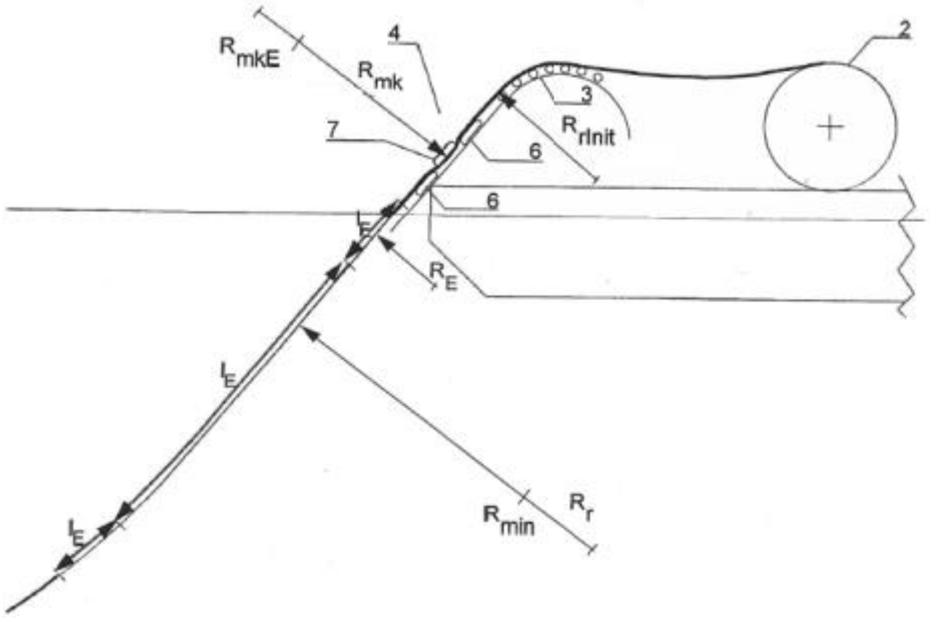


Figure 21: Straightener & residual curvatures during reel-lay installation, Ref [29]

The straightening equipment of the reel-lay is used to create imperfection in the pipeline by introducing residual strain at selected locations along the pipeline. This is achieved by adjusting the hydraulically operated tracks inside the straightener. A typical configuration of the residual curvature is to impose a residual strain of 0.15% - 0.25% over a 40m length for each kilometer during the reel-lay installation as illustrated in figure 22, Ref [6] [12] [15].

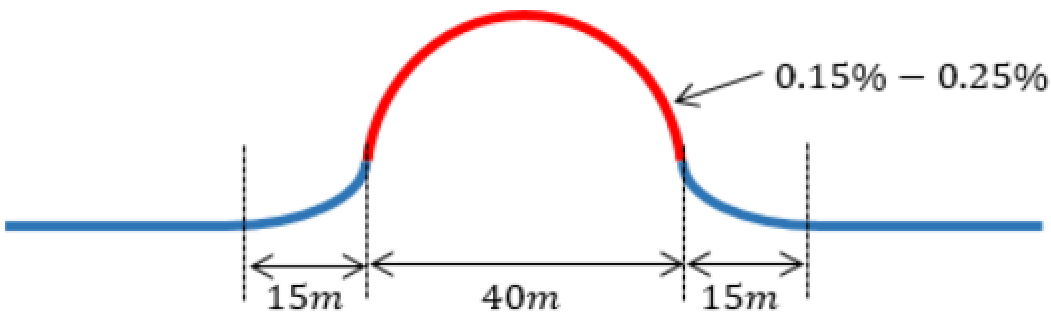


Figure 22: Typical pipe geometry of residual curvature section, Ref [6]

In place analysis and post installation survey under operational conditions confirm that the use of residual curvature is a suitable and efficient method when used as a means for controlled lateral buckling of marine pipelines because it requires no additional measure to ensure utilization within the acceptable criteria, Ref [12]. Moreover, the residual curvature method is a robust and cost-effective method as compared to the commonly used buckle initiation techniques as discussed in section 2.3.2.

2.3.4 Comparison of RCM & Common buckle initiation Techniques

The advantage of the residual curvature method for controlled lateral buckling over the commonly used techniques are summarized in table 2.

Item No.	Parameter	Description of Method	Advantage of RCM method
	I. General, Ref [2] [12] [35]		
1	**Methodology**	The conventional techniques are implemented with additional measures at the seabed, while the residual curvature method is by creating local curvatures in the pipeline by adjusting the straightener system during installation without any additional measure.	More economical and robust system.
2	**Installation time**	In conventional methods pipeline feed-out is stopped while installing initiation means or bending pipelines, whereas in residual curvature method the straightening takes additional vessel time of only 10-20 minutes per location and the feed-out is continuous.	Faster installation time
3	**Application area or lay radius**	The lay area for the application of snake lay is bigger as compared to the residual curvature method due to larger offset and bend radius.	Economical and faster
4	**Additional measures**	Pipeline installation with conventional technique is carried out with additional measures to trigger buckling during feed-in, while the residual curvature method requires no additional measures during pipe installation.	More economical
	II. Based on case study for a 10"/15" pipe-in-pipe flow line, Ref [11] [14]		
1	**Route Length**	The route length using a conventional technique snake lay is 14.0 km, whereas in the method of residual curvature is 13.3 km.	5% route length reduction is achieved.
2	**Lateral buckling force**	A lateral buckling force of 600 KN is required for the snake lay technique, but using RCM only 300 KN.	50% lateral buckling force is achieved.
3	**Lateral counteracts**	Snake lay method requires lateral counteracts for buckle initiation, while RCM method initiates buckle without counteracts.	reduction in cost of installation is achieved.
4	**Bending Moment Utilization**	The bending moment utilization in snake lay method is higher than in the residual curvature method.	Risk of overstressing is avoided.

Table 2: Advantages of Residual Curvature Methods over common buckling initiation techniques

The methodology and application of the method of residual curvatures is based on reel-lay installation, and hence its application is limited to pipe sizes of up to18" OD only

3. RESIDUAL CURVATURE & PIPE ROLL

3.1 Introduction

3.1.1 Bending moment and curvature

During the installation process, pipelines are frequently subjected to bending. In S-lay method the pipe is bent initially in the overbend and then in the sagbend. In the reel lay method, a pipeline is bent when it is wound onto the reel and is later straightened by reverse plastic bending, then bent again in the sagbend. Pipelines do bend also in situations where the seabed is uneven, or when it is trenched. Figure 23 demonstrates the relationship between bending moment and curvature in a pipeline bent well into the plastic range.

At a small curvature (large radius of curvature) the pipe bends elastically, and the ratio of the moment to the curvature is the flexural rigidity F. As the curvature is increased above the yield curvature, the outer most fibers start to yield plastically, the relationship starts to curve over.

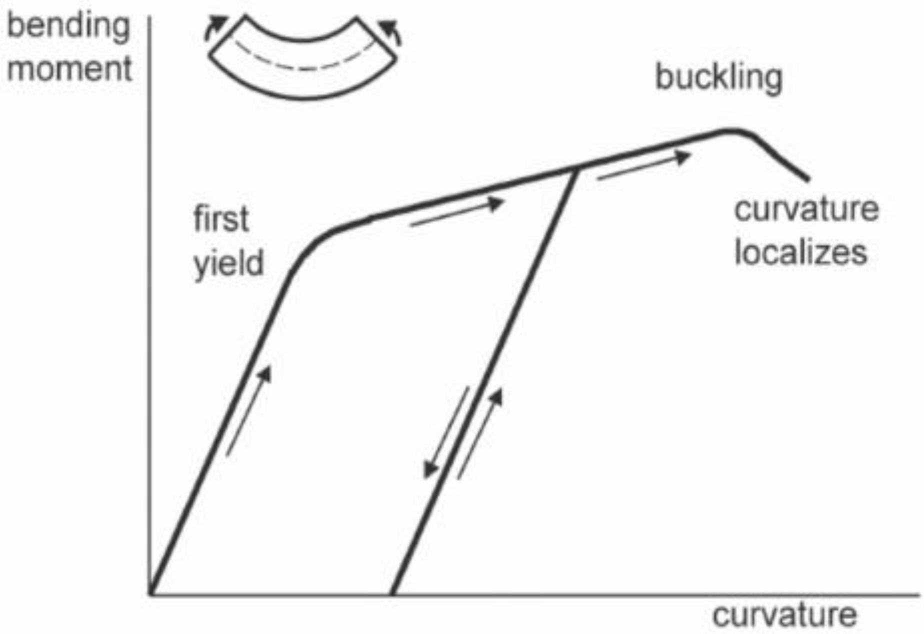


Figure 23: Relation Between Curvature and Bending Moment, Ref [27]

As the curvature is increased further, the bending moment continues to increase but slowly at a rate controlled by the interaction between strain-hardening (which tends to increase the bending moment) and ovalization (which tends to reduce the bending moment). If at that stage the curvature is reduced, the bending moment decreases linearly, and when the moment is zero, there is a residual curvature. If the curvature is continuously increased, the bending process eventually becomes unstable, and the pipe on the compression part starts to wrinkle. A buckle develops, and the bending moment decreases. The curvature is no longer uniform, and it localizes at the buckle forming a sharp twist, Ref [27].

3.1.2 Curvature and residual strain

The relationship between curvature and residual strain is illustrated in figure 24.

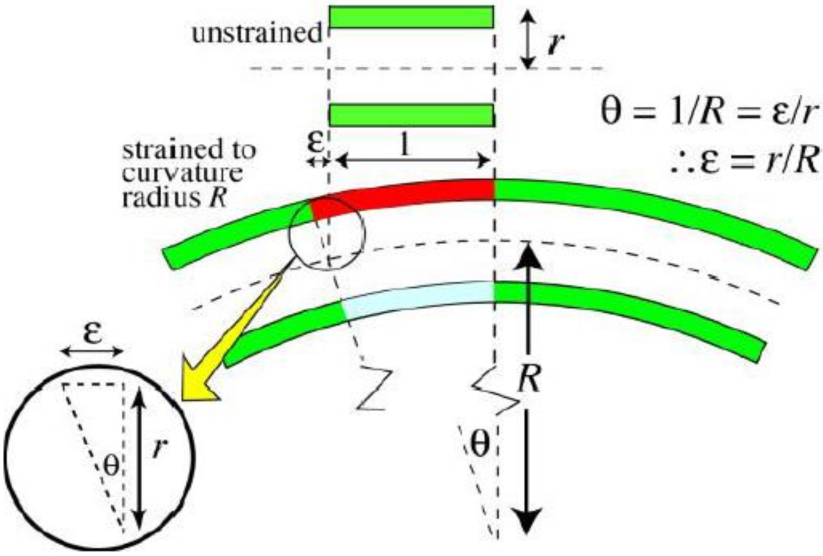


Figure 24: Curvature/strain relationship for a pipeline

For a pipe strained to a radius of curvature R:

$$tan\,\theta = \frac{1}{R} \qquad \text{but for small angle } \theta\text{, } \tan\theta = \theta \quad \Rightarrow \quad \theta = \frac{1}{R}$$

Similarly, from the small triangle:

$$\tan\theta = \frac{\varepsilon}{r} \qquad \text{but for small angle } \theta\text{, } \tan\theta = \theta \quad \Rightarrow \quad \theta = \frac{\varepsilon}{r}$$

$$\Rightarrow \quad \frac{1}{R} = \frac{\varepsilon}{r} \quad \Rightarrow \quad \varepsilon = \frac{r}{R} \tag{3.1}$$

From equation (3.1), strain and curvature can be defined as:

Strain; $\varepsilon = \frac{r}{R} = \frac{d}{2R}$

Curvature; $\theta = \kappa = \frac{1}{R}$ (3.2)

Hence, the following relation between curvature and residual strain can be made:

$$\varepsilon = \frac{r}{R} = r\kappa \tag{3.3}$$

Where, ε – strain

r – radius of pipeline

d – diameter of pipeline OD

κ – curvature

R – radius of curvature

Table 3 summarizes the residual strains used and the corresponding residual radii for the single sections of 12" ID, 14" ID and 18" OD pipe-in-pipe.

Item No.	Residual Strain	Radius of residual curvature			Remarks
		12" ID	14" ID	18" OD	
1	0.15%	116m	135m	152m	For a straight pipe, the radius of curvature should always exceed 500m.
2	0.20%	87m	101m	114m	
3	0.25%	70m	81m	91m	

Table 3 : Residual strains and corresponding radius of curvature

3.1.3 Nominal Longitudinal Strain at reel hub

The nominal longitudinal strain for the pipe on the reel is calculated in conjunction with the following equation, Ref [32]:

$$\varepsilon_F = \frac{r}{R+THK+r} \qquad (3.4)$$

Where, ε_F – Nominal functional strain during reeling

r – Pipeline OD/2

R – Minimum reel hub radius

THK – Coating thickness

Graphical representation of the parameters for the local buckling calculation method is given in figure 25.

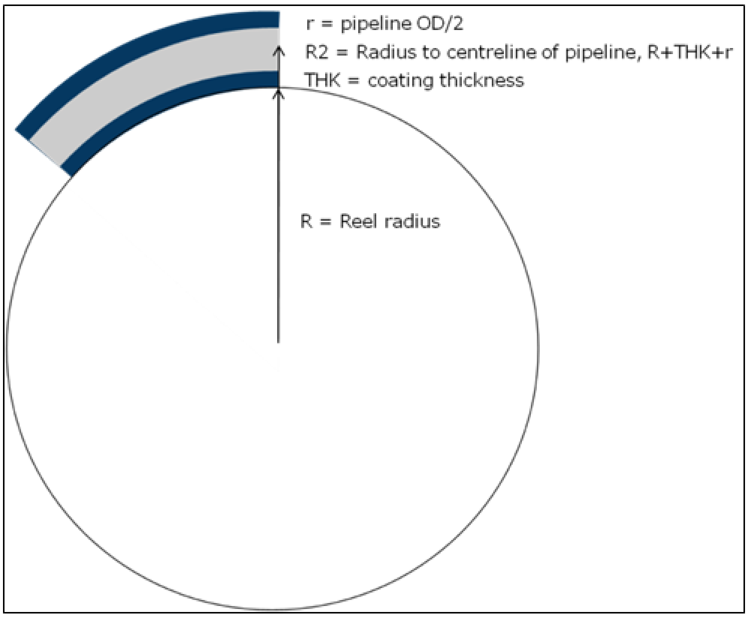


Figure 25: Local buckling calculation method, Ref [32]

3.1.4 Minimum reeling back-tension

Under normal pipeline reeling operations, the recommended minimum back tension can be calculated by the following equation, Ref [32]:

$$T \geq 1.5 \frac{M_p}{R_{reel}} \tag{3.5}$$

$$M_p \geq \frac{1}{6} \sigma_y [OD^3 - (OD - 2t)^3] \tag{3.6}$$

Where, T – Minimum recommended back tension

M_p – Plastic bending moment

R_{reel} – Minimum bending reel radius

σ_y – Mean yield stress

OD – Nominal outer pipe diameter

t – Nominal wall thickness

This minimum recommended reeling back-tension calculated from the above formula are indicative values and actual back tension required for safe reeling is always a higher value due to geometry and material strength variations. The optimum back tension range is to be determined from reeling analysis.

3.2 Residual Curvature in Reel-lay

As discussed in section 2.1.4, the installation of marine pipelines by the reel-lay method involves the reeling and unreeling of the pipeline. During this process, the pipeline experiences a plastic deformation and has a history of strains and bending cycles.

The reeling of the pipeline is done with the reel vessel at the spool base as shown in figure 26. During reeling, the straight pipeline under tension approaches the aligner and is supported on an inclined ramp. The pipe then goes over the aligner, bent and is spooled onto the reel drum. The slope of the inclined ramp is specified by the tower spooling angle (θ) measured from horizontal. The reeling of pipelines at spool base is carried out at a lower spooling angle of the inclined ramp, Ref [28]

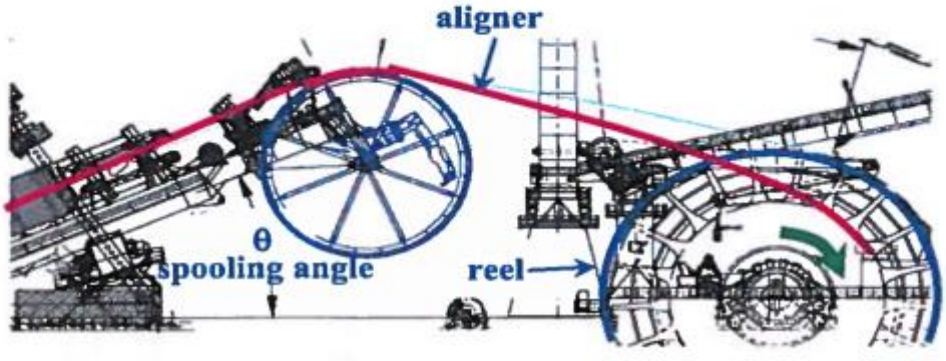


Figure 26: Reeling of a pipe at spool base, Ref [28]

The unreeling of pipeline is made by reversing the reeling process. Once the reel-vessel reaches the installation site, the inclined ramp is raised to the designed lay-angle. The pipe is then unspooled from the reel drum, goes over the aligner and reaches the straightener. A reverse bending is applied to the pipe as it makes contact with the upper track of the straightener. Figure 27 shows the unreeling of the pipeline.

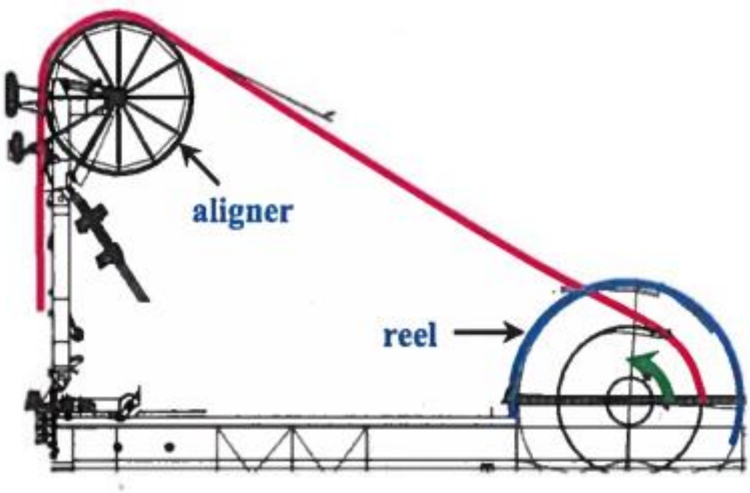


Figure 27: Unreeling of a pipe at installation location, Ref [28]

3.2.1 Pipe Straightening

The method of residual curvature is applicable for pipelines which are installed by reel-lay method. The pipelines installed by the reel-lay method are required to be straightened out before laying on the seabed. The reel-lay vessel is equipped with a straightener attached to the tower, the main function of which is to straighten the pipe as it is unreeled from the reel drum by removing the plastic deformation applied to the pipe during the reeling process. Figure 28 shows sketch of the reel ship's straightener and the suspended pipe during installation.

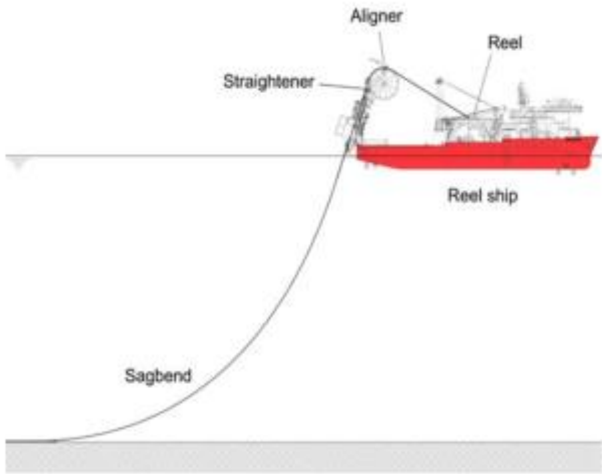


Figure 28 : Sketch of the reel ship's straightener and pipeline, Ref [12]

The straightener has three main components: Upper track, Sole drive and Lower track. As the pipe departs the aligner, it is reverse bent to the curvature of the upper track. The pipe then moves to the tensioner, where it is guided by the lower track to avoid any misalignment from happening during the point of entry. The process of pipe straightening is performed by properly adjusting the position and orientation of the upper track of the straightener and applying a reverse bending to the pipe until the pipe straightens out as shown in figure 29. The process gives the pipeline a nominally zero curvature and axial strain to the pipeline. A combination of three hydraulic cylinders (top, bottom and positioning cylinders) are used to control the upper track, Ref [28].

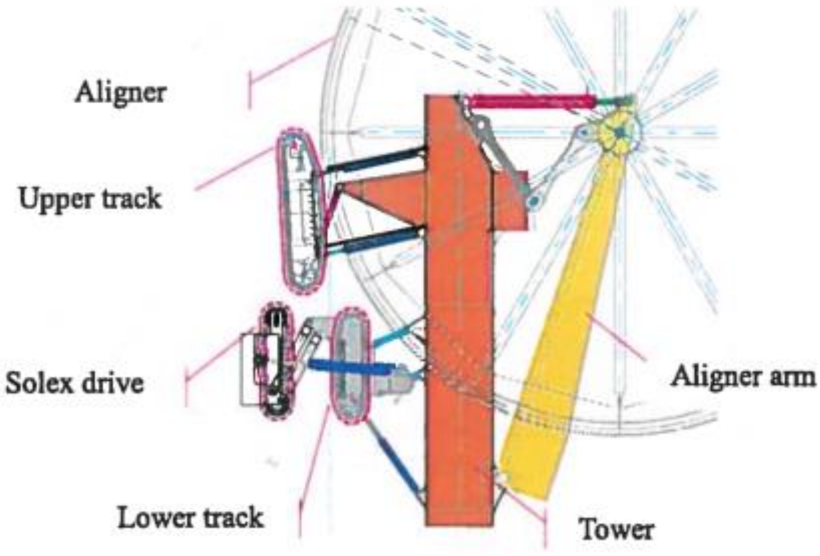


Figure 29: Straightening equipment, Ref [28]

According to Table 7-19 of DNV-OS-F101 code, a pipe is assumed to be a straight one if the out-of-straightness satisfies the requirement, Ref [7]:

$$OOS < 0.15\% \, L \tag{3.7}$$

Where, OOS – Out-of-straightness

L – Actual length of pipeline

The residual out-of-straightness is calculated over a 6m length pipe by measuring the offset value of pipe axis at the mid length (center) as shown in figure 30.

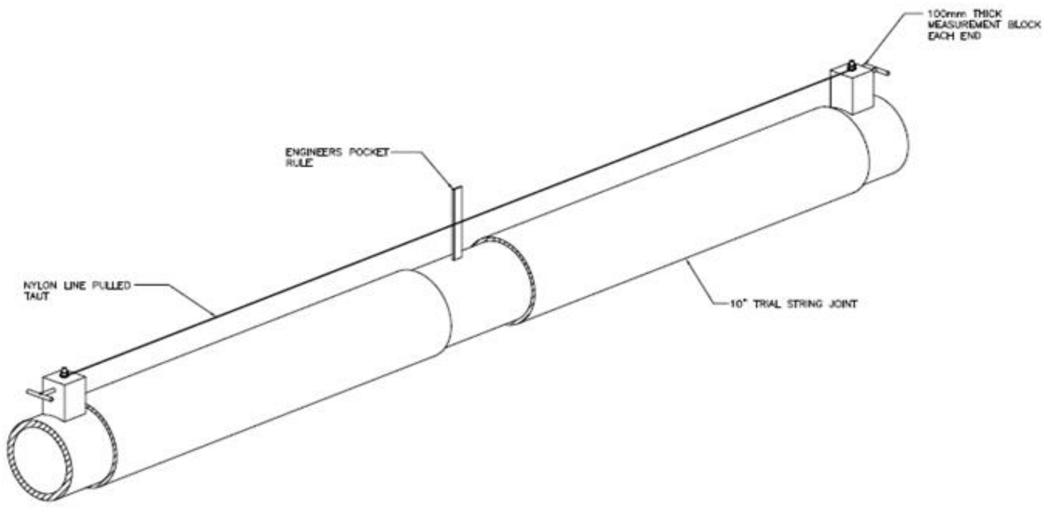


Figure 30: Residual Out-of-Straightness during Reeling trials, Ref [32]

Simply, the criteria can be interpreted as the measured OOS over a 6m pipe joint should not exceed 9mm as shown in figure 31 and the corresponding radius of curvature should always exceed 500m.

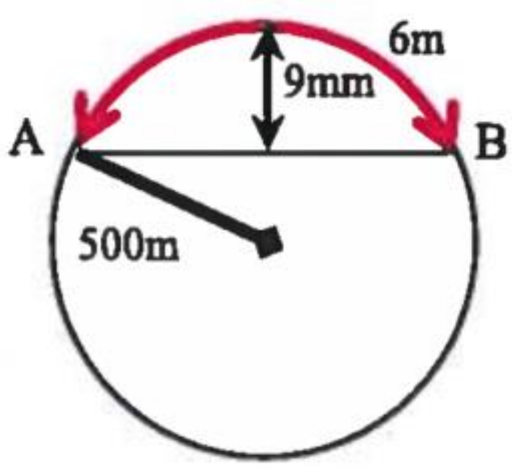


Figure 31: DNV criterion for a straight pipe, Ref [28]

The angle, θ, for a given arc length L can be calculated by:

$$\theta = \frac{(360^0 * L)}{2*\pi*R} \quad \Rightarrow \theta = \frac{(360^0*6m)}{2*\pi*500m} \quad \Rightarrow \theta = 0.6875^0$$

$$\cos\left(\frac{\theta}{2}\right) = \frac{y}{R} \quad \Rightarrow y = R * \cos\left(\frac{\theta}{2}\right) \Rightarrow y = 500m * \cos\left(\frac{0.6875^0}{2}\right)$$

$$y = 499.991m$$

$$\delta = R - y \quad \Rightarrow \delta = 500m - 499.991m = 9mm$$

The residual strain imposed on the pipeline at the straightener depends on the amount of reverse curvature applied. As a result, two types of curvatures are achieved: under-straightened and over-straightened curvatures, Ref [28].

3.2.2 Under-Straightened Curvature

If the reverse curvature applied to the pipe section by the upper track is smaller than the curvature of the pipe seen during the reeling process, we obtain a pipeline that is under straight and is called under-straightened pipe section. It means that there is a permanent curvature left at the pipe in the same direction of the originally applied reeling curvature, refer to figure 32.

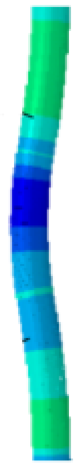


Figure 32: Under-straightened pipe section, Ref [15]

3.2.3 Over-straightened curvature

If the reverse curvature applied to the pipe section by the upper track exceeds the curvature of the pipeline seen during the reeling process, we obtain a pipeline that is over straight and is known as over-straightened pipe section. It means that there is a permanent curvature left at the pipe opposite to the originally applied reeling curvature refer to figure 33.

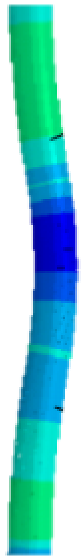


Figure 33: Over-straightened pipe section, Ref [15]

3.3 Residual Curvature in S-lay

As mentioned in section 2.1.2, the curvature of installation in S-lay method is controlled by the stinger. If residual strains are permitted in the pipe as it passes over the stinger, the pipe will have a residual curvature & this may lead the suspended pipe to twist as it passes through the underbend, Ref [13].

To create intermittent residual curvatures in pipeline using the S-lay method, it involves three steps, Ref [14]:

Step 1: The typical S-lay installation is performed by setting the stinger into normal configuration of radius R1 as shown in figure 34;

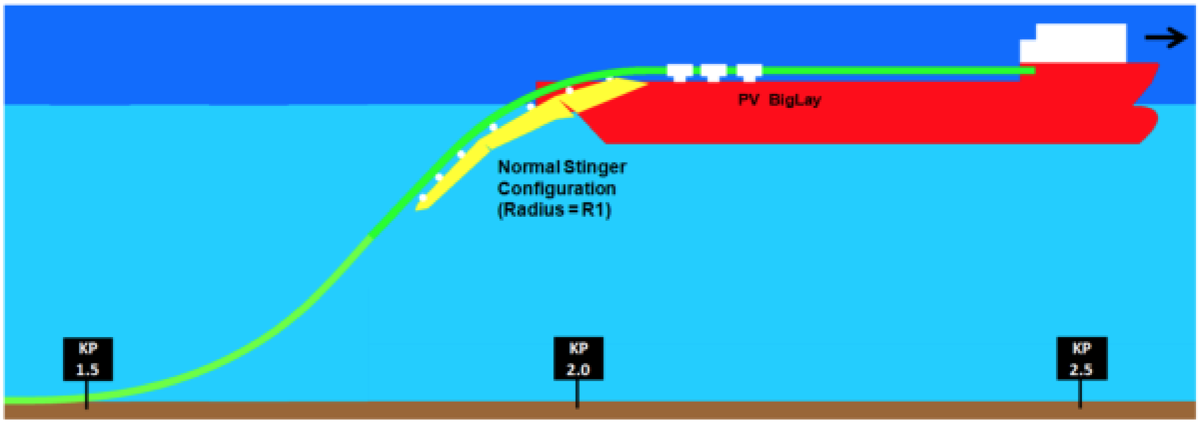


Figure 34: S-lay with normal stinger configuration [14]

Step 2: The residual curvature sections are introduced either by lifting rollers over the stinger or by adjusting the stinger to steep configuration of radius R2. In both methods, the radius of curvature is reduced and permanent curvatures are created as illustrated in figure 35;

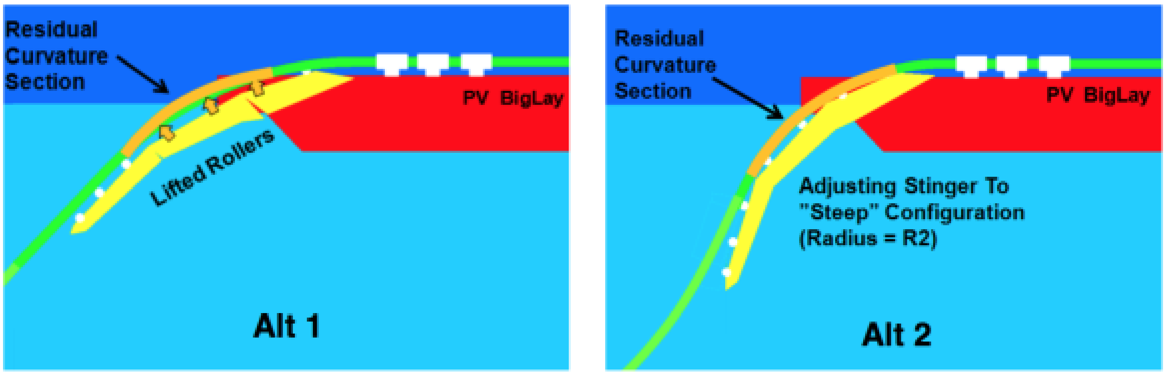


Figure 35: Introducing residual curvatures using two alternatives [14]

Step 3: Once the residual curvature section is created in the pipeline, the rollers or stinger configuration is adjusted to normal setting and continue lay as displayed in figure 36.

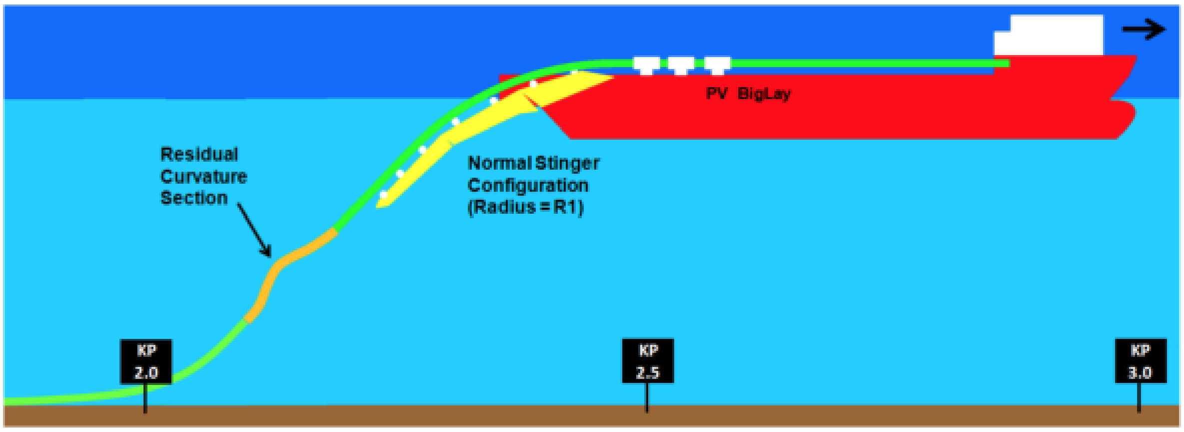


Figure 36: Pipeline with residual curvature section [14]

3.4 Residual Curvature & its applications

3.4.1 Why do we use residual curvatures?

Following the successful Skuld and Edradour installation projects, the residual curvature method has the potential to become the preferred option for lateral buckling design of reel-lay installation. The main advantages of the RCM as compared to the other conventional methods of lateral buckling controls are, Ref [6] [12] [35]:

I. It provides portions of the pipeline less stiffness so that extension in axial direction due to temperature may occur in a distributed and controlled manner;

II. It ensures sharing of the thermal expansion and acceptable and controlled utilization; and causes pipe deflection without producing large compressive forces;

III. It is a robust and effective method of lateral thermal buckling control by reducing pipeline installation costs significantly;

IV. It allows for late design changes since no additional mobilization is required to install a solution. This is possible due to the absence of any special coatings, welding or seabed structure.

V. Post-buckle strains are lower with RCM than with other methods, which avoids the need for special welding and AUT at buckle locations.

3.4.2 Residual Curvature Calculation

Referring to figure 37, the residual curvature in a pipeline can be determined from the following equations, Ref [33]:

$$\delta = R\left(1 - \cos\left(\frac{\theta}{2}\right)\right) \tag{3.8}$$

&

$$\sin\left(\frac{\theta}{2}\right) = \frac{L/2}{R} \tag{3.9}$$

Where, δ - Residual Out-of-Straightness

R - Residual radius of curvature

θ - Included angle

L - Measured Length

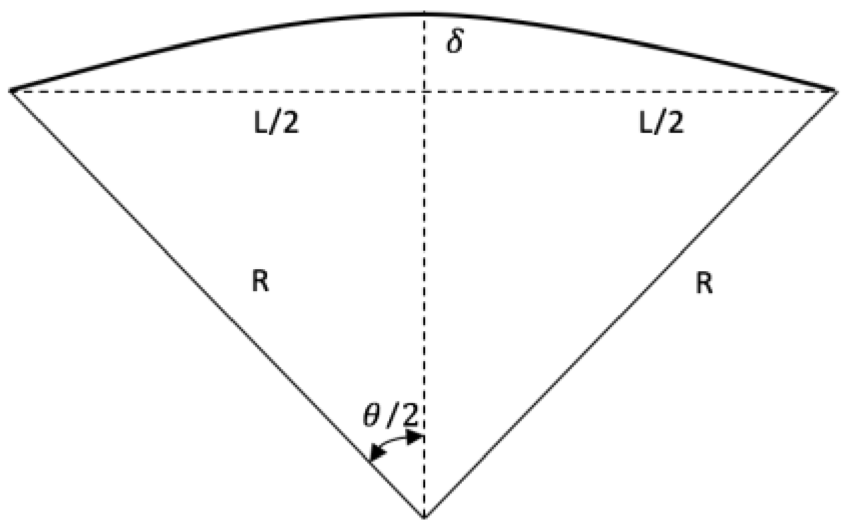


Figure 37: Residual Curvature in pipe, Ref [32]

3.4.3 Projects installed by residual curvature method

The residual curvature method (RCM) for lateral buckle initiator was developed and patented by Statoil, Ref [29]. The method is applied successfully in the development of the Statoil' Skuld Project on Norwegian sea and Total's Edradour Production pipeline on the UK continental shelf.

I. Skuld Project

The Skuld Project is located within the Halten Bank area, North of the Norne Field in the Norwegian Sea in an approximately 360m water depth. Statoil is the owner and operator of the project. The Residual Curvature Method was first applied on this project in 2012 for the installation of a 26 km long 14" – 16" dual diameter pipeline as shown in figure 38.

Post installation survey of the pipeline under operating conditions confirmed the suitability and effectiveness of the under-straightened sections. Each section is triggered as expected, by ensuring sharing of thermal expansion and acceptable load controlled utilization. The method was also found to be cost effective compared to the conventional methods, Ref [12].

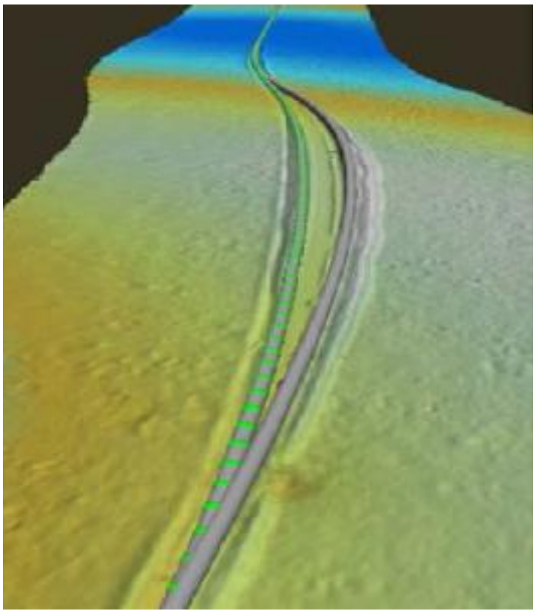


Figure 38: Skuld project - 26 km pipeline installed with RCM, Ref [12]

II. Edradour Production Pipeline

The Edradour gas field is located on the UK Continental Shelf (UKCS), about 75km North West of the Shetland Islands and about 35km East of the Laggan field in approximately 300m water depth. In 2016 Technip successfully installed a residual curvature method for a lateral buckling control on a 1.2 km long 12" cooling section, refer to figure 39.

Results have shown that the introduction of the residual curvature method buckle initiator at KP1.0 effectively mitigated the risk of the pipeline buckling elsewhere within the cooling section. The method is demonstrated to be a robust and reliable way to trigger pipeline buckling, Ref [5].

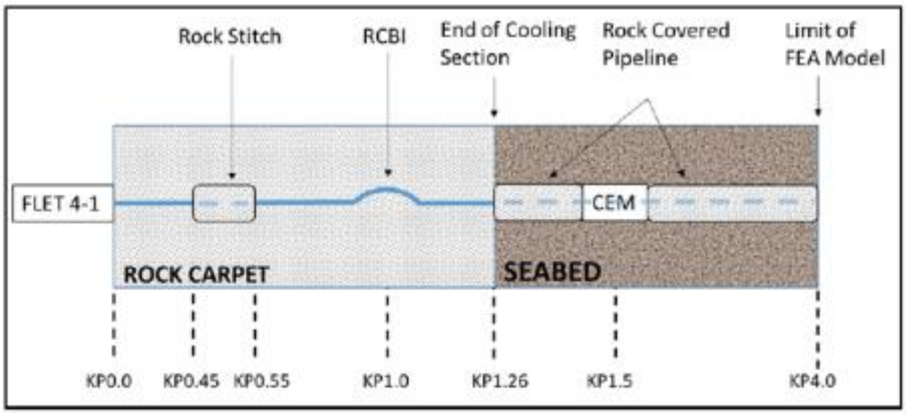


Figure 39: Schematic of the Edradour Cooling Section FEA Model, Ref [5]

3.4.4 Other applications of local residual curvatures

In addition to the use of the residual curvature methods for control of pipeline expansion and global buckling, the method of residual curvature is also applicable to, Ref [14]:

- Adapt to seabed topography
- Enable direct tie-in without use of spools
- Eliminate straightening trials for reel-laid pipelines
- Reduce stress and fatigue loads of steel catenary risers

3.5 Pipeline roll

Baynum and Havik have stated that the two main sources of pipeline roll are lateral forces on the pipeline and plastic overbend strains, Ref [4]. In this section estimation of pipe roll in reel-lay method and S-lay method is discussed.

3.5.1 Pipe roll in Reel-lay Method

Endal et al have provided the assumptions, starting point and ending formulas in the estimation of pipe roll using the method of residual curvatures, Ref [15]. In this thesis, efforts have been made to show the derivation of the formulas by showing the steps in between the starting point and the final equations except the nominal curvature.

If residual curvatures are used to control marine thermal lateral buckling under operating conditions, the residual curvature sections are introduced in the vertical plane of the pipeline during reel-laying. The under-straight residual curvatures are convex upward in the pipeline and can lead to pipe roll as it moves through the suspended section and the underbend where it is bent in the other direction, Ref [13].

I. Estimation of pipeline roll by energy approach

According to endal et al 2014, the simplified energy approach was used to calculate the tendency of pipeline roll due to the intermittent residual curvatures introduced at the straightener. The total work done from the sea surface to the touch down point at the sea bed is the sum of the bending and roll of the pipeline. It is the minimization of the total bending and rotational energy carried out in the suspended section of the pipeline that gives the roll angle, Ref [15].

Figure 40 shows the shape of the suspended pipeline along with the nominal curvature and roll angle.

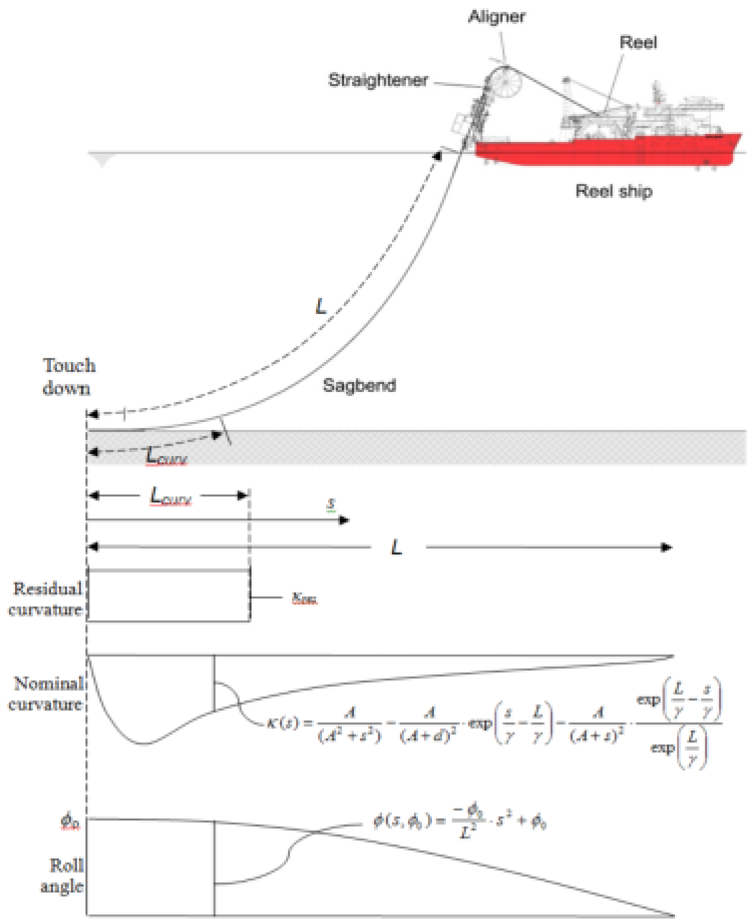


Figure 40: Simplified analytical approach of pipe roll in reeling, Ref [15]

The approach is based on the following assumptions:

- The pipeline roll is assumed to happen between the sea surface and the touch down point. This suspended distance is designated a length of L.
- The pipeline has a residual curvature K_{res} over a defined length due to the under-straightening in the section with local residual curvature. The relationship between residual curvature K_{res} and residual strain ε_{res} is given by:

$$K_{res} = \frac{\varepsilon_{res}}{r} \tag{3.10}$$

where, K_{res} - residual curvature

ε_{res} - residual strain

r - is the outer pipeline radius

- Catenary theory is used to estimate an approximate analytical expression for pipeline's nominal curvature *k(s)* along the suspended section. However, curvature based on natural catenary theory get its maximum value at the seabed. This is not correct for a pipeline with bending stiffness, where the curvature could be assumed to be zero both at the sea bed and at the surface, assuming simply supported pipe at these ends. After introducing extra terms to account for zero curvature for $s=0$ at the sea bed and for $s=L$ at the sea surface, Endal et al has derived the following approximate expression*:*

$$k(s) = \frac{A}{(A^2+s^2)} - \frac{A}{(A+d)^2} \cdot exp\left(\frac{s}{\gamma} - \frac{L}{\gamma}\right) - \frac{A}{(A+s)^2} \cdot \frac{exp(\frac{L}{\gamma} - \frac{s}{\gamma})}{exp(\frac{L}{\gamma})} \tag{3.11}$$

where, *k(s)* - nominal pipeline curvature

d - water depth

A = $\frac{horizontal\ lay\ tension}{the\ pipe's\ submerged\ weight}$

$$\gamma = \sqrt{\frac{E*I}{T}} \tag{3.12}$$

T - pipeline top tension during installation

- The total curvature is given by

$$K_{tot}(s,\phi_0) = \begin{matrix} k(s) + k_{res}.\cos(\phi(s,\phi_0)) & if\ s \le L_{curv} \\ k(s) & otherwise \end{matrix} \tag{3.13}$$

Where, *k(s)* = nominal pipeline curvature

$\phi(s,\phi_0)$ = roll angle along the suspended section

s = distance from the touch down point (At TDP, s=0)

- The roll angle $\phi(s)$ along the suspended section is assumed to be represented by a second-degree polynomial with boundary condition $\phi(0) = \phi_0$ and $\phi'(0) = \phi(L) = 0$

$$\phi(s) = as^2+bs+c$$

$$\phi(0) = \phi_0 \Rightarrow a\,(0^2) + b\,(0) + c = \phi_0 \Rightarrow \mathbf{c=\phi_0}$$

$$\phi'(s) = 2as+b$$

$$\phi'(0) = 0 \Rightarrow 2a\,(0) + b = 0 \Rightarrow \mathbf{b=0}$$

$$\phi(L)=0 \Rightarrow a(L^2) + \phi_0 = 0 \Rightarrow \mathbf{a = \frac{-\phi_0}{L^2}}$$

Hence, the roll angle $\phi(s)$ *is given by:*

$$\phi(s) = \frac{-\phi_0}{L^2}s^2 + \phi_0 \tag{3.14}$$

- The total work $W_{tot}(\phi_0)$ from the surface to the seabed is assumed to consist of a bending contribution $W_B(\phi_0)$ and a roll contribution $W_R(\phi_0)$:

$$W_{tot}(\phi_0) = W_B(\phi_0) + W_R(\phi_0) \tag{3.15}$$

Where:

$$W_B(\phi_0) = \begin{cases} \int_0^{L_{curv}} E.I.\{k(s) + k_{res}\cos(\phi(s,\phi_0))\}^2 ds + \int_{L_{curv}}^{L} E.I.\{k(s,\phi_0)\}^2 ds & if\ L_{curv} < L \\ \int_0^{L} E.I.\{k(s) + k_{res}\cos(\phi(s,\phi_0))\}^2 ds & Otherwise \end{cases} \tag{3.16}$$

$$W_R(\phi_0) = \int_0^L GI_T \left\{\frac{d}{ds}\phi(s,\phi_0)\right\}^2 ds \tag{3.17}$$

II. Derivation of work done by bending W_B (ϕ_0)

$$W_B(\phi_0) = \int_0^L M_B(s,\phi_0).k(s,\phi_0)ds \tag{3.18}$$

but $$M_B(s,\phi_0) = E.I.K(s,\phi_0) \tag{3.19}$$

For $L_{curv} < L$

$$W_B(\phi_0) = \int_0^{L_{curv}} E.I.k(s,\phi_0).k(s,\phi_0)ds + \int_{L_{curv}}^{L} E.I.k(s,\phi_0).k(s,\phi_0)ds$$

$$W_B(\phi_0) = \int_0^{L_{curv}} E.I.\{k(s) + k_{res}\cos(\phi(s,\phi_0))\}.\{k(s) + k_{res}\cos(\phi(s,\phi_0))\}ds + \int_{L_{curv}}^{L} E.I.\{k(s,\phi_0)\}.\{k(s,\phi_0)\}ds$$

$$W_B(\phi_0) = \int_0^{L_{curv}} E.I.\left\{k(s) + k_{res}\cos\left(\phi(s,\phi_0)\right)\right\}^2 ds + \int_{L_{curv}}^{L} E.I.\{k(s,\phi_0)\}^2 ds$$

For $L_{curv} > L$

$$W_B(\phi_0) = \int_0^L E.I.\{k(s) + k_{res}\cos(\phi(s,\phi_0))\}^2 ds$$

III. Derivation of work done by roll W_R (ϕ_0)

$$W_R(\phi_0) = \int_0^L M_\phi(s,\phi_0)\frac{d}{ds}\phi(s,\phi_0)ds \quad (3.20)$$

but $$M_\phi(s,\phi_0) = GI_T\frac{d}{ds}\phi(s,\phi_0) \quad (3.21)$$

$$W_R(\phi_0) = \int_0^L GI_T\left\{\frac{d}{ds}\phi(s,\phi_0)\right\}.\left\{\frac{d}{ds}\phi(s,\phi_0)\right\}ds$$

$$W_R(\phi_0) = \int_0^L GI_T\left\{\frac{d}{ds}\phi(s,\phi_0)\right\}^2 ds$$

3.5.2 Pipe roll in S-lay Method

Endal et al have provided the assumptions, starting point and ending formulas in the estimation of pipe roll using the S-lay method, Ref [13]. In this thesis, efforts have been made to show the derivation of the formulas by showing the steps in between the starting point and the final equations for all the formulas given in the S-lay method.

In S-lay method of pipeline installation, residual curvatures appear when the pipeline is exposed to plastic strains as it passes over a stinger exceeding certain curvature limits. As the pipeline passes the inflection point under the sea surface, the bending of the pipeline is reversed. This means that the configuration of the pipeline changes from overbend to underbend. In doing so the pipeline overcomes the residual curvature through bending and roll, Ref [13].

Endal et al have shown the basic theory of the behavior of marine pipelines subjected to residual curvatures during S-lay method. Three approaches were used to study the effects of the residual strains due to the bending over the stinger and the subsequent pipeline roll. The results show that there is a good agreement among the models and demonstrated that the plastic strains from the bending over the stinger are likely to cause pipeline roll in the underbend. The pipe roll depends also on water depth, the pipe tension, the pipe diameter, the submerged weight and the bending stiffness of the pipeline.

Moreover, the plastic strains over the stinger and the subsequent pipe roll in the underbend does not affect the on-bottom stability of the pipeline but give additional stresses and strains to the as-laid pipe.

Vaughan & Nystrøm have also shown good understanding of pipeline rotation during S-lay installation, Ref [36]

I. Estimation of pipeline roll by energy approach

The method is based on minimizing the work done in the underbend due to the reversed bending of the pipeline. The following assumptions hold for the approach:

- The pipeline roll is assumed to happen between the inflection point and the touch down point. The pipeline length between the inflection point and seabed TDP is designated as L, refer figure 41.

- The pipeline has a residual curvature k_r from the on-stinger bending. The following relationship holds for the residual curvature K_r and the residual strain ε_r:

$$K_r = \frac{\varepsilon_r}{r} \tag{3.22}$$

where, K_r - residual curvature

ε_{res} - residual strain

r - the outer pipeline radius

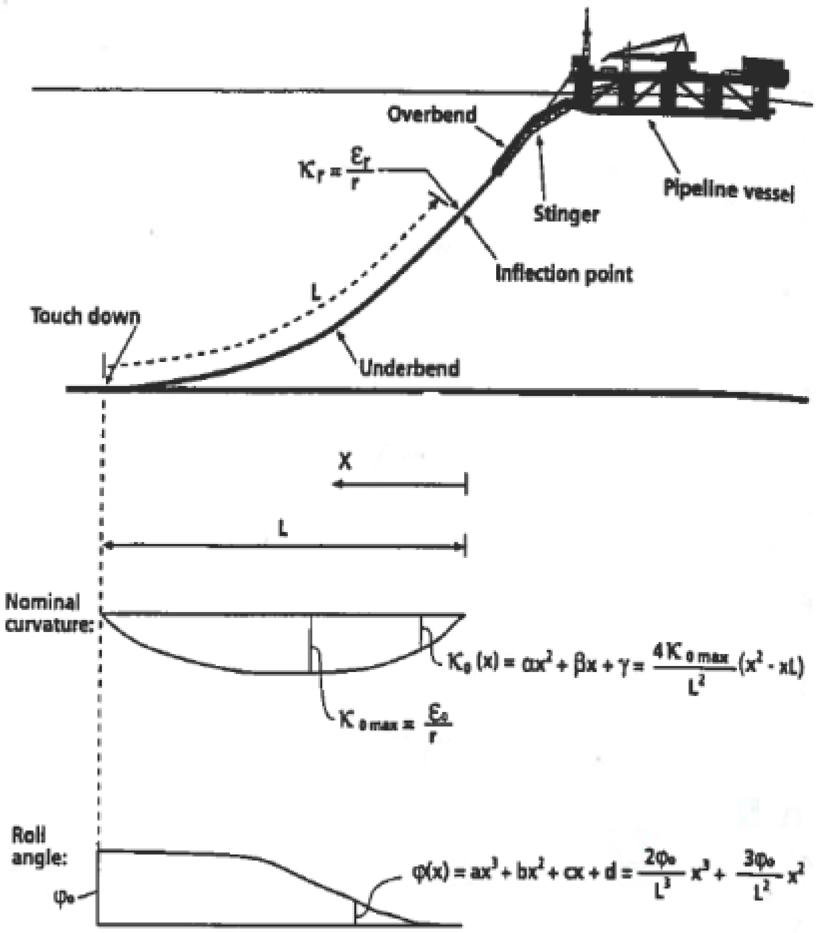


Figure 41: Simplified analytical approach of pipe roll in S-lay method, Ref [13]

- The underbend pipeline curvature k(x) is assumed to consist of the nominal pipeline curvature and residual curvature from the on-stinger bending:

$$k(x) = k_0(x) + k_r \cos\phi(x) \tag{3.23}$$

where, $\phi(x)$ - roll angle

$k_0(x)$ – the nominal pipeline curvature

- The nominal pipeline curvature is represented by second order polynomial function with boundary conditions $k_0(0) = k_0(L) = 0$ & the maximum nominal underbend curvature

$$K_{0max} = \frac{\varepsilon_{0max}}{r} \tag{3.24}$$

$$k_0(x) = \alpha x^2 + \beta x + \gamma$$

$$k_0(0) = 0 \Rightarrow k_0(0) = \alpha 0^2 + \beta 0 + \gamma = 0 \Rightarrow \gamma = 0$$

$$k_0(L) = 0 \Rightarrow k_0(L) = \alpha L^2 + \beta L = 0 \Rightarrow \beta = -\alpha L$$

$$K_{0max} = \frac{\varepsilon_{0max}}{r} \Rightarrow \frac{d}{dx}(K_0) = 0 \Rightarrow 2\alpha x + \beta = 0 \Rightarrow 2\alpha x - \alpha L = 0 \Rightarrow x = \frac{L}{2}$$

Solving $k_0(x)$ for $\mathbf{x} = \frac{\boldsymbol{L}}{\mathbf{2}}$

$$k_0\left(\frac{L}{2}\right) = \alpha(\tfrac{L}{2})^2 + \beta\frac{L}{2} = \frac{\varepsilon_{0max}}{r}, \qquad \text{but } \beta = -\alpha L$$

$$\alpha(\tfrac{L}{2})^2 - \alpha L\frac{L}{2} = \frac{\varepsilon_{0max}}{r}$$

$$\alpha\frac{L^2}{4} - \alpha\frac{L^2}{2} = \frac{\varepsilon_{0max}}{r}, \qquad \text{multiplying by 4}$$

$$\alpha L^2 - 2\alpha L^2 = 4\frac{\varepsilon_{0max}}{r}$$

$$-\alpha L^2 = 4\frac{\varepsilon_{0max}}{r}$$

$$\alpha = -4\frac{\varepsilon_{0max}}{L^2 r},$$

$$\beta = -\alpha L \Rightarrow \beta = -(-4\frac{\varepsilon_{0max}}{L^2 r})L \Rightarrow \beta = 4\frac{\varepsilon_{0max}}{Lr}$$

$$k_0(x) = \alpha x^2 + \beta x + \gamma$$

$$= -4\frac{\varepsilon_{0max}}{L^2 r}x^2 + 4\frac{\varepsilon_{0max}}{Lr}x$$

$$= -4\frac{\varepsilon_{0max}}{Lr}(x^2 + xL)\,, \qquad but \qquad K_{0max} = \frac{\varepsilon_{0max}}{r}$$

$$k_0(x) = -4\frac{K_{0max}}{L^2}(x^2 + xL) \tag{3.25}$$

- The roll angle $\phi(x)$ along the pipeline in the underbend is assumed to be represented by a third-degree polynomial with boundary condition $\phi(0) = \phi'(0) = \phi'(L) = 0$, and $\phi(L) = \phi_0$ as a function of the maximum roll angle ϕ_0.

$$\phi(x) = ax^3 + bx^2 + cx + d$$

$$\phi(0) = 0 \implies a * 0^3 + b * 0^2 + c * 0 + d = 0 \implies \boldsymbol{d = 0}$$

$$\phi'(0) = 0 \implies 3ax^2 + 2bx + c = 0 \implies 3a * 0^2 + 2b * 0 + c = 0 \implies \boldsymbol{c = 0}$$

$$\phi(L) = \phi_0 \implies a * L^3 + b * L^2 = \phi_0$$

$$aL^3 + bL^2 = \phi_0 \tag{3.26}$$

$$\phi'(L) = 0 \implies 3ax^2 + 2bx = 0 \implies 3aL^2 + 2bL = 0$$

$$b = \frac{-3}{2}aL \tag{3.27}$$

Solving for (3.26) and (3.27)

$$aL^3 + bL^2 = \phi_0\text{ , } replacing\ b = \frac{-3}{2}aL$$

$$aL^3 - \frac{3}{2}aL^3 = \phi_0 \qquad multiplying\ by\ 2$$

$$2aL^3 - 3aL^3 = 2\phi_0$$

$$-aL^3 = 2\phi_0 \quad \implies \quad \boldsymbol{a = \frac{-2}{L^3}\phi_0}$$

$$b = \frac{-3}{2}aL \quad \implies \quad b = \frac{-3}{2} * \frac{-2}{L^3}\phi_0\, L \implies \boldsymbol{b = \frac{3}{L^2}\phi_0}$$

Thus, the polynomial function will be:

$$\phi(x) = \frac{-2}{L^3}\phi_0 x^3 + \frac{3}{L^2}\phi_0 x^2 \tag{3.28}$$

- The total work done $W_{tot}(x)$ in the underbend from the inflection point to the touch down point is assumed to consist of a bending contribution $W_B\ (\phi_0)$ and a roll contribution $W_R\ (\phi_0)$:

$$W_{tot}(\phi_0) = W_B(\phi_0) + W_R(\phi_0) = \int_0^L M_R(x)\frac{d}{dx}\phi(x)dx + \int_0^L M_B(x).k(x)dx \tag{3.29}$$

Where: $M_R(x)$ is the roll-momentum given as:

$$M_R(x) = GI_T\frac{d\phi}{dx} \tag{3.30}$$

$M_B(x)$ is the bending moment given as

$$M_B(x) = EIk(x) \tag{3.31}$$

Substituting $M_R(x)$ and $M_B(x)$ into the W_{tot} gives:

$$W_{tot}(\phi_0) = \frac{6}{5}\frac{GI_T}{L}{\phi_0}^2 + EI\int_0^L\{4K_{0max}\left(\frac{x}{L} - \frac{x^2}{L^2}\right) + K_r cos(3\phi_0\frac{x^2}{L^2} - 2\phi_0\frac{x^3}{L^3})\}^2\,dx$$

(3.32)

The expression for W_{tot} can be solved when assuming a roll angle ϕ_0. The value of ϕ_0 which gives the lowest value of W_{tot} is the solution of ϕ_0.

II. Derivation of work done by roll W_R (ϕ_0)

$$W_R(\phi_0) = \int_0^L M_R(x)\frac{d}{dx}\phi(x)dx, \quad \textit{using equation (3.30)}\ M_R(x) = GI_T\frac{d\phi}{dx}$$

$$= \int_0^L GI_T\frac{d\phi}{dx}.\frac{d\phi(x)}{dx}dx = \int_0^L GI_T(\frac{d\phi}{dx})^2dx$$

$$= \int_0^L GI_T(-6\frac{\phi_0}{L^3}x^2 + 6\frac{\phi_0}{L^2}x)^2dx$$

$$= \int_0^L GI_T(36\frac{{\phi_0}^2}{L^6}x^4 - 72\frac{{\phi_0}^2}{L^5}x^3 + 36\frac{{\phi_0}^2}{L^4}x^2)dx$$

$$= GI_T\left[36\frac{{\phi_0}^2}{5L^6}x^5 - 72\frac{{\phi_0}^2}{4L^5}x^4 + 36\frac{{\phi_0}^2}{3L^4}x^3\right]_0^L$$

$$= GI_T\left[36\frac{{\phi_0}^2}{5L^6}L^5 - 72\frac{{\phi_0}^2}{4L^5}L^4 + 36\frac{{\phi_0}^2}{3L^4}L^3\right]$$

$$= GI_T(\frac{432{\phi_0}^2L^5 - 1080{\phi_0}^2L^5 + 720{\phi_0}^2L^5}{60L^6})$$

$$= GI_T(\frac{72{\phi_0}^2L^5}{60L^6})$$

$$W_R(\phi_0) = \frac{6}{5}GI_T\frac{{\phi_0}^2}{L}$$

$$W_R\ (\phi_0) = \int_0^L\ M_R(x)\frac{d}{dx}\phi(x)dx = \ \frac{6}{5}GI_T\frac{{\phi_0}^2}{L}$$

III. Derivation of work done by bending $W_B\ (\phi_0)$

$$W_B(\phi_0) = \int_0^L M_B(x).k(x)dx, \quad \textit{using equation (3.31)}\ M_B(x) = EIk(x)$$

$$= \int_0^L EIk(x).k(x)dx = \ \int_0^L EI(k(x))^2\ dx$$

$$= \ EI\int_0^L(k_0(x) + k_r cos\phi(x))^2dx$$

$$= \ EI\int_0^L(-4\frac{k_{0max}}{L^2}(x^2 - xL) + k_r cos(-2\frac{\phi_0}{L^3}x^3 + 3\frac{\phi_0}{L^2}x^2)^2dx$$

$$W_B(\phi_0) = \ EI\int_0^L\{4k_{0max}(\frac{x}{L} - \frac{x^2}{L^2}) + k_r cos(3\phi_0\frac{x^2}{L^2} - 2\phi_0\frac{x^3}{L^3}\}^2dx$$

Hence,

$$W_{tot}(\phi_0) \ = \ W_B(\phi_0) \ + \ W_R(\phi_0)$$

$$W_{tot}(\phi_0) \ = \int_0^L\ M_R(x)\frac{d}{dx}\phi(x)dx + \int_0^L\ M_B(x).k(x)dx$$

$$W_{tot}(\phi_0) = \frac{6}{5}GI_T\frac{{\phi_0}^2}{L} + EI\int_0^L\{4k_{0max}(\frac{x}{L} - \frac{x^2}{L^2}) + k_r cos(3\phi_0\frac{x^2}{L^2} - 2\phi_0\frac{x^3}{L^3}\}^2dx$$

4. METHODOLOGY AND ANALYSIS DATA

4.1 Introduction

This section provides detailed description of the methodology used in this thesis work, including input datas for modeling and estimating pipe roll when residual curvatures are used for lateral buckling control. All calculations and procedures are clearly shown and explained. Some of the input data are actual values taken from a project installed by Subsea 7 and whenever no data is available reasonable assumptions are made.

4.2 General Description

The first step in the results and discussions of the thesis is to determine the optimized residual curvature length and corresponding roll angle at TDP using the method of total work done to bend and twist the pipeline from the surface to the seabed. The results obtained from the analytical method and global analysis are compared and analyzed. For the remaining part of the section, the sensitivity studies are carried out based on the analytical approach only. Following are list of the parameters considered for the sensitivity study of the pipe roll at TDP:

- Pipe OD - Outer Diameter
  - ✓ 12” ID & 14” ID Single pipe section
  - ✓ 18” OD Pipe-in-pipe
- Diameter to thickness (D_0/t) ratio
- Horizontal component of lay tension
- Residual Strain
- Water depth

4.3 Pipelay Modeling

4.3.1 Analytical Method

The analytical part in this thesis work is carried out using Mathcad 15. It is a powerful computer software primarily intended for handling and documentation of engineering calculations. Mathcad is a user-friendly software where equations are written as mathematical functions. It always provides an up-to-date numerical results and graphs. A short and brief description of the software is given in Appendix I.

The inputs, calculations, results and graphs obtained for the sensitivity study of outer diameter OD is given in Appendix H as a sample for the works performed in Mathcad.

4.3.2 Global Analysis - OrcaFlex

OrcaFlex is a computer software which enables to perform modeling and analysis of marine systems such as pipelines and risers. It is a leading software package for the dynamic analysis of marine systems, Ref [25] [26]. Further information about OrcaFlex can be obtained in their website www.orcina.com.

In the current thesis work, two models of pipelines with residual curvature are analyzed in OrcaFlex version 9.8. Modeling in OrcaFlex is done by placing default shaped objects on the screen. There are several objects from OrcaFlex library to be included in the model, such as Vessel, Line, 6D Buoy, 3D Buoy, winch, link and shape.

Model I: Short pipeline rotationally free at the TDP and fixed at the Vessel

A graphic representation of Model I: Short pipeline is presented in figure 42. The short pipeline is rotationally free at the TDP and fixed at the vessel.

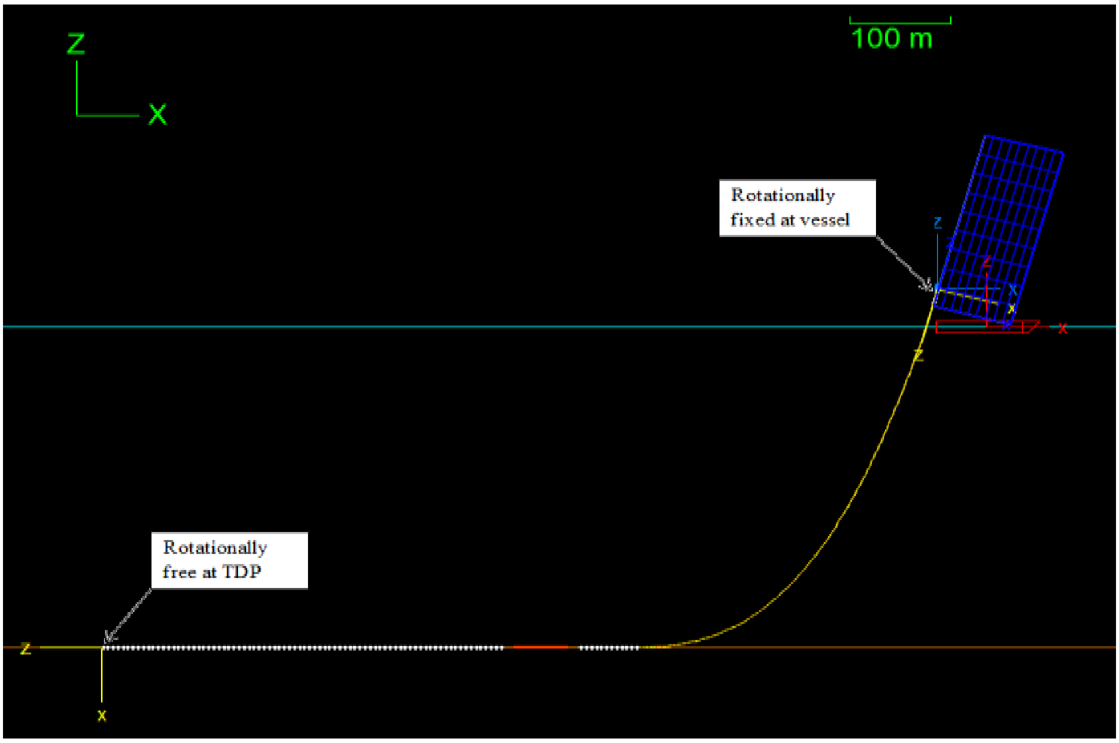


Figure 42: Model of the short pipeline at 360m water depth

In figure above, the small red colored line at the seabed is the 70m under-straightened residual curvature introduced as a pre-bent curvature. The white color dots indicate that there is contact between the pipeline and seabed.

The following default shaped objects are used for modeling the short pipeline in OrcaFlex:

Vessel: A default vessel is selected and an initial position is given. A constant speed of 0.5m/s is assigned to the vessel for a duration of 340s.

Line: A line default is selected to model the pipeline. One end of the pipeline is connected to a 3D Buoy at the vessel while the other end is anchored to the sea bed. The x bending, y bending and twisting stiffness is set to zero at the seabed while infinity at the vessel. The pipeline is assumed to leave the vessel at 15^0 from the vertical by assigning the declination angle to 165^0. Details about angle measurements in OrcaFlex are given in Appendix D. OrcaFlex provides a line setup wizard to calculate anchor positions at the seabed.

3D Buoy: 3D Buoys are elements with only transitional degree of freedom in X, Y, Z. They do not have rotational properties and therefore they are used for rotational fixity. A 3D Buoy is used to rotationally fix the pipeline at the vessel by assigning the bending stiffness to infinity in the x-bending, y-bending and twisting.

Winch: A winch is used in order to payout pipeline while the vessel moves. It is connected to the vessel and the 3D Buoy. The statics winch control mode is set to specific length and the unstretched length of the wire paid out is set to the value 170. The value is based on the speed of the vessel and its duration time.

Shape: A shape size of 80x50x200 is used to support the pipeline while the winch is paying out. The shape is rotated by 15^0 to make sure that the pipeline leaves the vessel at 15^0 from the vertical during the whole simulation time.

Model II: Long pipeline rotationally fixed at both the TDP and Vessel

A graphic representation of Model II: Long pipeline is illustrated in figure 43. The long pipeline is rotationally fixed at both the seabed TDP and vessel.

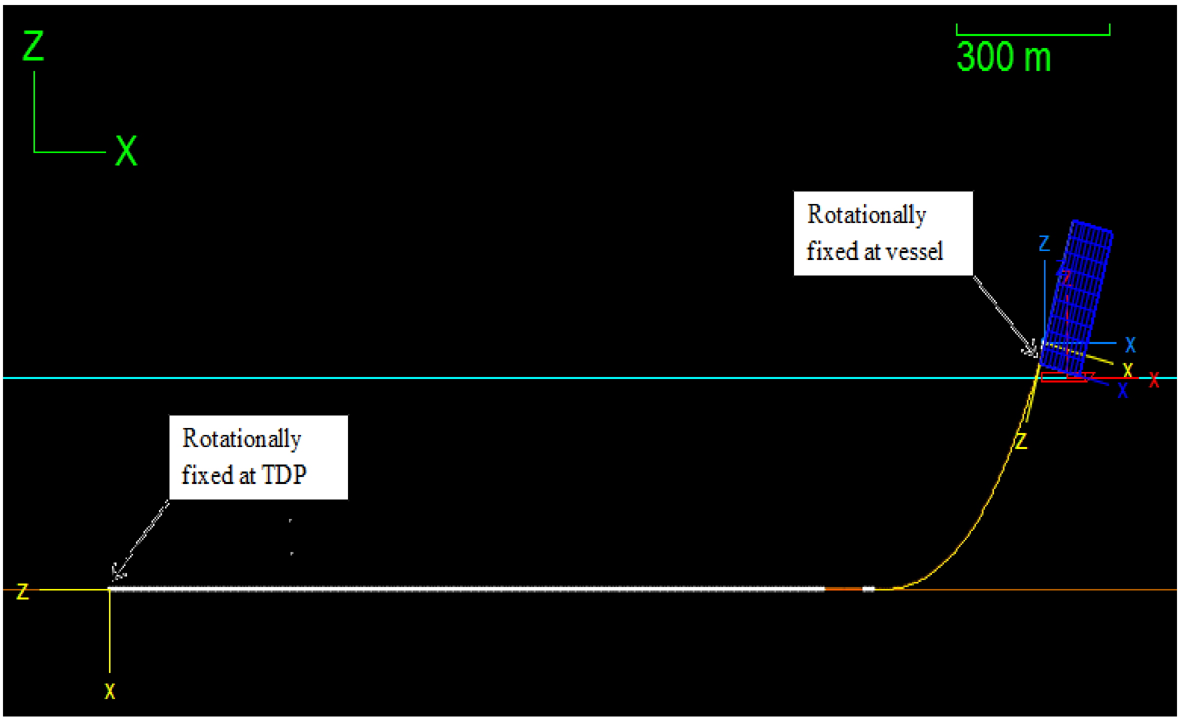


Figure 43: Model of the long pipeline at 360m water depth

In figure above, the small red colored line at the seabed is the 70m under-straightened residual curvature introduced as a pre-bent curvature. The white color dots indicate that there is contact between the pipeline and seabed.

To model the long pipeline, the following changes are made to the short pipeline model:

Vessel: A constant speed of 0.5m/s is assigned to the vessel for a duration of 400s.

Line: The length of the pipeline is increased from 1070m to 2070m. The seabed friction is included in the static analysis in order to observe its effect on the pipeline roll. The x bending, y bending and twisting stiffness is set to infinity at both ends of the pipeline.

Winch: The statics winch control mode is set to specific length and the unstretched length of the wire paid out is set to the value 200. The value is based on the speed of the vessel and its duration time.

Shape: A shape size was increased to 80x50x250 in order to accommodate the duration of the analysis.

4.4 Input data for Analysis

This section presents the basic input datas and material properties.

4.4.1 Material grades

The material grade of marine pipelines is according to the API standard, Ref [7]. The Specified Minimum Yield Strength (SMYS) and Specified Minimum Tensile Strength (SMTS) for API grade X42 to X80 are listed in table 3. For the current thesis analysis API grade X65 with SMYS value of 450MPa is used. According to DNV, the SMYS is defined as the tensile stress at 0.5% elongation of the specimen gage length, Ref [8].

API Material Grades				
API Grade	SMYS		SMTS	
	Ksi	Mpa	Ksi	MPa
X42	42	289	60	413
X46	46	317	63	434
X52	52	358	66	455
X56	56	386	71	489
X60	60	413	75	517
X65	65	448	77	530
X70	70	482	82	565
X80	80	551	90	620
1 Ksi = 6.895 MPa; 1 MPa = 0.145 Ksi; 1 Ksi = 1000 psi (lb f/in2)				

Table 4: API Material Grades, Ref [7]

4.4.2 Pipe cross-section sizes

Two single pipe sections of 12” ID and 14” ID and a pipe-in-pipe section with an outer pipe of 18” OD & inner pipe of 12.75” OD are considered for the pipe roll calculations.

I. Single pipe section

A single pipe section is usually defined by the size of the outer diameter and inner diameter or by outer diameter along with the wall thickness. The two single pipe sections that are considered in the analysis of the pipe roll are adopted from the Skuld project and the details of the pipelines are given in table 4.

Description	Value	
	12" ID	14" ID
Pipe OD (mm)	348.8	405.6
Pipe ID (mm)	304.8	355.6
Wall thickness (mm)	19.0	22.0
Cladding (mm)	3.0	3.0
YS/TS(X65) (MPa)	450/530	450/530

Table 5: 12” & 14” Linepipe properties, Ref [15]

II. Pipe-in-pipe

The best way of exploiting a high pressure and high temperature (HP/HT) reservoirs is using a single pipe-in-pipe and pipe bundles configurations. A pipe-in-pipe system comprises of a rigid steel flowline inside a rigid sleeve pipe. Spacers at the end of each joint, and bulkheads at the ends of the pipelines are used to keep the spacing between the inner and outer pipe. The purpose of the inner pipe is to transport oil and gas fluids and is usually designed for internal pressure containment (burst). The inner pipe is thermally insulated to attain the required arrival temperature of the fluids. The outer pipe protects the insulation materials from the external hydrostatic pressure and other mechanical damage, Ref [1]. Table 5 summarizes the sectional details of the pipe-in-pipe i.e. 18” outer pipe and 12.75”.

Description	Value	
	Outer Pipe 18"	Inner Pipe 12.75"
Pipe OD (mm)	457	324
Pipe ID (mm)	413	282
Wall thickness (mm)	22	21
Cladding (mm)	3.0	3.0
YS/TS(X65) (MPa)	450/530	450/530

Table 6: 18” OD & 12.75” OD Pipe-in-pipe sectional properties

To analyze pipelines having pipe-in-pipe cross section, first the plastic moment capacity of the section is calculated and then it is converted into an equivalent single pipe cross-section of thickness t_w having the same plastic moment capacity. The calculations for converting a pipe-in-pipe section into an equivalent single pipe section is shown below:

The plastic moment capacity of a pipe-in-pipe section is given by:

$$M_{pip} = \frac{1}{6} * SMYS * \left[{D_{01}}^3 - (D_{01} - 2 * t_{w1})^3 + {D_{02}}^3 - (D_{02} - 2 * t_{w2})^3\right] \tag{4.1}$$

where, M_{pip} - Plastic moment section capacity for a pipe in pipe [Nm]

SMYS - Specified minimum yield strength [N/m^2]

D_{01} – Outside diameter of outer pipe [m]

t_{w1} – Wall thickness of outer pipe [m]

D_{02} – Outside diameter of inner pipe [m]

t_{w2} – Wall thickness of inner pipe [m]

The plastic moment capacity for the pipe-in-pipe section given in table 5 is:

$$M_{pip} = \frac{1}{6} * 450 * 10^6[0.457^3 - (0.457 - 2 * 0.022)^3 + 0.324^3 - (0.324 - 2 * 0.021)^3]$$

$$M_{pip} = 2.746 * 10^6\ Nm$$

$$M_{pip} = 2.746 * 10^3\ KNm$$

The plastic moment capacity for a single pipe section is:

$$M_p = \frac{1}{6} * SMYS * \left[{D_0}^3 - (D_0 - 2 * t_w)^3\right] \tag{4.2}$$

where, Mp = Plastic moment capacity for a single pipe section [Nm]

SMYS = Specified minimum yield strength [N/m2]

D_0 – Outside diameter of outer pipe [m]

t_w – Wall thickness of outer pipe [m]

Solving equation (4.2) for t_w and replacing $M_{pip} = M_{pi} = 2.746 * 10^6 \ N.m$

$$t_w = \frac{1}{2} * \left[D_0 - \sqrt[3]{{D_0}^3 - \frac{6 * M_p}{SMYS}} \right]$$

$$t_w = \frac{1}{2} * \left[0.457 - \sqrt[3]{0.457^3 - \frac{6 * 2.746 * 10^6}{450 * 10^6}} \right]$$

$$t_w = 0.034 \ m$$

Hence, a single pipe section having 18” OD and 34mm wall thickness is used to represent the pipe-in-pipe given in table 4-3 for the analytical calculations.

4.4.3 Environmental Data

In the installation of marine pipelines, the environment is a key parameter. It comprises water depth, sea water properties, seabed slope and its nature, sea-states (wave height, wave period, wave direction…), winds, currents etc. All the relevant data associated to the environmental data are provided from reports.

I. Water depth

The water depth is defined by the vertical distance between the still water level and the seabed floor. For the analysis purpose of the thesis work three water depths are considered: 360m, 800m and 1200m

II. Seawater Properties

The pipeline submerged weight and hydrodynamic forces results directly from the seawater density which is therefore relevant for installation analysis. The density of seawater is assumed to be 1025 kg/m^3

III. Seabed slopes

Local seabed slopes are generally too insignificant to have a real influence for the pipeline installation i.e. curvature at TDP. Hence for the installation analysis seabed slopes are neglected and a flat seabed is adopted.

4.4.4 Residual curvature data

The residual curvatures that are applied at the straightener of the reel-lay installation are specified using residual strains or corresponding radius of residual curvature. In OrcaFlex residual curvatures are introduced to the pipeline as pre-bend curvatures (rad/m) by allocating offsets from the central axis of the pipeline in the positive y direction (12 o’clock).

A typical configuration of the residual curvature is to impose 0.15% - 0.25% nominal residual strain over a 40m length and two 15m transition sections on either side for a gradual introduction of the strains from a straight section to the curvature radius and vice versa.

For 14” ID pipeline and nominal residual strain of 0.20%, the residual curvature is calculated by the equation (3.10) given in section 3.5.1:

$$K_{res} = \frac{\varepsilon_{res}}{r}$$

where, K_{res} - residual curvature

ε_{res} - residual strain

r - is the outer pipeline radius

Thus, $K_{res} = \frac{0.002}{(0.4056/2)} = 0.00986$

For the transition section, the residual strains are calculated proportionally for every 5 meters:

The first five meters (0-5m), $K_{res} = 1/4 * 0.00986 = 0.00247$

The second five meters (5-10m), $K_{res} = 2/4 * 0.00986 = 0.00493$ and so on.

The residual curvature values to the remaining sections of the transition length are summarized in table 6. The residual curvatures for the corresponding values of residual strains 0.15% and 0.25% are also provided.

Item No.	Res. Strain	14" ID Typical Configuration of Residual Curvatures (rad/m)								
		Straight Section	0-5m	5-10m	10-15m	15-55m	55-60m	60-65	65-70m	Straight Section
1	0.15%	0.00	0.00185	0.00369	0.00554	0.00739	0.00554	0.00369	0.00185	0.00
2	0.20%	0.00	0.00247	0.00493	0.00740	0.00986	0.00740	0.00493	0.00247	0.00
3	0.25%	0.00	0.00308	0.00616	0.00925	0.0123	0.00925	0.00616	0.00308	0.00

Table 7: 14” ID distribution of residual curvature in the transition section

5. RESULTS AND DISCUSSIONS

5.1 Analytical Method

5.1.1 Residual Curvature length and roll angle

Residual curvatures for lateral buckling control of marine pipelines are introduced in the vertical plane as an under-straightened section (12 O'clock) of the pipeline. The pipeline is then expected to rotate as the under-straightened section of the pipeline reaches the sagbend. This happens due to the imbalance from the imperfection of the pipeline as a result of the permanent deviation of its longitudinal axis from the center line. At the seabed, the under-straightened section of the pipeline is likely to end up on the sea floor i.e. on the horizontal plane. However, the relative position of the under-straightened section at the seabed can be dependent on the length of the residual curvature. Table 7 shows summary of the analytically calculated total work done to bend and rotate single section pipelines 12" ID & 14" ID and 18" OD pipe-in-pipe section for roll angles between 0^0 and 120^0 at TDP. The calculations are based on a range of residual curvatures varying from 0m up to 150m.

Total Work, x10^5 J,											
Item No.	**Res. Curv. Length**	**Pipe Description**	**Pipe roll at TDP**								
			0^0	**15^0**	**30^0**	**45^0**	**60^0**	**75^0**	**90^0**	**105^0**	**120^0**
1	**0 m**	12" ID/14" OD	3.321	3.407	3.668	4.103	4.711	5.494	6.45	7.58	8.884
		14" ID/16" OD	5.183	5.337	5.798	6.568	7.645	9.03	10.72	12.72	15.03
		18" OD PiP	9.773	10.09	11.02	12.59	14.77	17.58	21.02	25.08	29.77
2	**25 m**	12" ID/14" OD	6.92	6.826	6.582	6.285	6.073	6.091	6.454	7.227	8.41
		14" ID/16" OD	9.872	9.788	9.585	9.394	9.40	9.792	10.73	12.29	14.47
		18" OD PiP	17.47	17.39	17.24	17.22	17.65	18.84	21.03	24.37	28.85
3	**50 m**	12" ID/14" OD	11.22	10.92	10.11	8.979	7.809	6.896	6.482	6.71	7.595
		14" ID/16" OD	15.7	15.35	14.37	13.05	11.76	10.89	10.76	11.58	13.35
		18" OD PiP	27.14	26.61	25.18	23.29	21.57	20.65	21.09	23.18	26.96
4	**75 m**	12" ID/14" OD	15.16	14.68	13.34	11.45	9.407	7.653	6.549	6.31	6.965
		14" ID/16" OD	21.22	20.6	18.9	16.52	14.01	11.96	10.86	10.99	12.41
		18" OD PiP	36.41	35.45	32.81	29.15	25.38	22.47	21.24	22.15	25.29
5	**100 m**	12" ID/14" OD	18.66	18.02	16.22	13.65	10.84	8.35	6.658	6.041	6.543
		14" ID/16" OD	26.22	25.37	23.02	19.68	16.08	12.97	11.01	10.57	11.72
		18" OD PiP	44.95	43.60	39.85	34.57	28.93	24.22	21.49	21.39	24.01
6	**125 m**	12" ID/14" OD	21.8	21.01	18.8	15.63	12.14	9.009	6.807	5.877	6.277
		14" ID/16" OD	30.74	29.69	26.76	22.57	17.99	13.95	11.23	10.30	11.24
		18" OD PiP	52.74	51.04	46.3	39.56	32.25	25.92	21.86	20.86	23.08
7	**150 m**	12" ID/14" OD	24.64	23.72	21.15	17.46	13.37	9.659	7.001	5.792	6.112
		14" ID/16" OD	34.86	33.63	30.18	25.23	19.78	14.91	11.51	10.14	10.93
		18" OD PiP	59.88	57.87	52.25	44.20	35.40	27.61	22.35	20.56	22.42

Table 8: Total work done for 12" ID & 14" ID single pipe sections & 18" OD pipe-in-pipe section for residual curvature lengths 0m – 150m (0.20% residual strain)

From Table 7, we can understand that:

- When there is no residual curvature in the pipeline (0m), the predicted total work done value is minimum at 0^0 and increases gradually as the roll angle is increased to 120^0. This implies that the pipeline is stable and there is no rotation (or minimal rotation) at the touch down point and external energy is required every time the pipe is rotated at the TDP.

- When short residual curvature is used in the pipeline (25m), there is relatively little variation in the external work done for smaller angles and the external energy reaches its minimum value at certain roll angles thereafter increases significantly. It should be noted that an increase in pipe diameter reduces the roll angle at which the external work done is minimum. For example, the 12" ID pipe section has its minimum value between 65^0 and 70^0 whereas the 14" ID pipe is between 50^0 and 55^0. The 18" OD pipe-in-pipe section has the smallest value of the work done at angle of 45^0. This indicates that the pipeline is relatively unstable and it can possibly roll to the angles where energy is minimum. However, further pipe roll requires an increase in external work done.

- As the residual curvature length is increased (50m – 150m), the external work done decreases abruptly for smaller angles and reaches its minimum value at a noticeable roll angle thereafter increasing again instantly. The roll angle at which the energy is minimum differs depending on the residual curvature length, however, it ranges between 80^0 & 120^0. This demonstrates that the pipeline is very unstable and it can very easily rotate to the roll angle at which the energy is minimum. Further pipe roll requires enormous external energy.

The length of the under-straightened section should be optimized when the method of residual curvature is used for lateral buckling control of marine pipelines. Shorter residual curvatures tend to give relatively smaller angles as the point of minimum external energy, on the contrary, longer residual curvature lengths result in a larger pipe roll angle at which the energy is minimum. Hence, the length of the under-straightening section should be compromised in such a way that the pipeline is unstable enough and can easily roll and fall to the seabed as intended. Residual curvature length in the range of 50m to 80m predict roll angles of about 80^0 - 100^0 as the minimum value of energy as can be seen in figure 44 (for a residual curvature length of 50m) & figure 45 (for residual curvature length of 80m). Thus, we can consider the under-straightened sections in the range of 50m to 80m are optimized lengths.

However, several factors can influence pipe roll during and after installation and hence the length of the under-straightened section should be determined in conjunction with other disciplines through an inplace analysis or finite element analysis. A typical configuration could be to impose 0.15%-0.25% residual strain over a 40m length and a 15m transition section on either side of the central section for every kilometer during the reel-lay installation. Figure 46 illustrates the pipe geometry associated with this procedure, Ref [6] [12] [15] [28].

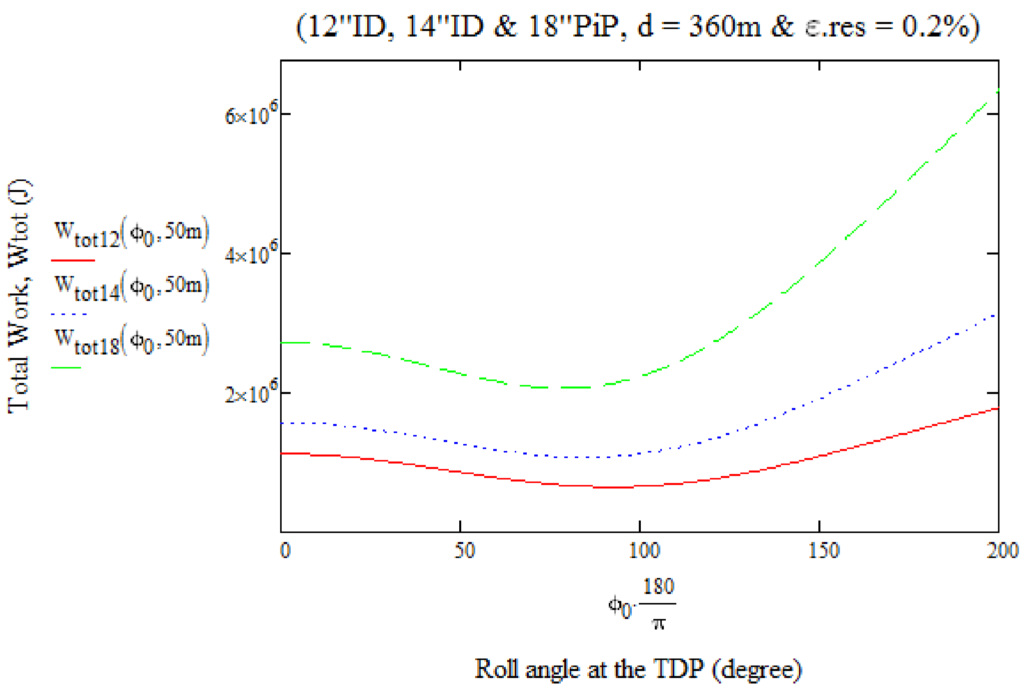


Figure 44: Pipe roll for 12"ID, 14"ID & 18" OD PiP with a residual curvature length of 50m (water depth 360m & 0.2% Residual strain)

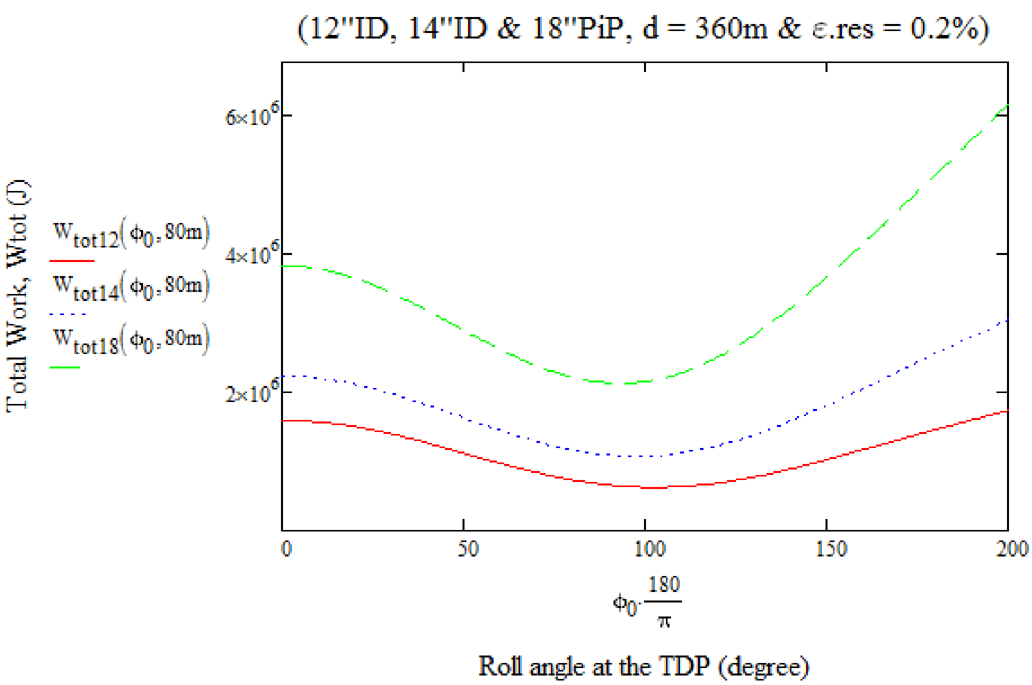


Figure 45: Pipe roll for 12"ID, 14"ID & 18" OD PiP with a residual curvature length of 80m (water depth 360m & 0.2% Residual strain)

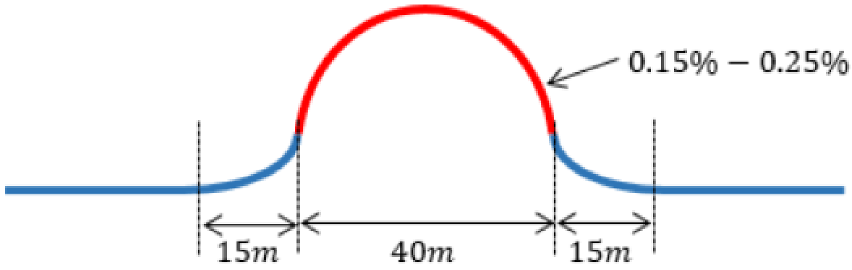


Figure 46: Typical pipe geometry of residual curvature section [6]

5.1.2 Pipe outer diameter

The OD of a pipeline is one of the most important parameters that influence the roll of pipelines at the seabed TDP when installing pipelines with residual curvature.

I. Single pipe sections – 12” ID & 14” ID

The total work done to bend and twist the 12” ID and 14” ID pipeline from the surface to the seabed is shown in figures 47 and figure 48 for roll angles between 0^0 and 200^0 respectively. Residual curvature sections ranging from 0m to 150m are used to show how it influences the rotation of the pipeline. The figures show for residual strain of 0.20% at 360m water depth.

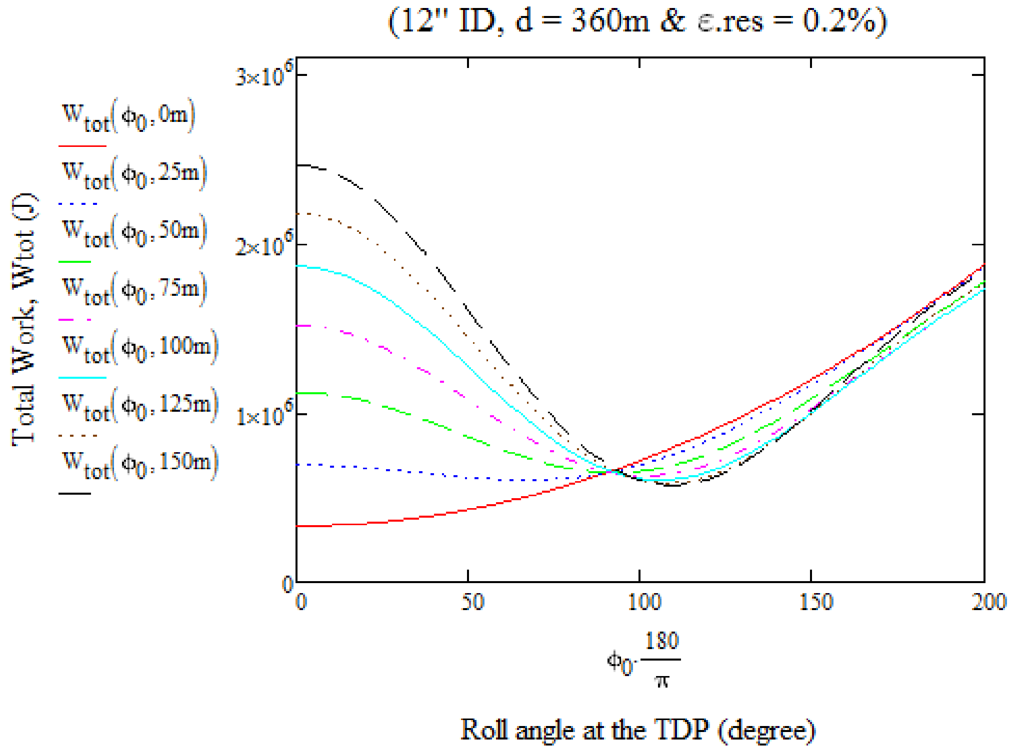


Figure 47: Total work to bend & twist 12” ID pipe from surface to seabed for various lengths on the section with residual curvature (water depth 360m & local residual strain 0.20%)

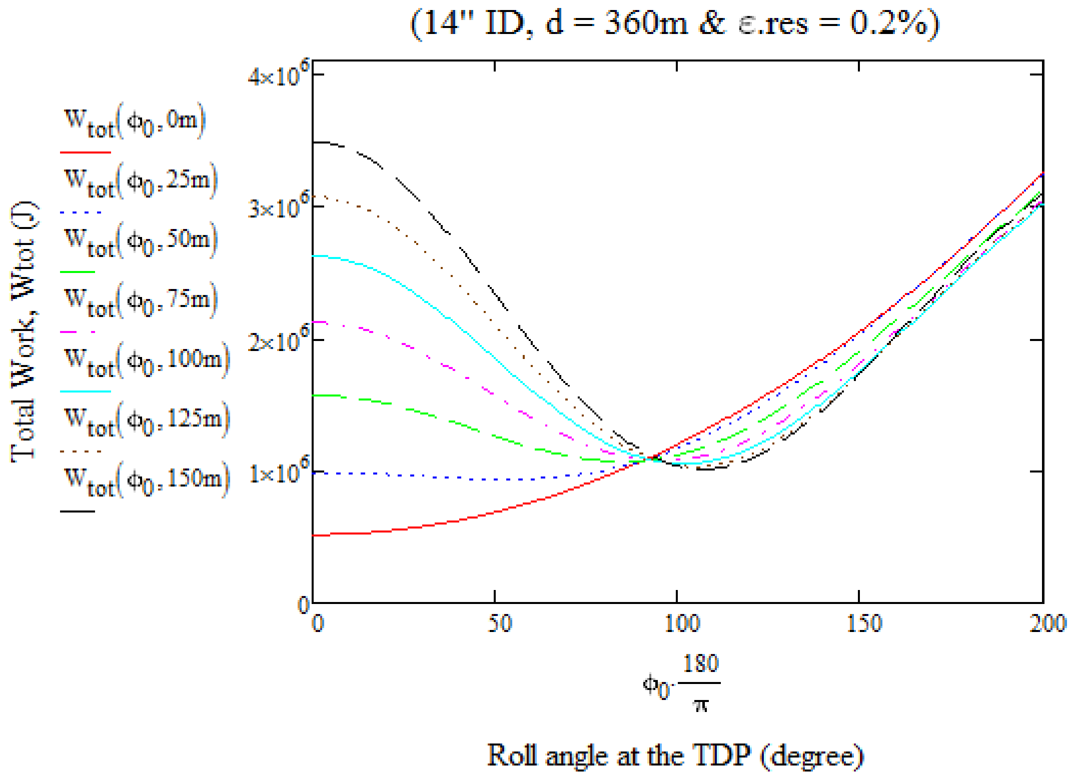


Figure 48: Total work to bend & twist 14" ID pipe from surface to seabed for various lengths on the section with residual curvature (water depth 360m & local residual strain 0.20%)

The pipeline roll as shown in above figures predict:

- If there are no residual curvature sections introduced in the pipeline (0m), the function is a continuously increasing curve as the roll angles increase from 0^0 to 200^0. This implies that the pipeline has resistance to twist/roll and hence an external energy is required to rotate the pipe line at the seabed.
- For shorter residual curvature lengths (25m), the graph is relatively flat for small angles and increases afterwards. This shows that the pipeline is relatively unstable and can easily roll to a certain degree but further pipe roll needs an increase in work done.
- As the residual curvature length increases (50-150m) the curve gradually starts to obtain a turning point with a local minimum point. This indicates that the pipeline is unstable and pipe roll is easily initiated to the point where the curve has its local minimum value. Further pipe roll requires external work to be done.

II. Pipe-in-pipe – 18" OD

For the pipe in pipe case, the approach is made by calculating first the plastic moment capacity of the pipe-in-pipe section and it is converted into an equivalent single pipe cross-section of thickness t_w having the same plastic section moment capacity. For the pipe-in-pipe section with an outer pipe of 18" OD & inner pipe of 12.75" OD, the equivalent single section thickness is calculated as 0.034m (the calculation is shown in section 4.4.2 of chapter 4 – Methodology and Analysis Data). The total work done to bend and twist the 18" OD pipe-in-pipe line from the surface to the seabed is shown in figure 49.

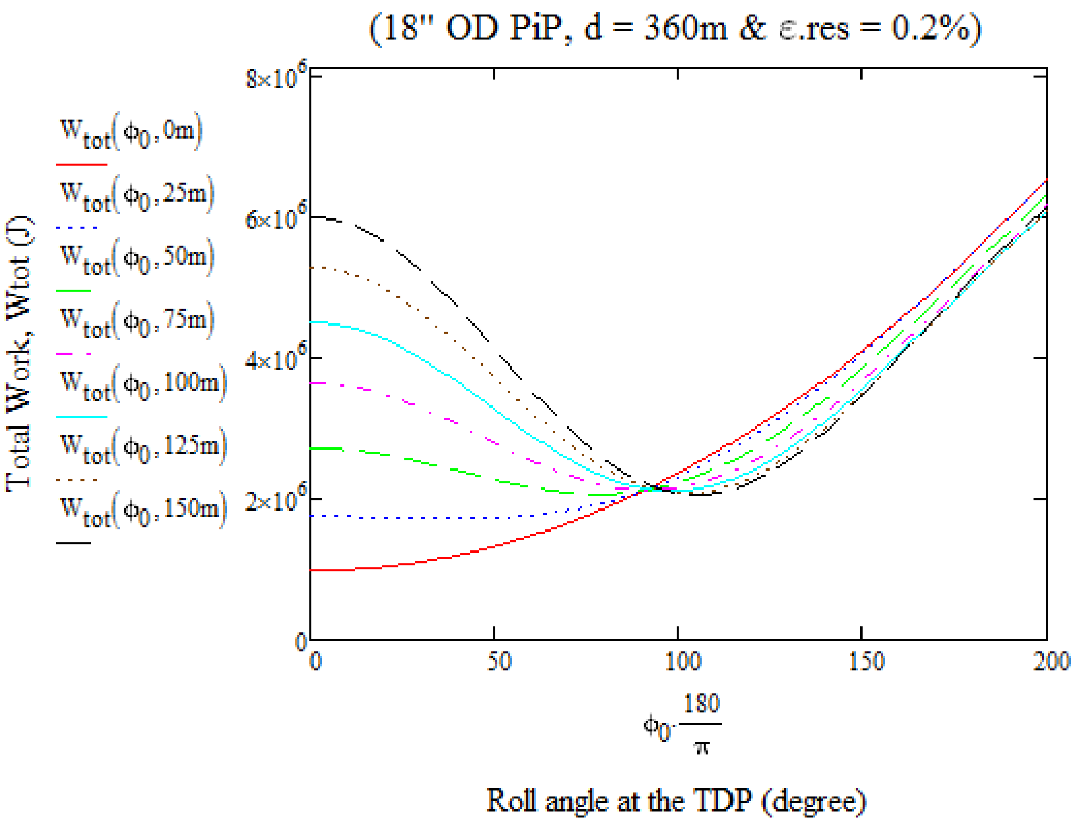


Figure 49: Total work to bend & twist 18" OD pipe-in-pipe from surface to seabed for various lengths on the section with residual curvature (water depth 360m & local residual strain 0.20%)

The same interpretation can be given to the 18" OD pipe-in-pipe as the 12" ID and 14" ID single sections as given in section 6.2.1.

5.2 Global Analysis

Two models are analyzed using a global analysis tool OrcaFlex to verify if the same results can be obtained as the analytical energy approach method refer to section 4.3.2.

- **Model I: Short pipeline rotationally free at the TDP and fixed at the Vessel**
- **Model II: Long pipeline rotationally fixed at both TDP and Vessel**

The models are run for different residual curvature lengths with 15m transition section on either side of the under-straightened section as shown in figure 50.

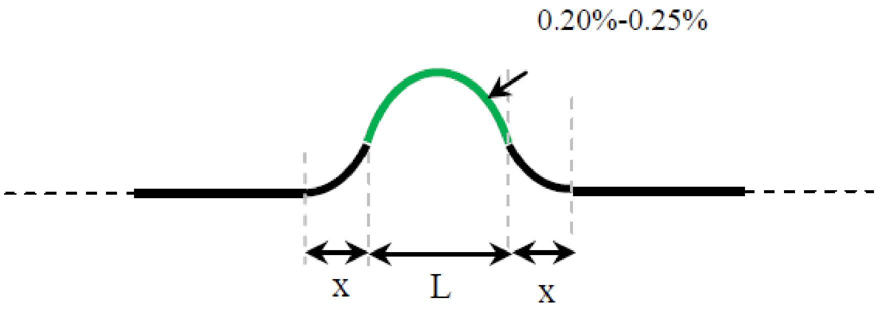


Figure 50: Configuration of an under-straightened section with transition section, Ref [10]

Model I: Short pipeline rotationally free at the TDP and fixed at the Vessel

The simulation of short pipeline model was carried out for different residual curvature lengths (40m – 120m) in order to assess the effects of the various under-straightened sections on pipe roll. The rotation of the pipeline can be visualized by switching on the node axes. Figure 51 shows a graphical view of pipe rotation, under a whole simulation, for an under-straightened section of 80m (15+50+15). During dynamic simulation, the winch starts to payout while the vessel moves at a constant speed in the direction of pipelay. The OrcaFlex Azimuth, Declination and Gamma angles report the local orientation of the line relative to the global axes. Looking at the instantaneous range graph of the Gamma result, it shows that the line twists to about 130^0 initially due to the pre-bent curvatures introduced and then rotates back to around 50^0 at the seabed. Gamma results for the whole simulation are given as a maximum, minimum and mean values as can be seen in figure 52 for an 80m under-straightened section. Considering the mean gamma values as the measure of pipe rotation at the seabed, the rotation angles for corresponding pre-bent curvature lengths are given in Appendix A. The table demonstrates that, an increase in the length of the pre-bent curvature results in an increase in pipe roll, however the rate at which the piperoll changes decreases. In addition, longer residual curvature sections cause the under-straightened section to deflect like a cantilever beam whereby the crown touches down on the sea bed leaving a gap between the sea bed and the pipeline on either side. Hence, optimized length of under-straightened sections should be selected if residual curvatures are to be used as a method to control lateral buckling efficiently. From the results, pre-bent sections of 70m – 80m can be regarded as the optimized lengths.

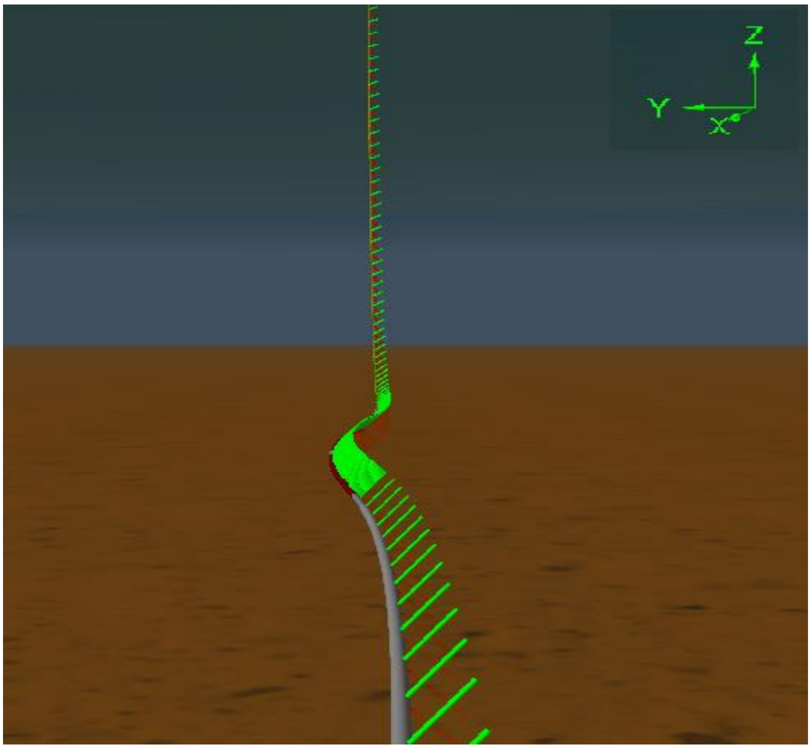


Figure 51: Model I - Graphical view for an under-straightened section of 80m (15+50+15) at 360m water depth

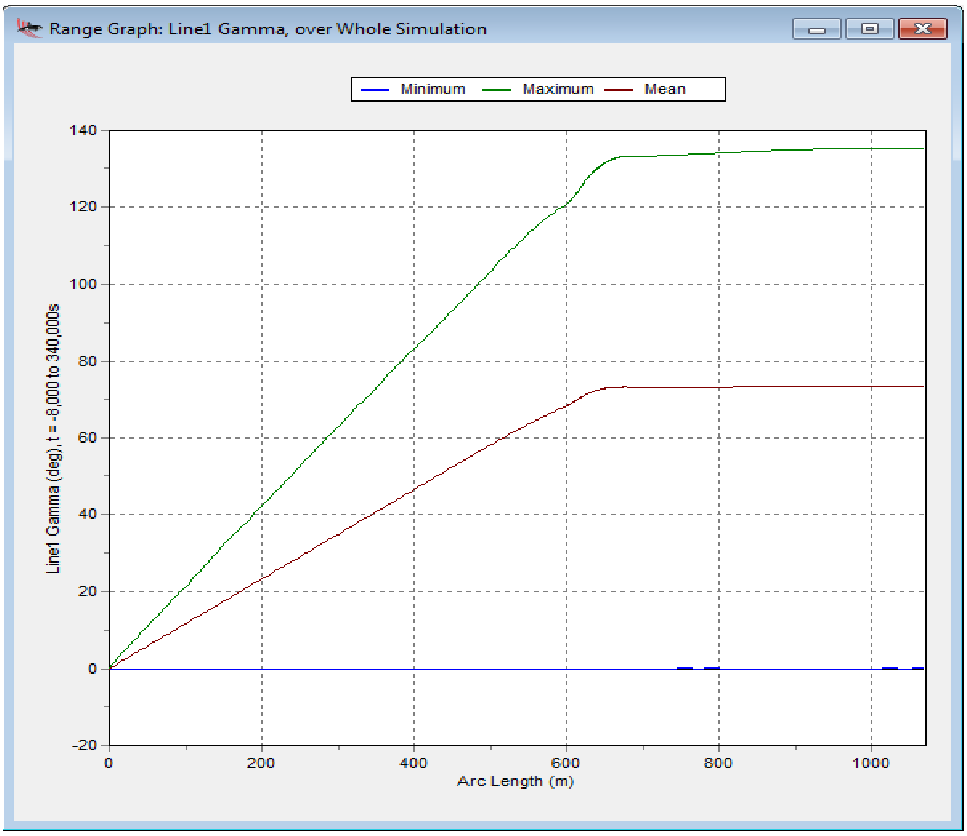


Figure 52: Model I - Gamma results of the entire pipeline for under-straightened of 80m (15+50+15) – whole simulation

The mean gamma results for the assumed optimized pre-bent curvature sections demonstrate that the roll angle is around 69^0 - 73^0.

However, the relative position of the under-straightened section with respect to the vertical plane can also be measured from the model itself after running the dynamic simulation. The results obtained are summarized in table 9. The corresponding angles for the 70m – 80m residual curvature sections are 79.5^0 and 86.70 respectively. These values are about 15% - 18% higher than the mean gamma angles. The same can be said about the bending of the under-straightened section as the pre-bend curvature lengths are increased i.e. the section bends like a cantilever about its longitudinal straight axis and the crown touches down the seabed leaving an opening between the sea floor and the pipe on either side of the crown.

Model	Pre-bent Curvature length (m)	Total Length (m)	Avg. Angle relative to vertical (degrees)	% of increase in angle w.r.t. vertical	Maximum vertical sea bed clearance (m)	Remarks
1	15+10+15	40	0^0	-	0.636	No pipe rotation
2	15+20+15	50	32.5^0	-	0.750	
3	15+30+15	60	72.5^0	123.08%	0.436	
4	15+40+15	70	79.5^0	9.65%	0.262	
5	15+50+15	80	86.7^0	9.06%	0.073	The crown of the under-straightened section touches the seabed while creating a gap between the seabed and pipeline.
6	15+60+15	90	86.6^0	(0.12%)	0.078	
7	15+70+15	100	86.1^0	(0.58%)	0.083	
N.B. 15m transition section is introduced on each side of the residual curvature. The pipeline is short and is rotationally free at the TDP & fixed at the vessel.						

Table 9: Roll angles of the under-straightened section relative to the vertical plane measured from the short pipeline model at the seabed

Model II: Long pipeline rotationally fixed at the TDP and Vessel

In the case of the long pipeline model, the pipeline is rotationally fixed at the TDP and the vessel. The aim of the long pipe line model is to see the effect of the pipe-soil friction coefficient on pipe roll. The simulation of the long pipeline model was also carried out for different curvature lengths (40m – 130m) in order to assess the effects of the various under-straightened sections on pipe roll. Figure 53 illustrates the graphical view of the long pipe rotation under a whole simulation for an under-straightened section of 80m (15+50+15). During dynamic simulation, the winch starts to payout while the vessel moves at a constant speed in the direction of pipelay. Looking at the instantaneous range graph, the gamma angle shows that the pipe line twists to about 110^0 initially due to the pre-bent curvatures introduced, and then rotates back to around 30^0 at the seabed. The gamma values (maximum, minimum and mean) under the whole simulation of the 80m under-straightened section is displayed in figure 54. Following the same procedure as the short pipe model and considering the mean gamma values as the measure of pipe rotation, the twist angles for corresponding pre-bent curvature lengths are given in Appendix B. The table demonstrates that, an increase in the length of the pre-bent curvature results in an increase in pipe roll, however the rate at which the pipe roll changes decreases slightly. In addition, longer residual curvature sections cause the under-straightened section to deflect as a cantilever so the crown touches down on the seabed leaving a gap between the sea bed and the pipeline on either side. Similarly, it shows that if the method of residual curvature is to be used efficiently, optimized length of under-straightened sections should be considered.

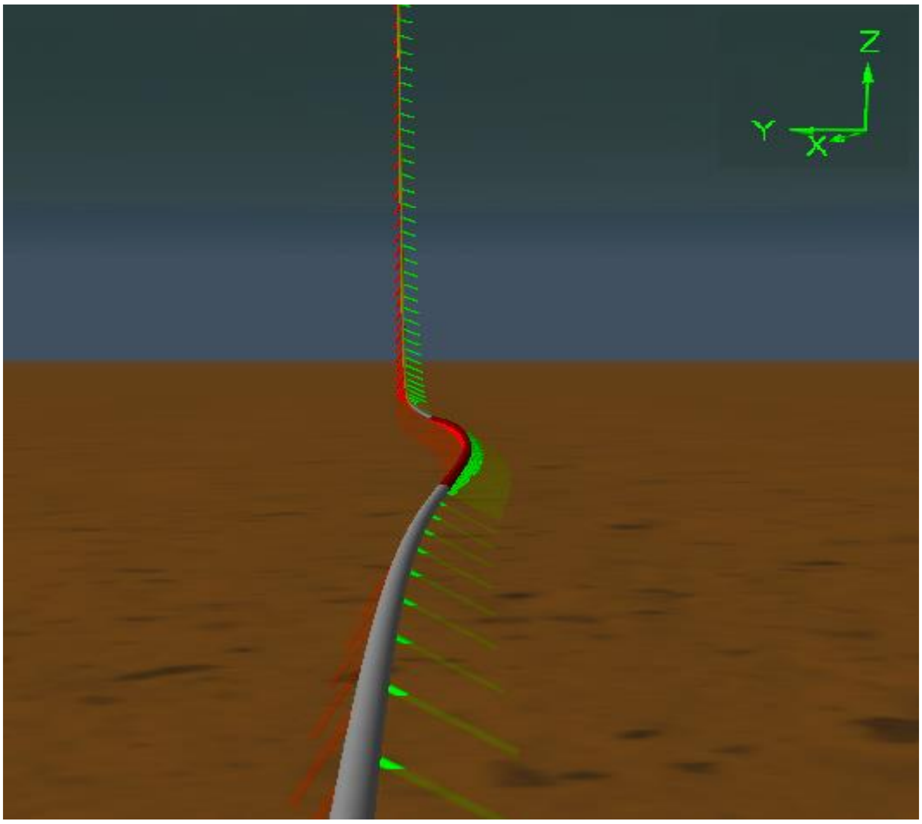


Figure 53: Model II - Graphical view for the under-straightened section of 80m (15+50+15) @ 360m water depth

From the result, if pre-bent section of 80m is regarded as the optimized under-straightened section, the corresponding mean gamma result is about 64^0. The mean gamma angle is quite low compared to the short pipeline model. This reduction in angle is the result of the resistance force developed between the soil particles and pipeline due to the friction.

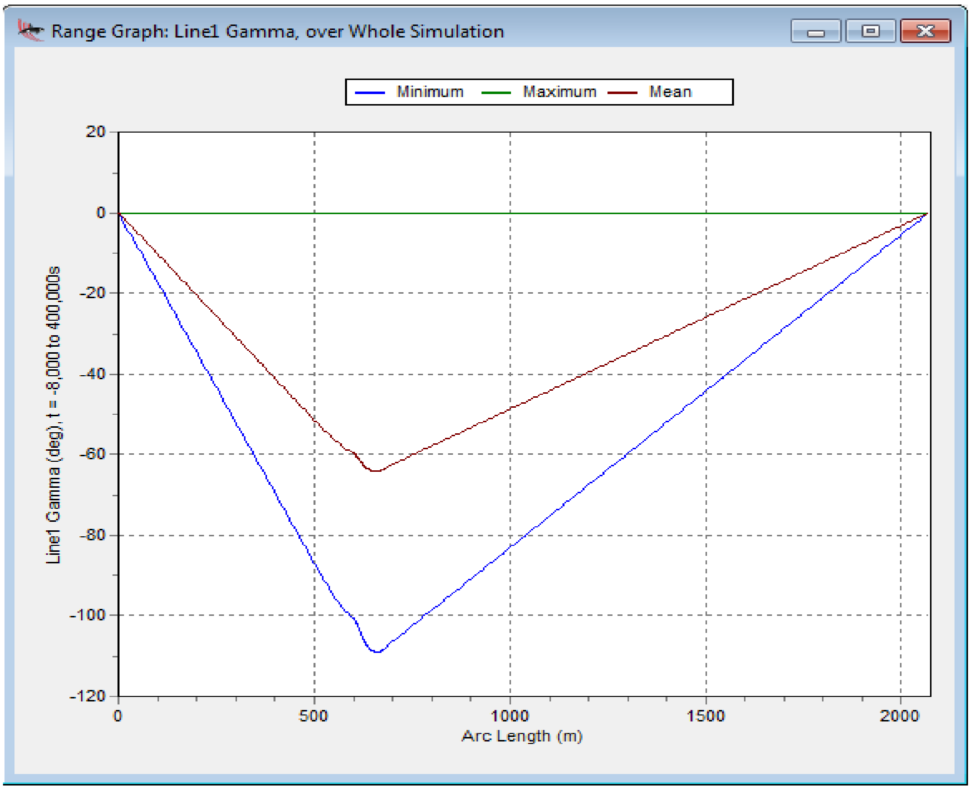


Figure 54: Model II - Gamma results of the entire pipeline for under-straightened section of 80m (15+50+15) – whole simulation

Model	Curvature length (m)	Total Length (m)	Avg. Angle relative to vertical (degrees)	% of increase in angel w.r.t. vertical	Maximum vertical sea bed clearance (m)	Remarks
1	15+10+15	40	0^0	-	0.652	No pipe rotation
2	15+20+15	50	30^0	-	0.789	
3	15+30+15	60	49^0	63.33%	0.781	
4	15+40+15	70	70^0	42.86%	0.528	
5	15+50+15	80	80^0	14.29%	0.202	
6	15+60+15	90	84^0	5.0%	0.116	The crown of the under-straightened section touches the seabed while creating a gap between the seabed and pipeline.
7	15+70+15	100	85^0	1.19%	0.115	
8	15+80+15	110	84.5^0	0.59%	0.122	
9	15+90+15	120	83.75^0	(0.89%)	0.126	
10	15+100+15	130	83.1^0	(0.78%)	0.128	
N.B. 15m transition section is introduced on each side of the residual curvature. The pipeline is long and is rotationally fixed at both the vessel and TDP.						

Table 10: Roll angles of the under-straightened section relative to the vertical plane measured from the long pipeline model at the seabed

Similarly, roll angle measurements for the relative position of the under-straightened section with respect to the vertical plane are taken for model II (long pipeline) the same way as model I (short pipeline). The results are illustrated in table 9 along with the percentage of the rate of increase in roll angles. The roll angle for the 80m pre-bent curvature length is around 80^0, 25% more than the corresponding mean gamma angle obtained from the mean gamma results.

Thus, it can be concluded that the mean gamma angles for measuring pipe roll at the TDP are not representative and therefore, it can't be used to measure pipe-roll in OrcaFlex. For the subsequent parts of the section, the analytical energy approach is solely used for the sensitivity analysis of the different parameters.

5.3 Sensitivity Study – Pipe Outer Diameter (OD)

The sensitivity analysis for the outer diameter is based on the residual curvature length of 70m. The individual analytical results for the total work done to bend and twist the 12" ID & 14" ID single pipe sections and 18" OD pipe-in-pipe from the surface to the seabed in water depths of 360m, 800m and 1200m are presented in Appendix C. In all three cases, results indicate that an increase in the OD of the pipeline increases the work done required to twist the pipe line at TDP for all roll angles. Larger OD pipe lines need more energy to rotate the pipeline at the seabed. This is due to the fact that with an increase in outer diameter the stiffness of the pipeline increases and more work is required to bend and twist the section. The same can be said about the total work done at the point when pipelines end roll at seabed TDP. Figure 55 illustrates the total work done to bend and twist the 12" ID & 14" ID single pipe sections and 18" OD pipe-in-pipe when the curve has its minimum value at different water depths.

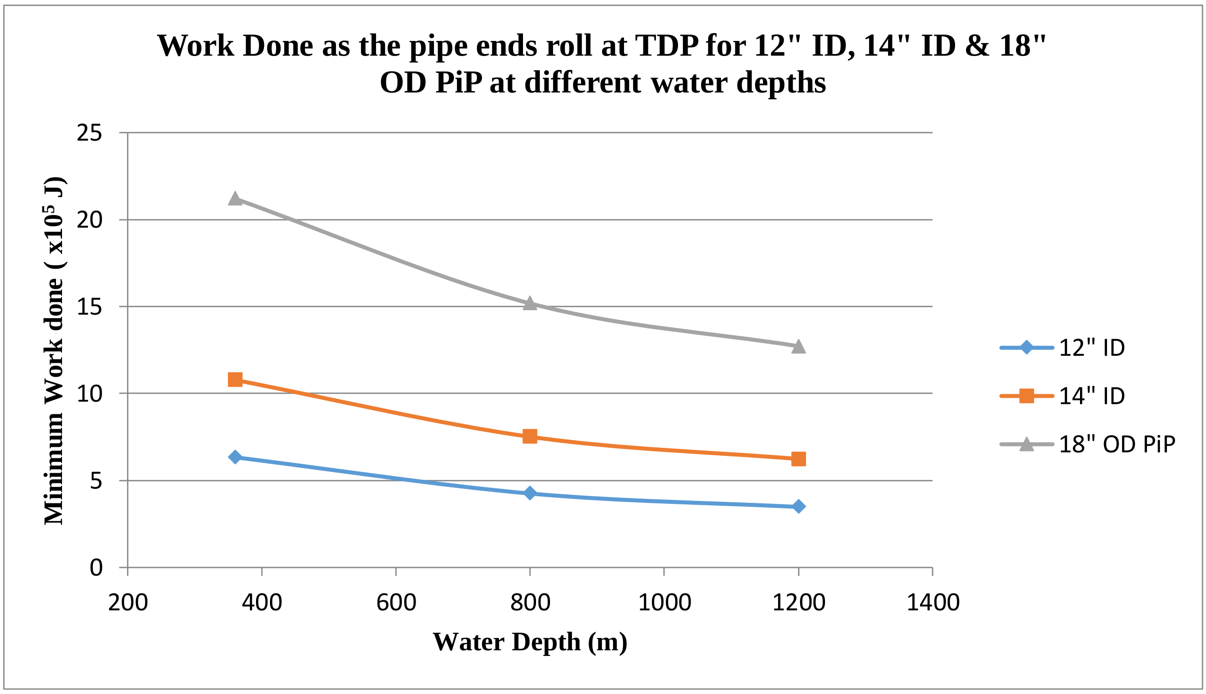


Figure 55: Minimum work done as pipe ends roll at TDP for the sensitivity test of pipe OD at different water depth

Larger OD pipelines tend to end rotation and reach equilibrium position at smaller roll angles than smaller OD pipelines do for all water depth cases. Generally, the range of the roll angles at TDP is between 89.5^0 and 100^0 for a water depth of 360m and between 112^0 and 117^0 for a 1200m water depth. This can be demonstrated by plotting the TDP roll angles of each pipeline, when the predicted work done curve has its local minimum value, for each water depth as shown in figure 56. At a depth of 360m, a 14" ID pipeline ends roll at an angle 5.5% smaller than a 12" ID pipeline does. Similarly, the percentage of reduction in roll angle for an 18" pipe-in-pipe is 10.5%. With an increase in water depth, the tendency of the pipelines to end roll and reach the equilibrium position is increased. Considering a water depth of 1200m, the roll angle of a 14" ID pipeline is 2.14% smaller than a 12" ID pipeline does. Similarly, the roll angle of an 18" pipe-in-pipe is 4.27% smaller.

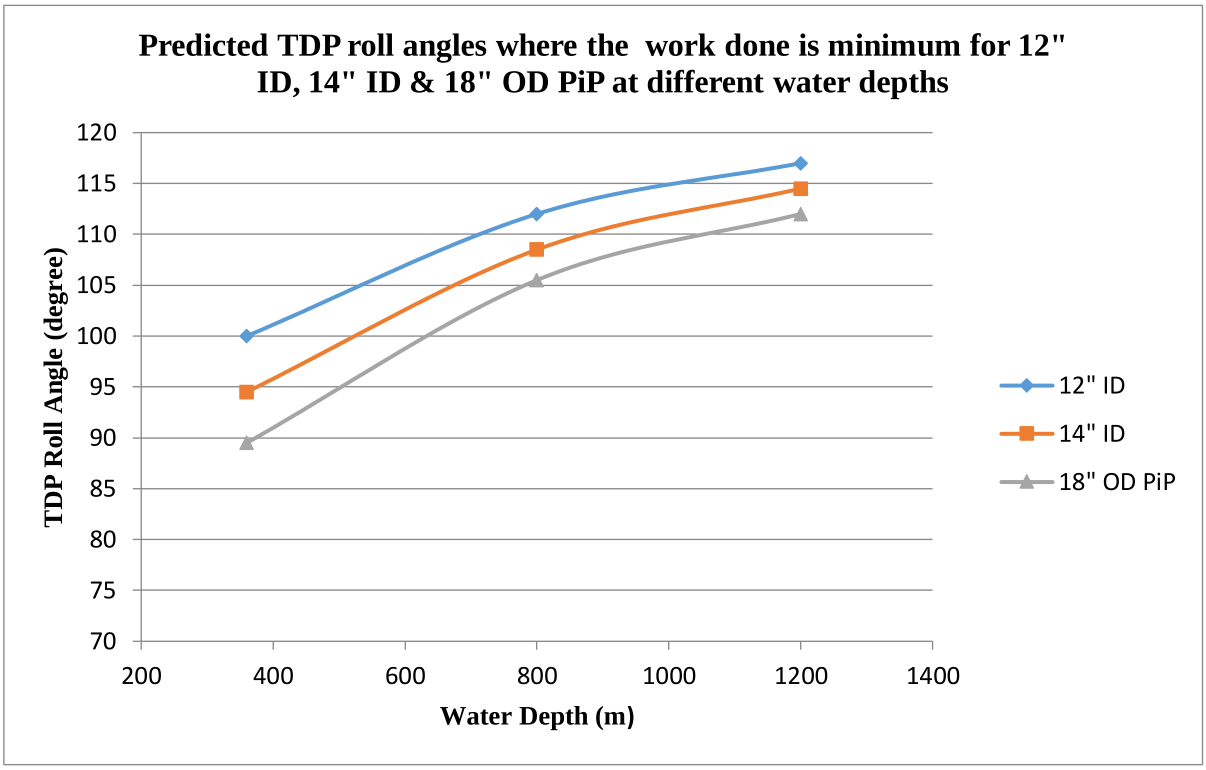


Figure 56: Results of the predicted roll angles at TDP for the sensitivity test of pipe OD at different water depth

The predicted roll angle of pipelines in ending rotation at TDP for different water depths is summarized in table 11. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

The sensitivity analysis demonstrates that for a given water depth the pipeline roll response at TDP is little sensitive to pipeline OD. However, the pipeline response to roll increases with an increase in water depths due to reduced stiffness.

Item No.	Pipe Type	Roll angle at which the external work done is minimum @ different water depth						Remarks
		@360m		@800m		@1200m		
		Roll Angle (deg)	Work done ($x10^5$ J)	Roll Angle (deg)	Work done ($x10^5$ J)	Roll Angle (deg)	Work done ($x10^5$ J)	
1	12" ID	100^0	6.334	112^0	4.25	117^0	3.48	Single pipe section
2	14" ID	94.5^0	10.78	108.5^0	7.512	114.5^0	6.236	Single pipe section
3	18" OD	89.5^0	21.2	105.5^0	15.18	112^0	12.72	Pipe-in-pipe

Table 11: Predicted roll angles at TDP and corresponding work done for different pipe OD @ different water depths

5.4 Sensitivity Study - Diameter to thickness ratio (D_0/t)

The individual analytical results for the total work done to bend and twist the 12” ID & 14” ID single pipe sections and 18” OD pipe-in-pipe from the surface to the seabed for diameter to thickness (D_0/t) ratios of 10, 13, 16 and 20 in water depth of 360m are presented in Appendix D. For each case of the pipelines considered, the total work done is always greater for sections having smaller D_0/t ratios than the larger ones for all roll angles at the seabed TDP. Smaller D_0/t means a thicker wall thickness; and for a given OD, an increase in wall thickness (larger cross-sectional area) increases the flexural and rotational stiffness of the pipeline. This in turn leads to an increase in the amount of external work done for the thick-walled pipelines than the corresponding thin-walled pipelines. The total work done for the different D_0/t ratios when the curve has its minimum value at water depth of 360m is illustrated in figure 57.

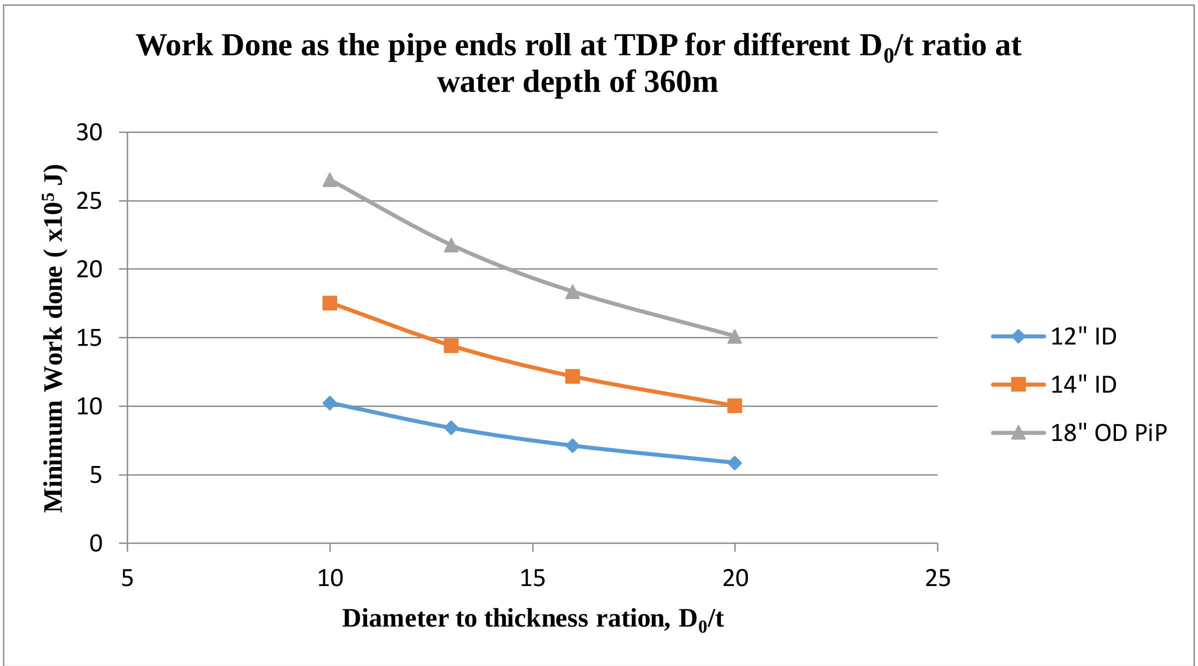


Figure 57: Minimum work done as pipe ends roll at TDP for various D_0/t ratios at water depth of 360m

Considering the roll angle at TDP, the variation in D_0/t ratio doesn't have any influence on pipelines ending roll at the seabed as long as pipe OD is kept constant. For a given pipe OD, the roll angle at which a pipeline can easily initiate and end rotation is the same for the various D_0/t ratios considered, i.e. 100^0 for a 12" ID pipe, 95^0 for a 14" ID pipe and 90^0 for an 18" OD pipe-in-pipe. The results of the roll angles at TDP for the various D_0/t ratios are illustrated in figure 55. Moreover, figure 58 demonstrates that for a given water depth, larger OD pipelines end rotation and reach equilibrium position at smaller roll angles than the corresponding smaller OD pipelines regardless of the D_0/t.

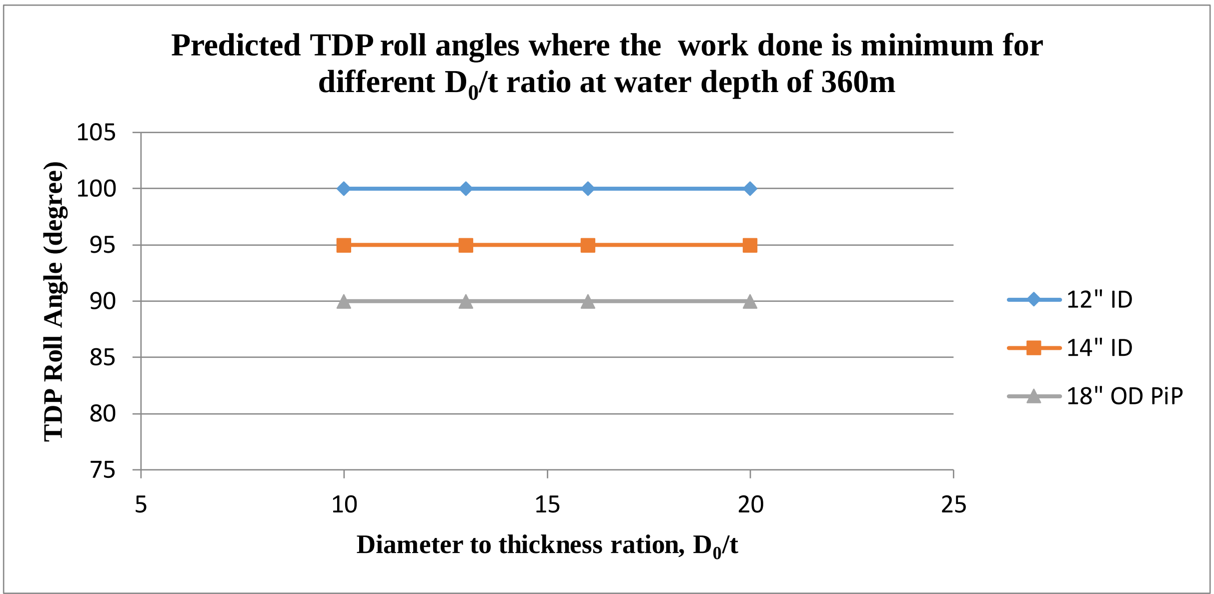


Figure 58: Results of the predicted roll angles at TDP for various D_0/t ratios at water depth of 360m

For the various D_0/t ratios considered, the predicted roll angle at TDP as the pipe ends rotation is summarized in table 12. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included. From the results, it can be easily noticed that a variation in D_0/t ratio doesn't change the pipeline roll response at TDP.

Item No.	Pipe Type	Roll angle at which the external work done is minimum @ 360m water depth								Remarks
		D_0/t =10		D_0/t =13		D_0/t =16		D_0/t =20		
		Roll angle (deg)	Work done (x10^5 J)	Roll angle (deg)	Work done (x10^5 J)	Roll angle (deg)	Work done (x10^5 J)	Roll angle (deg)	Work done (x10^5 J)	
1	12" ID	100^0	10.25	100^0	8.416	100^0	7.12	100^0	5.876	Single pipe section
2	14" ID	95^0	17.56	95^0	14.42	95^0	12.18	95^0	10.03	single pipe section
3	18" OD	90^0	26.53	90^0	21.77	90^0	18.37	90^0	15.12	Pipe-in-pipe

Table 12: Predicted roll angles at TDP & corresponding work done for different D_0/t @ 360m water depth

For a specific diameter to thickness ratio, $D_0/t=16$, the analytical results for the total work done to bend and twist the 12” ID & 14” ID single pipe sections and 18” OD pipe-in-pipe from the surface to the seabed in water depths of 360m, 800m and 1200m are presented in Appendix D. The results predict that for a given D_0/t and water depth, the external work done to bend and twist a pipeline with a larger OD is higher than a pipeline with a smaller OD for all roll angles at TDP. The results obtained are in line with the results of the sensitivity test of pipe OD and hence the same explanation can be given as in section 5.3. The total work done to the pipe when the curve has a local minimum value at different water depths is given in figure 59. The result shows that the work done at the point where pipe ends roll decreases with an increase in water depth.

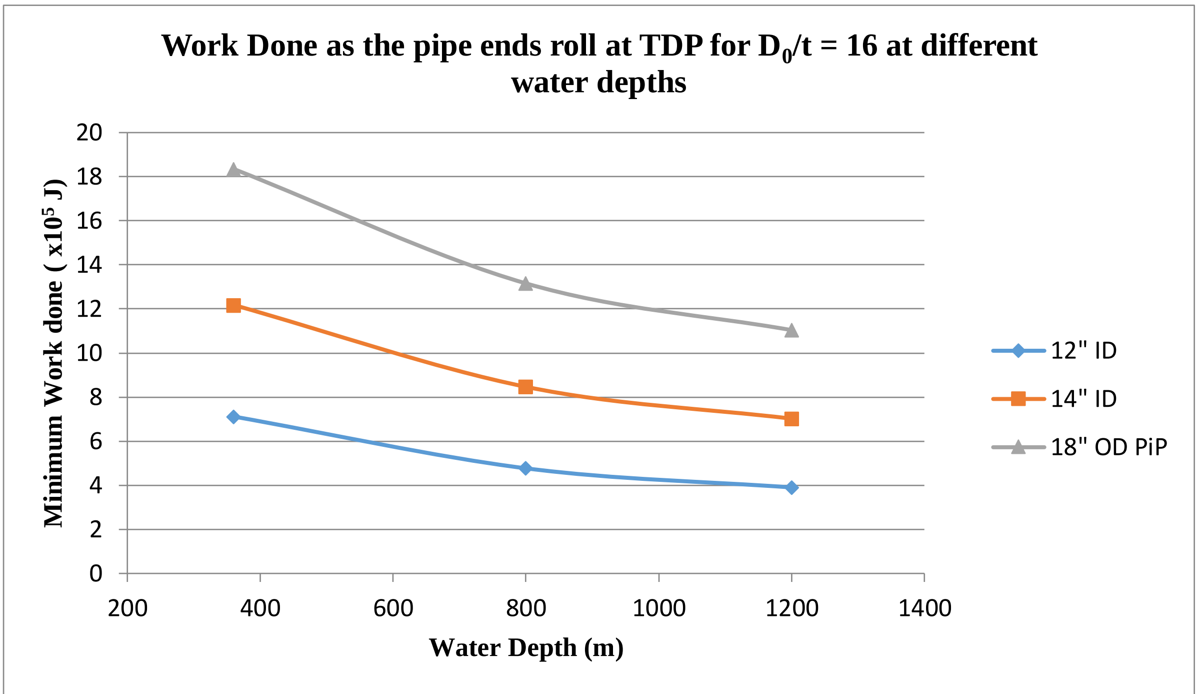


Figure 59: Minimum work done as pipe ends roll at TDP for $D_0/t=16$ at various water depths

Given a specific D_0/t ratio, the roll angles as the pipeline ends roll vary considerably as the pipe OD changes. Pipelines having large OD end roll to reach equilibrium position at a smaller angle than the corresponding smaller OD pipelines do. Nevertheless, the work done required is higher for large OD pipelines. Figure 60 displays the predicted pipe roll angles at TDP when the curve has its minimum work done for $D_0/t = 16$ at various water depth. For a given pipe OD, the predicted roll angle increases with an increase in water depth. For example, the roll angle of a 12” ID pipe is increased from 100^0 to 117.5^0 as the water depth varies from 360m to 1200m. On the contrary, for a given water depth, the roll angle decreases with an increase in pipe OD. The range of the roll angles at TDP is between 90^0 and 100^0 for a 360m water depth and between 111.5^0 and 117.5^0 for a 1200m water depth. It can be noticed that the predicted pipe roll angle at TDP is not significantly influenced by the diameter to thickness ratio, rather by the pipeline OD.

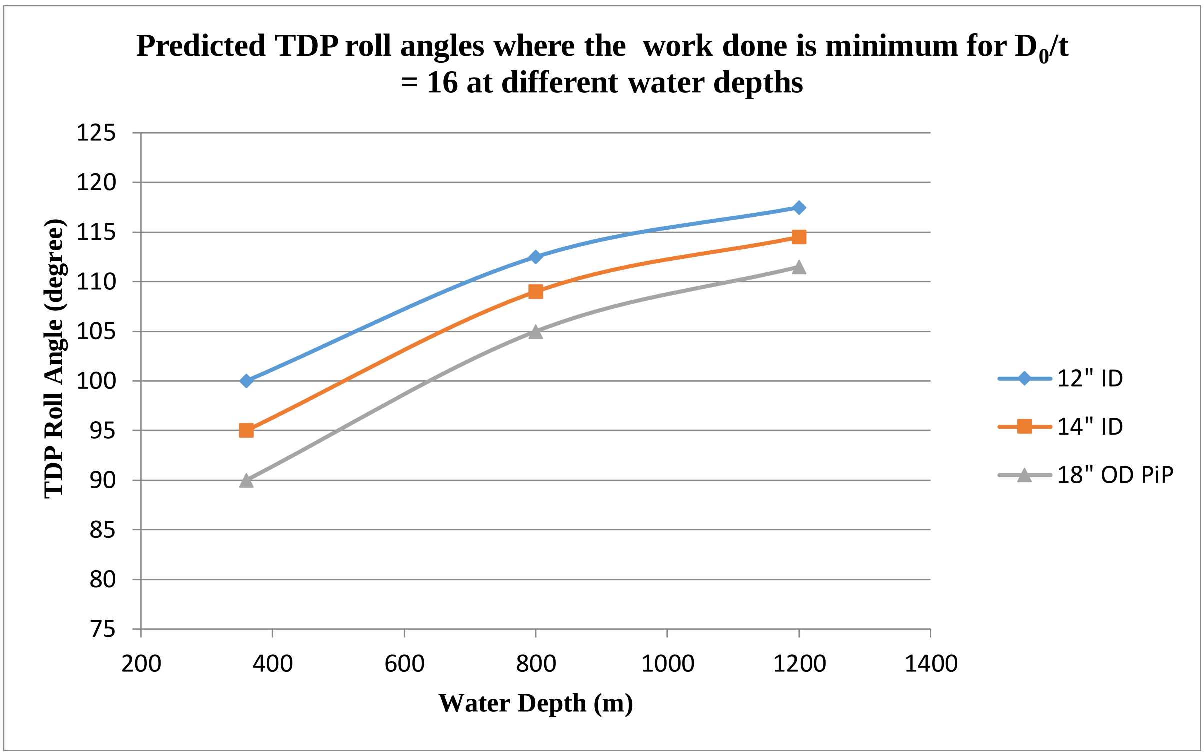


Figure 60: Results of the predicted roll angles at TDP for $D_0/t=16$ at various water depth

Table 13 summarizes the predicted roll angle of pipelines as it ends rotation at TDP for D_0/t = 16. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

Item No.	Pipe Type	Roll angle at which the external work done is minimum for $D_0/t = 16$						Remarks
		@360m		@800m		@1200m		
		Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	
1	12" ID	100^0	7.12	112.5^0	4.77	117.5^0	3.903	Single pipe section
2	14" ID	95^0	12.18	109^0	8.467	114.5^0	7.023	Single pipe section
3	18" OD	90^0	18.35	105^0	13.16	111.5^0	11.04	Pipe-in-pipe

Table 13: Predicted roll angles at TDP for D0/t = 16 @ different water depths

The sensitivity analysis demonstrates that for a given water depth, the pipeline roll response at TDP is not sensitive at all to the changes in D_0/t ratio as long as pipe OD is kept constant. However, as the water depth is increased, the roll response of the pipeline starts to vary considerably.

5.5 Sensitivity Study - Horizontal component of lay tension

The horizontal component of the lay tension is dependent on the maximum allowable bending strain in the pipeline. The horizontal component of the tension at the lay vessel is inversely proportional to the allowable bending strain as described in the estimation of horizontal component of tension in section 2.2.2 part II.

The individual analytical results of the predicted total work done to bend and twist the 12” ID, 14” ID and 18” OD pipe-in-pipe from the surface to the seabed for bending strains (ε_b) corresponding to 50%, 60% and 75% of SMYS/E in water depth of 360m are given in Appendix E. The extent of the total work done in a pipe having the stated allowable bending strains doesn’t vary considerably as compared to the other parameters; yet there is slightly more work done for pipes installed with higher allowable bending strain. It is true that an increase in allowable bending strain reduces the overall length of the suspended pipeline and horizontal component of the lay tension. However, the nominal and total curvatures of the pipeline is greatly increased as the under-straightened section reaches the sagbend which give rise to a considerable increase in the work done due to bending. The nominal curvatures for the different allowable bending strains considered in a pipe of 12” ID, 14” ID and 18” OD pipe in pipe is shown in Appendix E. It should be noted that the total work done is proportional to the square of the nominal and total curvatures of the pipeline.

For a water depth of 360m, the total work done for the various allowable bending strains when the curve has its minimum value is illustrated in figure 61. As it can be clearly seen from the slope of the lines, the rate of change of work done as the pipe ends roll is higher in larger OD pipelines than smaller OD pipelines.

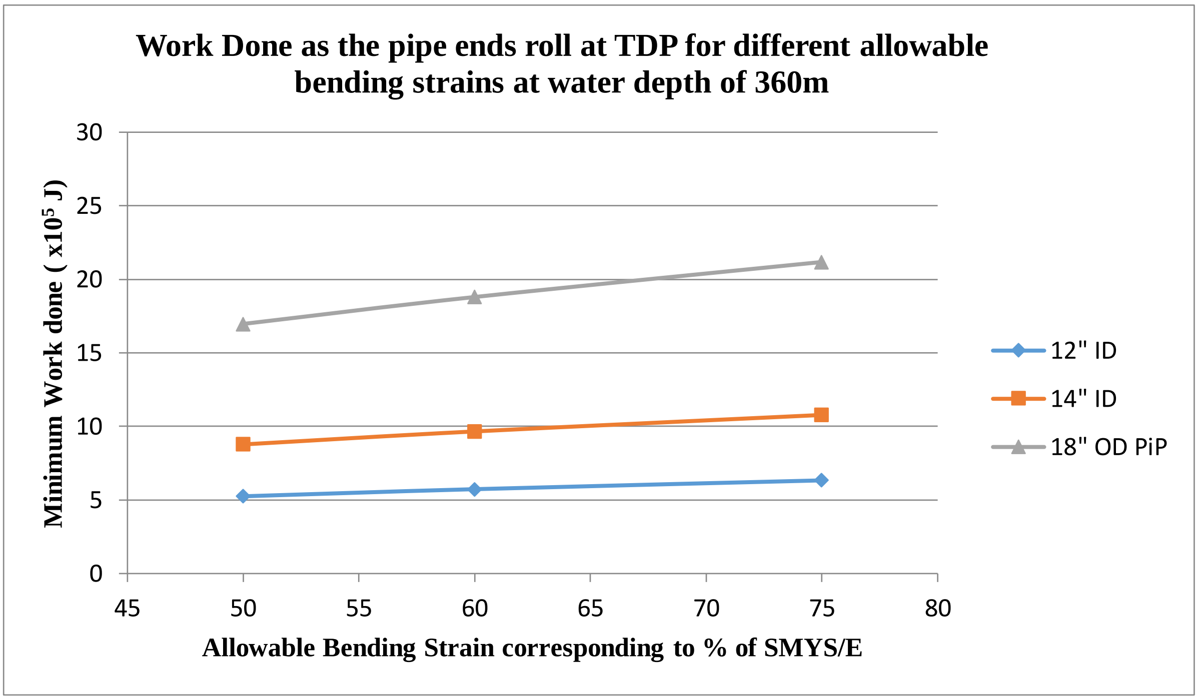


Figure 61: Minimum work done as pipe ends roll at TDP for various allowable bending strains in water depth of 360m

When considering the angle as the pipe ends rotation, the roll angle increases with an increase in allowable bending strain. This implies that the allowable bending strain has a considerable influence on pipeline's roll angle as it ends rotation at the seabed TDP. The roll angles for a 12" ID pipe increases from 93.5^0 to 100^0, while for a 14" ID pipe the angle varies from 88.5^0 to 94.5^0. It should be noted that the roll angles as the pipe ends rotation are inversely related to the increase in OD of pipelines. This happens due to the increased rotational stiffness of the pipeline. A pipe with large rotational stiffness has more resistance to twist than a pipe of smaller stiffness. In an 18" OD pipe-in-pipe, the roll angle increases from 84^0 to 89.5^0 for the same allowable bending strains. The results of the angles as the pipe ends roll for the various allowable bending strains are presented in figure 62.

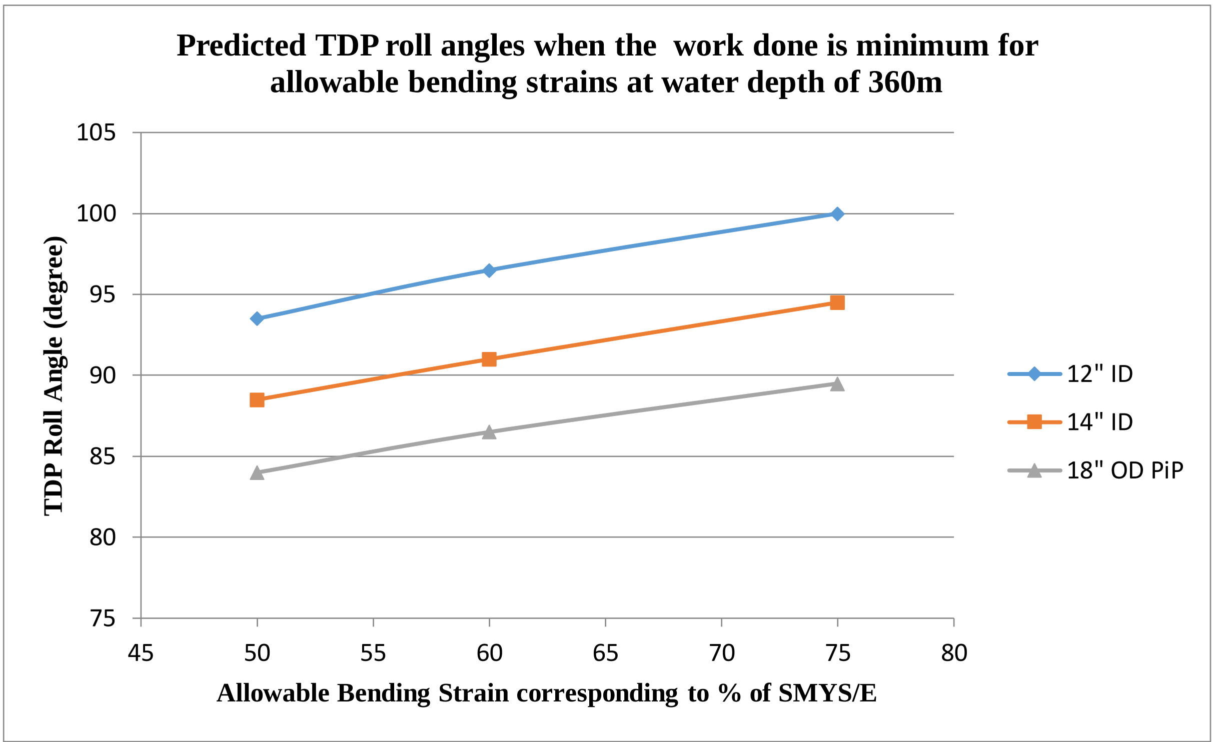


Figure 62: Minimum work done as pipe ends roll at TDP for various allowable bending strains at water depth of 360m

For the various allowable bending strains considered, the predicted roll angle at TDP as pipe ends rotation is summarized in table 14. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

Results indicated that the pipeline roll response at TDP is little sensitive to the changes in allowable bending strains.

Item No.	Pipe Type	Roll angle at which the external work done is minimum @ 360m water depth						Remarks
		ε_b = 50%*SMYS/E		ε_b = 60%*SMYS/E		ε_b = 75%*SMYS/E		
		Roll angle (deg)	Work done (x10^5 J)	Roll angle (deg)	Work done (x10^5 J)	Roll angle (deg)	Work done (x10^5 J)	
1	12" ID	93.5^0	5.252	96.5^0	5.735	100^0	6.334	Single pipe section
2	14" ID	88.5^0	8.778	91^0	9.661	94.5^0	10.78	Single pipe section
3	18" OD	84^0	16.97	86.5^0	18.8	89.5^0	21.18	Pipe-in-pipe

Table 14: Predicted roll angles at TDP for different allowable bending strains ε_b @ 360m water depth

For a specific bending strain ε_b corresponding to 75%*SMYS/E, the analytical results for the total work done to bend and twist the 12" ID & 14" ID single pipe sections and 18" OD pipe-in-pipe from the surface to the seabed in water depths of 360m, 800m and 1200m are presented in Appendix E. The results in each case predict that the external work done to bend and twist a pipeline with a larger OD is higher than a pipeline with a smaller OD for all roll angles at TDP. The results obtained are in line with the results of the sensitivity test of pipe OD and hence the same explanation can be given as in section 5.3. The total work done to the pipe when the curve has a local minimum value at different water depths is given in figure 63. It shows that the work done at the point where pipe ends roll decreases with an increase in water depth.

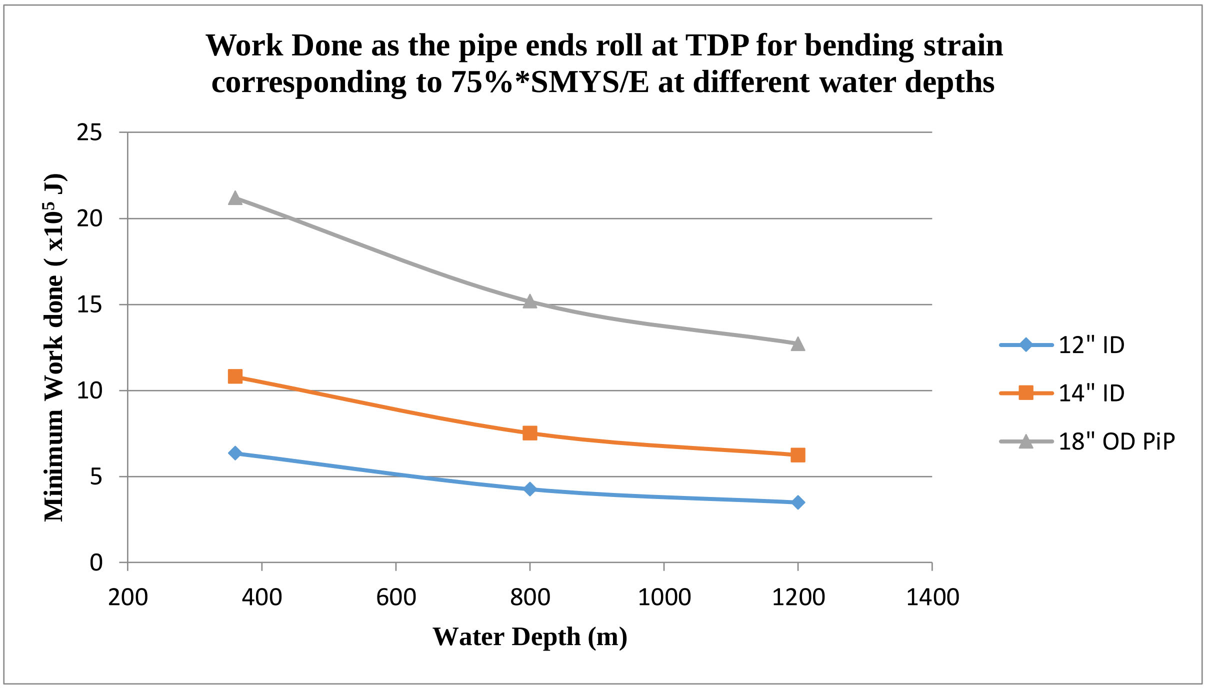


*Figure 63: Minimum work done as pipe ends roll at TDP for allowable ε_b= 75%*SMYS/E at various water depths*

Given a specific allowable bending strain ε_b, the roll angles as the pipeline ends roll vary considerably as the pipe OD changes. Pipelines having large OD end roll to reach equilibrium position at a smaller angle than the corresponding smaller OD pipelines do. Nevertheless, the work done required is higher for large OD pipelines. Figure 64 displays the predicted pipe roll angles at TDP when the curve has its minimum work done for allowable bending strain ε_b corresponding to 75%*SMYS at various water depth. For a given pipe OD, the predicted roll angle increases with an increase in water depth. For example, the roll angle of a 12" ID pipe is increased from 100^0 to 117.5^0 as the water depth varies from 360m to 1200m. On the contrary, for a given water depth, the roll angle decreases with an increase in pipe OD. The range of the roll angles at TDP are between 89.5^0 and 100^0 for a 360m water depth and between 112^0 and 117.5^0 for a 1200m water depth.

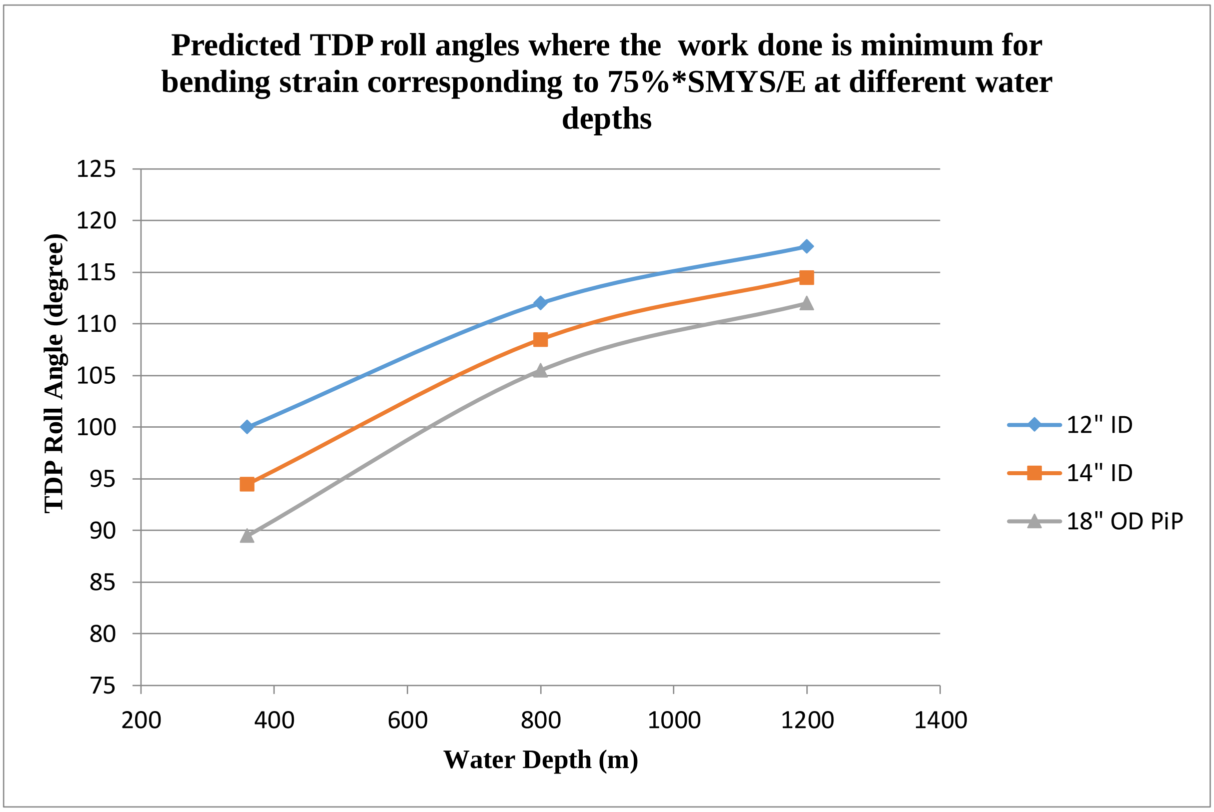


*Figure 64: Results of the predicted roll angles at TDP for allowable ε_b= 75%*SMYS/E at various water depths*

Table 15 summarizes the predicted angle of pipelines ending rotation at TDP for allowable bending strains corresponding to 75%*SMYS/E. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

Item No.	Pipe Type	Roll angle at which the external work done is minimum for ε_b = 75%*SMYS/E						Remarks
		@360m		@800m		@1200m		
		Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	
1	12" ID	100^0	6.334	112^0	4.25	117.5^0	3.48	Single pipe section
2	14" ID	94.5^0	10.78	108.5^0	7.512	114.5^0	6.236	Single pipe section
3	18" OD	89.5^0	21.18	105.5^0	15.16	112^0	12.71	Pipe-in-pipe

*Table 15: Predicted roll angles at TDP for allowable bending strain ε_b = 75%*SMYS/E @ different water depths*

For a given water depth, the sensitivity analysis indicates that the pipeline roll response at TDP is not singnificantly sensitive to the changes in bending strain (or horizontal lay tension). However, with an increase in water depth, the roll angles are observed to increase gradually.

5.6 Sensitivity Study - Residual Strain (ε_{res})

The individual analytical results for the total work done to bend and twist the 12" ID & 14" ID single pipe sections and 18" OD pipe-in-pipe from the surface to the seabed for residual strains (ε_{res}) of 0.15%, 0.20% and 0.25% in water depth of 360m are presented in Appendix F. Results indicate that the difference in the amount of work done due to the variation in residual strains is relatively large for small roll angles at TDP. However, as the roll angle increases the amount of work done converges and is nearly identical in the area where the curve has its minimum value i.e. as the pipeline ends rotation and attains stability. It should be noted that with an increase in residual strain, the total curvature is increased for small roll angles. Consequently, the total work done due to bending is increased as the under-straightened section reaches the sagbend. The total curvature of a pipeline is squarely related to the total work done. Figures are provided in Appendix F to show how the total curvatures changes due to the variations in residual strains in single pipes of 12" ID & 14" ID and 18" OD pipe-in-pipe. The total curvature is a function of roll angle, distance from TDP (s) and residual curvature length. Thus, the figures provided are taken at a point 50m from TDP and a residual curvature length of 70m.

The total work done for the different residual strains as the curve has its minimum value in water depth of 360m is illustrated in figure 65. As the figure depicts, the total work done as the pipe reaches equilibrium position is very close for different values of residual strain. The change in residual strain from 0.15% to 0.25% leads to a change in the amount of work done by less than 5%. Moreover, the figure shows that the work done in large OD pipelines is higher than small OD pipelines.

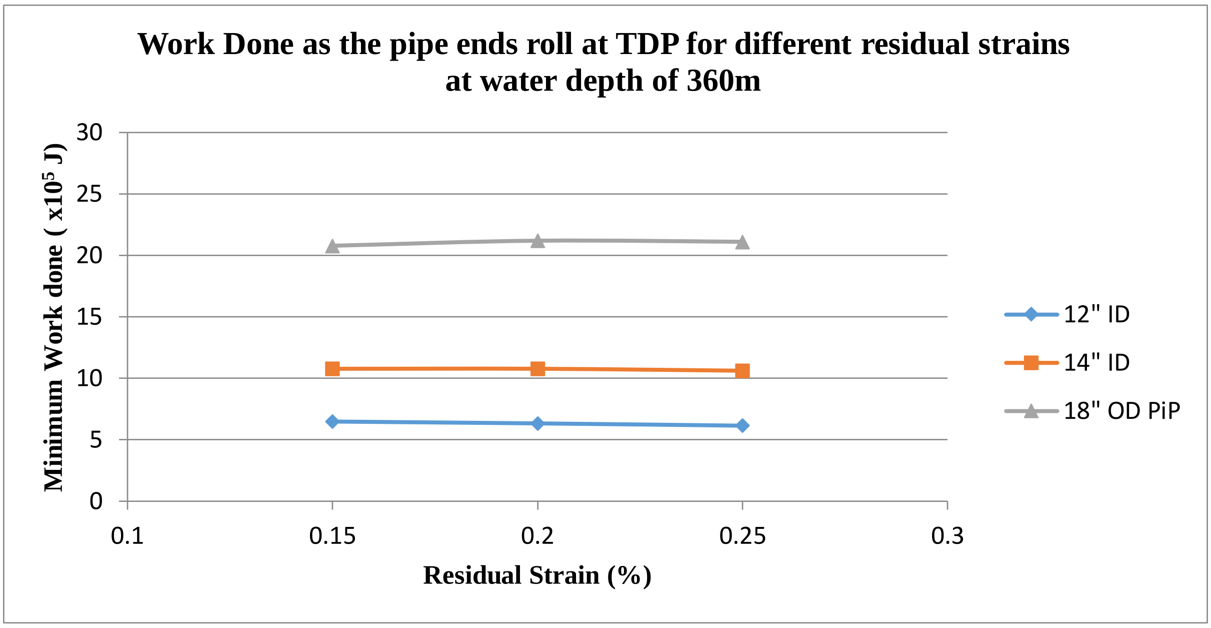


Figure 65: Minimum work done as pipe ends roll at TDP for various residual strains in water depth of 360m

However, the minimum work done doesn't occur at the same roll angle for the different residual strains. There is a significant increase in roll angle as the residual strain is increased. This indicates that the residual strain is likely to have influence on pipeline's roll angle as it reaches stability position. The roll angle at TDP increases from 94.5^0 to 102.5^0 for a 12" ID pipe and from 85.5^0 to 98^0 for a 14" ID pipe. The size of the pipelines is inversely related to the roll angles. This happens due to the increased rotational stiffness of the pipeline. A pipe with large rotational stiffness has more resistance to twist than a pipe of smaller stiffness. In an 18" OD pipe-in-pipe, the roll angle increases from 79^0 to 94.5^0 as the residual strain increased from 0.15% to 0.25%. Plots of the pipe roll angles and residual strains at the equilibrium position are provided in figure 66.

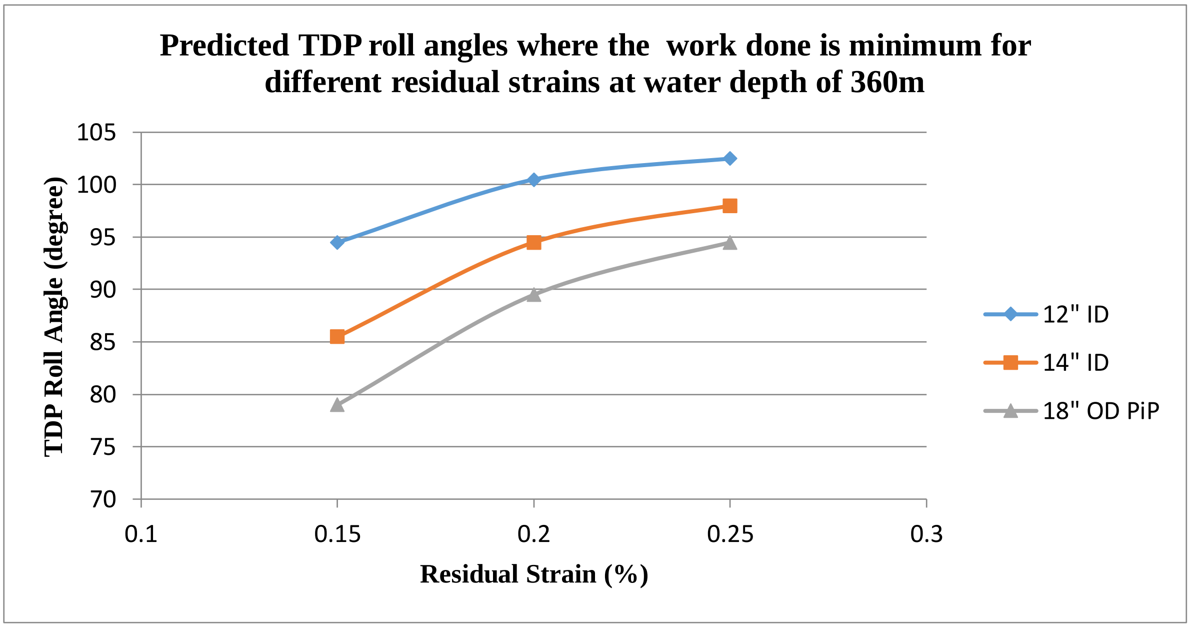


Figure 66: Minimum work done as pipe ends roll at TDP for various residual strains at water depth of 360m

For the various residual strains considered, the predicted roll angle at TDP as pipe reaches stability is summarized in table 16. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

Results indicated that the pipeline roll response at TDP is slightly sensitive to the changes in residual strains.

Item No.	Pipe Type	Roll angle at which the external work done is minimum @ 360m water depth						Remarks
		ε.res = 0.15%		ε.res = 0.20%		ε.res = 0.25%		
		Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	
1	12" ID	94.5^0	6.485	100.5^0	6.334	102.5^0	6.149	Single pipe section
2	14" ID	85.5^0	10.78	94.5^0	10.78	98^0	10.62	single pipe section
3	18" OD	79^0	20.79	89.5^0	21.2	94.5^0	21.11	Pipe-in-pipe

Table 16: Predicted roll angles at TDP for different residual strain, ε.res, @ 360m water depth

For residual strain, ε_{res} = 0.20%, the analytical results for the total work done to bend and twist the 12” ID & 14” ID single pipe sections and 18” OD pipe-in-pipe from the surface to the seabed in water depths of 360m, 800m and 1200m are presented in Appendix F.

The outcome obtained is identical to the sensitivity study carried out to pipe OD, since both studies are based on equal input values. Hence, the work done for a specific value of residual strain can be interpreted in the same way done to pipe OD given in section 5.3. The total work done, as the pipe reaches stability by ending rotation, in different water depths is given in figure 67.

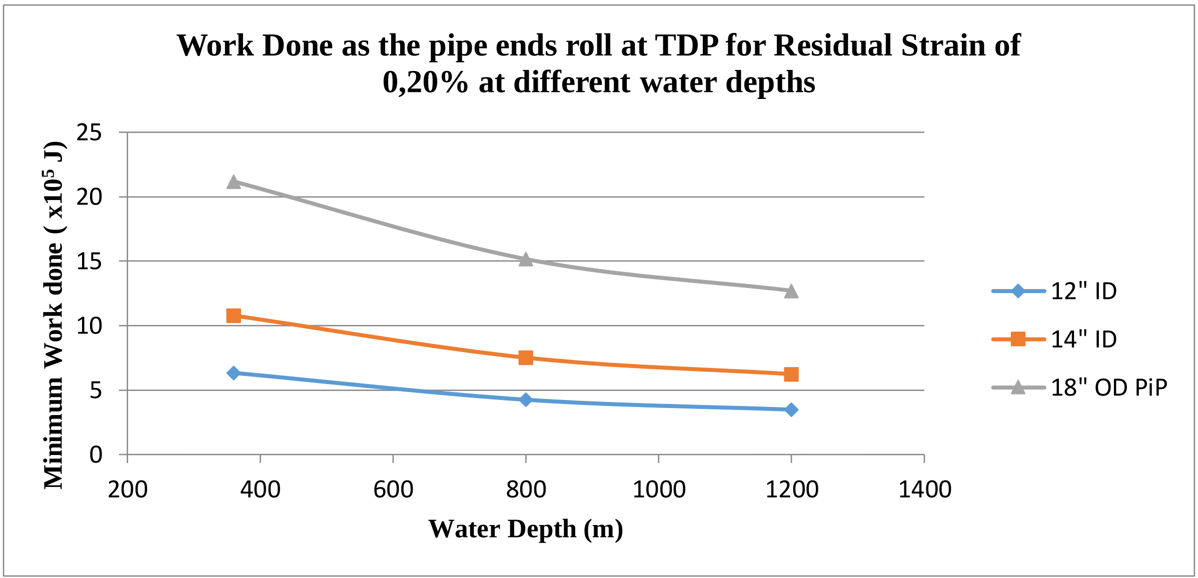


Figure 67: Minimum work done as pipe ends roll at TDP for residual strain of 0.20% at various water depths

Figure 68 displays the predicted pipe roll angles at TDP, when the pipe attains stability by ending rotation, for residual strain ε_{res} = 0.20% at varying water depth. For a given pipe OD, the predicted roll angle increases with an increase in water depth. For example, the roll angle of a 12" ID pipe is increased from 100.5^0 to 117.5^0 as the water depth varies from 360m to 1200m. On the contrary, for a given water depth, the roll angle decreases with an increase in pipe OD. The range of the roll angles at TDP for the different pipe OD are between 89.5^0 and 100.5^0 for a 360m water depth and between 112^0 and 117.5^0 for a 1200m water depth.

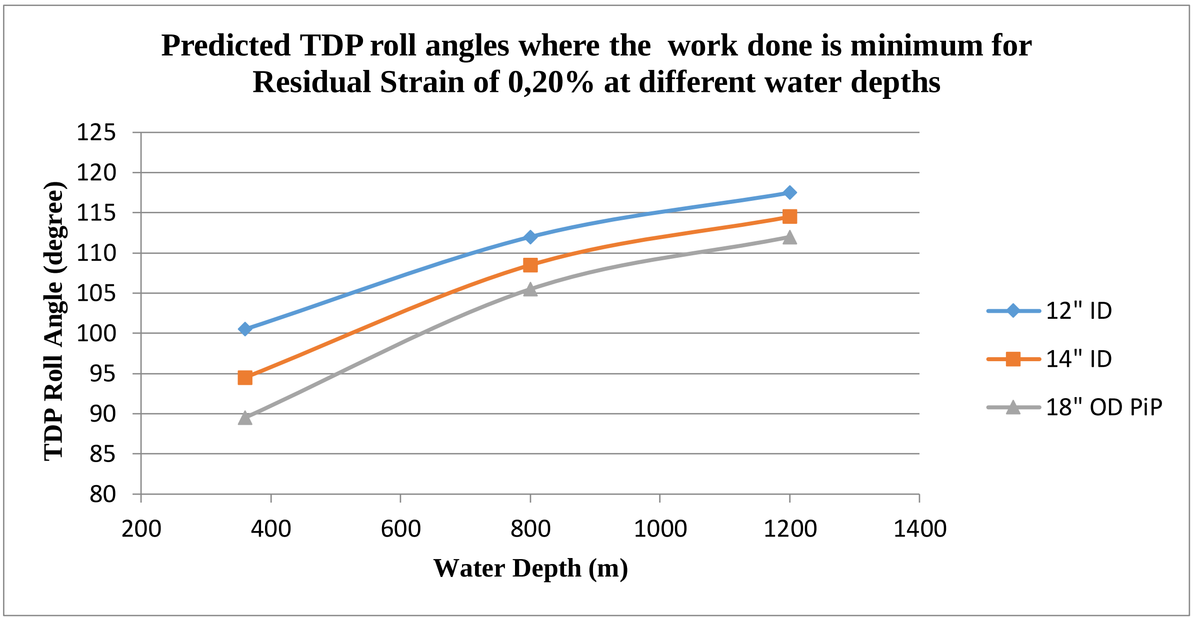


Figure 68: Results of the predicted roll angles at TDP for residual strains of 0.20% at various water depths

Table 17 summarizes the predicted angle of pipelines ending rotation at TDP for residual strains of 0.20%. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

Item No.	Pipe Type	Roll angle at which the external work done is minimum for ε.res = 0.20%						Remarks
		@360m		@800m		@1200m		
		Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	
1	12" ID	100.5^0	6.334	112^0	4.25	117.5^0	3.48	Single pipe section
2	14" ID	94.5^0	10.78	108.5^0	7.512	114.5^0	6.236	single pipe section
3	18" OD	89.5^0	21.18	105.5^0	15.16	112^0	12.71	Pipe-in-pipe

Table 17: Predicted roll angles at TDP for residual strain, ε.res = 0.20% @ different water depths

From the sensitivity analysis, it can be concluded that the pipeline's tendency to end roll and attain stable position at TDP is slightly sensitive to the changes in residual strain. However, the total work done at the equilibrium position is not influenced by the variations in residual strain.

5.7 Sensitivity Study - Water Depth (d)

The influence of water depth on pipe roll at the seabed TDP has been discussed along with the sensitivity study of the other parameters. In this section, a generalized summary of the effect of water depth is presented. The individual analytical results of the total work done to bend and twist 12" ID & 14" ID single pipes and 18" OD pipe-in-pipe from the surface to the seabed for water depths of 360m, 800m and 1200m are given in Appendix G. At small roll angles, the work done is slightly higher in deeper waters compared to the shallow waters. As the roll angle approaches around 45^0, the total work done converges and is equal regardless of the water depth. Table 18 shows the amount of work done for the three pipe types as the roll angle approaches 45^0 at different water depths.

Item No.	Pipe Type	45^0 TDP roll angle & corresponding work done at different water depths						Remarks
		@360m		@800m		@1200m		
		Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	
1	12" ID	44^0	11.1	44^0	11.1	44^0	11.15	Single pipe section
2	14" ID	46^0	15.7	46^0	15.56	46^0	15.6	Single pipe section
3	18" OD	46^0	27.78	46^0	27.32	46^0	27.31	Pipe-in-pipe

Table 18: 45^0 TDP roll angles and corresponding work done values @ different water depths

As the roll angle increases beyond 45^0, the amount of work done experienced by pipelines is higher in shallow waters than in deep water. In this regard, the significance of the water depth is apparent, the stiffness of pipelines reduces with an increase in water depth. Figure 69 shows the total work done as the pipe ends rotation to reach equilibrium position in different water depths.

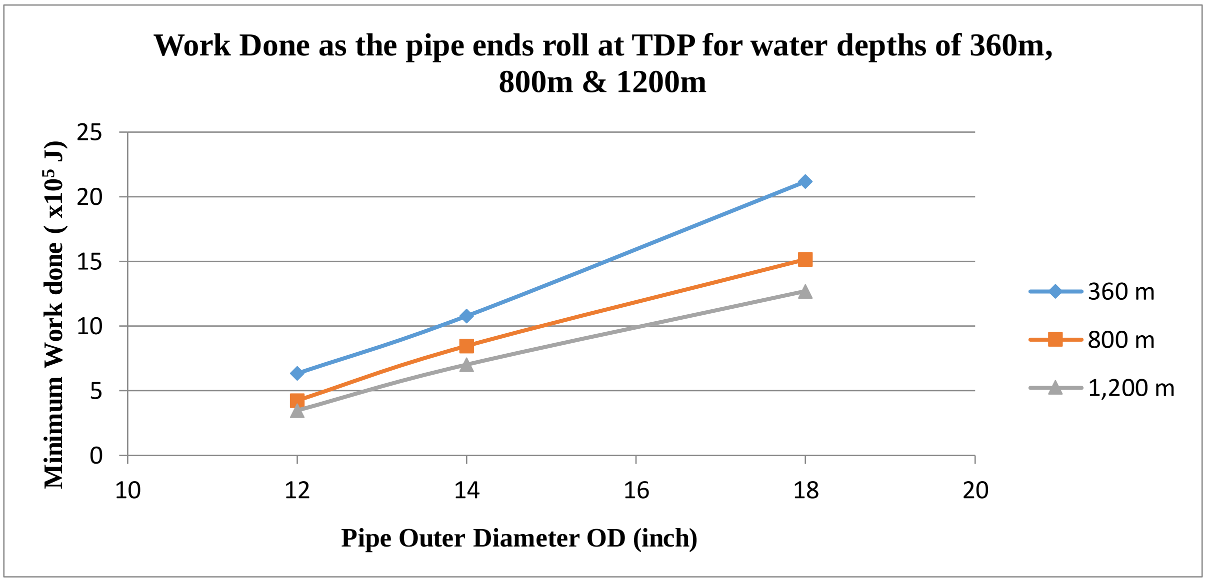


Figure 69: Minimum work done as pipelines end roll at water depths of 360m, 800m and 1200m

Although the total work done as pipe ends roll is higher in shallow waters, pipelines do reach equilibrium position at a relatively smaller angle in shallow waters than in deeper waters. At a water depth of 360m, the roll angle at stability position reduces from 100^0 to 89.5^0 as the pipe size increases from 12" ID to 18" OD. The roll angles become larger as the water depth increases. In water depth of 800m the roll angles range between 112^0 & 105.5^0, whereas the roll angles are between 117^0 and 112^0 for water depth of 1200m. The total work done at equilibrium positions for the different water depths is given in figure 70. The results obtained are in full conformity with the results obtained for the sensitivity study of the pipeline OD discussed in section 5.3.

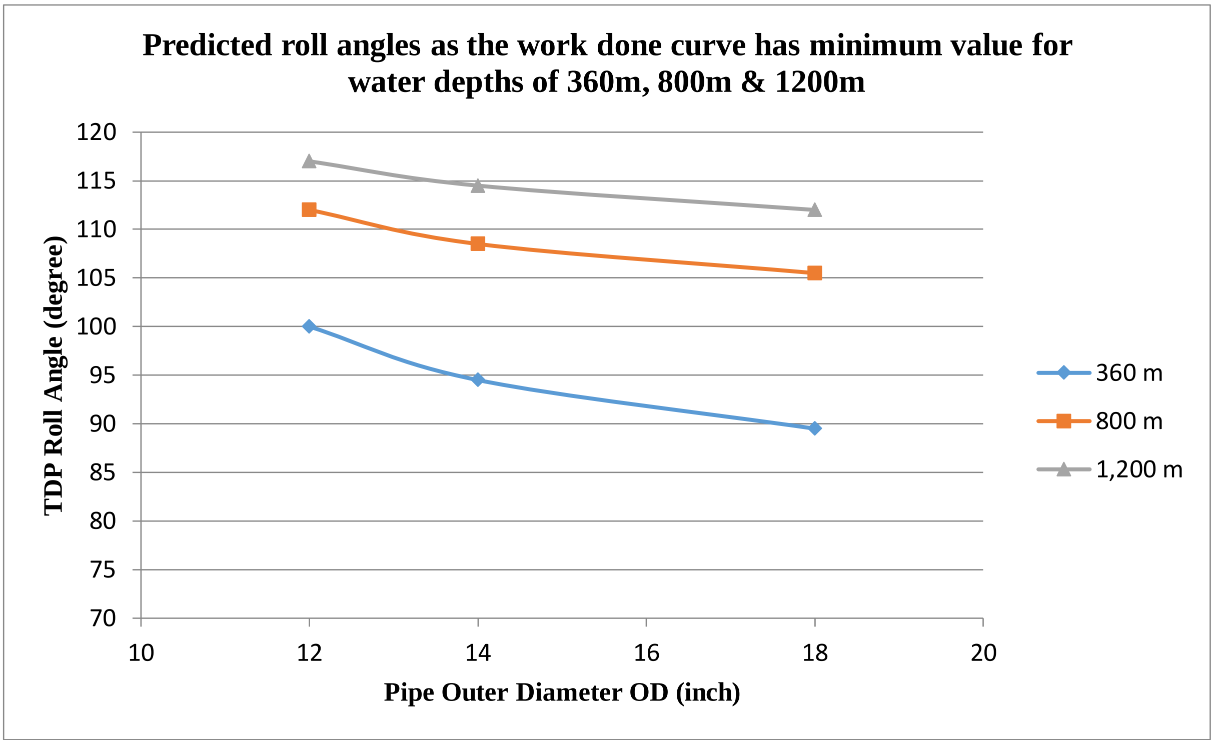


Figure 70: Results of the predicted roll angles at TDP against pipe OD for different water depths

Table 19 summarizes the predicted roll angle of pipelines as it ends rotation at seabed TDP in water depths of 360m, 800m and 1200m. The corresponding value of total work done due to bending and twisting of the pipelines from the surface to the seabed is also included.

Item No.	Water depth (m)	Roll angle at which the external work done is minimum @ different water depth						Remarks
		12" ID		14" ID		18" OD		
		Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	Roll angle (deg)	Work done ($x10^5$ J)	
1	@360 m	100^0	6.334	94.5^0	10.78	89.5^0	21.18	Single pipe section
2	@800 m	112^0	4.25	108.5^0	8.468	105.5^0	15.16	Single pipe section
3	@1200 m	117^0	3.48	114.5^0	7.023	112^0	12.71	Pipe-in-pipe

Table 19: Predicted roll angles at TDP for different water depths of 360m, 800m & 1200m

The sensitivity analysis indicates that the pipeline's tendency to end roll and attain stable position at TDP is relatively sensitive to the changes in water depth. With an increasing water depth, the roll angle at TDP also increases. It can easily be noticed that the pipe OD and water depth strongly influence the stiffness of the pipeline which ultimately determines the roll angle of pipelines at the point of stability. Similarly, the total work done as the pipe reaches equilibrium position is influenced to a certain extent by the variation in water depth.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusion

The main objective of the thesis is to estimate pipe roll at the seabed TDP when the method of residual curvature is used to control lateral buckling of pipelines under operating conditions. The estimation is based on minimization of the total work done to bend and twist the pipeline from the surface to the seabed. Pipelines laid with residual curvatures initiate & end roll to achieve stable positions when the total work done reaches its lowest value; and the angle at which this value is minimum gives the roll angle in the pipeline.

In this thesis, several parameters related to pipelay with residual curvature have been investigated. The major part of the study has been carried out analytically using Mathcad. Two pipe models in global analysis tool OrcaFlex have also been investigated to find out if the same results can be obtained as the analytical method.

Based on the study of the residual curvature method, the following points are drawn:

- The installation of pipe line with residual curvature involves bending and twisting as the pipe passes through the sagbend. This occurs due to the applied permanent strains to the pipe sections in the vertical plane at the straightener of the reel-lay vessel. OrcaFlex models clearly show the sudden twist of the pipeline as the residual curvature section passes through the sagbend. Although the main focus of the thesis is based on the reel-lay method, it is possible to create residual curvatures using S-lay method by adjusting the stinger to steep configuration or by lifting the rollers above the stinger to the required curvature.

- When pipelines are installed with residual curvatures, the extent of roll angle basically depends on the length of the plastic curvature configuration applied at the straightener. Results have indicated that under-straightened sections of about 50m to 80m are effective sections since the corresponding predicted roll angles at TDP range between 80^0 and 100^0. As reflected in global analysis, residual curvature sections extending beyond 80m are subjected to a cantilever type of deflection in which the crown of the under-straightened section touches down on the seabed leaving a gap between the sea floor and the pipeline on either side.

- The analytical analysis is carried out for an under-straightened section of 70m. Results have indicated that pipe roll at TDP is influenced by the pipe OD. An increase in pipe OD increases the total work done required to bend and twist the pipe line for all roll angles at TDP due to increased stiffness. However, the roll angle at which stability is reached decreases. Considering a water depth of 360m, a 12” ID and 14” ID pipe sections reach stability by ending roll at 100^0 and 94.5^0 respectively. Similarly, an 18” OD pipe-in-pipe attains stable position at 89.5^0. The result obtained shows that for a given water depth, pipe roll is little sensitive to changes in pipe OD.

- Pipeline's roll response at TDP is not sensitive at all to changes in diameter to thickness D_0/t ratio as long as pipe OD is kept constant. Results have shown that for various D_0/t ratios, the roll angle at which pipelines end roll remains constant. For a water depth of 360m and various D_0/t ratios, the corresponding roll angles for 12" ID, 14" ID single pipe sections and 18" OD pipe-in-pipe are 100^0, 95^0 and 90^0 respectively. Nevertheless, the total work done increases as the ratio of D_0/t decreases for all roll angles. This happens due to an increase in stiffness as the pipe wall thickness increases.

- As discussed in pipeline basic theory, the horizontal component of the lay tension holds an inverse relationship to the allowable bending strain in the pipeline. Likewise, the maximum allowable bending strain in the pipeline is limited in such a way that the corresponding bending stress is a fraction of the SMYS. The prediction shows that an increase in allowable bending strain increases the total work done slightly for all roll angles at TDP. This happens as a result of increased nominal and total curvatures although the suspended length and horizontal component of lay tension is reduced. Similarly, the roll angle as the pipeline reaches stable position increases with the increase in allowable bending strain. For an 18" OD pipe-in-pipe and a water depth of 360m, the predicted roll angle at TDP using a maximum allowable bending strain that corresponds to 50% of SMYS is 84^0. A 20% increase in allowable bending strain i.e. value corresponding to 60% of SMYS, increases the roll angle by 3% to 86.5^0. If bending strain is further increased by 50% i.e. corresponding to 75% of SMYS, the predicted roll angle at TDP increases by 6.5% to 89.5^0. The result shows that pipe roll is less sensitive to changes in the horizontal component of lay tension.

- The sensitivity analysis indicates that the residual strain is likely to have an influence on the pipeline's roll angle as the pipe reaches stable position at the seabed. Results obtained from an 18" OD pipe-in-pipe in water depth of 360m have shown that as the value of the residual strain is increased from 0.15% to 0.20% i.e. an increase of 33%, the roll angle increased from 79^0 to 89.5^0 – a 13% increase. When residual strain increases from 0.15% to 0.25% i.e. an increase of 67%, the roll angle increases by 19% to 94.5^0. Therefore, pipe roll is slightly sensitive to the variation in residual strain.

- By comparison, pipeline roll angle at TDP is influenced more by pipe OD and water depth than by any other parameters considered. Both parameters affect the stiffness of the pipeline to a significant degree. As a result, pipe roll angle at TDP is slightly sensitive to changes in water depth.

Thus, the points drawn above can be summarized as follows:

- The method of the simplified analytical energy approach provides a good indication in estimating pipe roll angle at TDP as the pipe reaches stable position by ending roll. The successful implementation of the RCM method in projects confirms the validity of the approach.

- When pipelines reach stable positions at the seabed, there is no substantial variation in pipe roll angle at TDP as a result of the parametric changes. If variations do occur, the percentage of increase or decrease in roll angle is not significant.

- The method of residual curvature is capable of performing without significant deviation in roll angle under a wide range of conditions. Thus, the RCM method is a robust and reliable technique.

- Following the successful implementation of the RCM method in Skuld project and Edradour production pipeline, it provides a cost-effective technical solution as compared to the conventional methods.

6.2 Recommendation for further studies

The application of the method of residual curvatures is not limited to the lateral buckling control of pipelines under operating conditions. The method can have a significant role in other areas of the offshore industry. Some of the recommendations for further studies are:

- The estimation of the pipe roll when using RCM is carried out analytically using simplified energy approach method. Further studies can be carried out in finite element to expand and include other parameters which can influence pipe roll angle at TDP.

- A residual curvature section is likely to follow the roll direction of its previous section. However, the first residual curvature section can possibly twist in either CW or CCW direction. Studies can be made as to what determines the roll direction of a residual curvature section during pipelaying.

- Whenever pipe roll is permitted in an offshore pipeline, it is very important to know the distance the roll extends longitudinally in the pipeline. This helps us to avoid potential overturning moments at connections of Tee intersections, valves as well as subsea equipments as a direct result of the piperoll, Ref [16]. Hence, further studies can be carried out to estimate safe longitudinal distance due to the effect of piperoll.

- The principle of the method of residual curvature can be used in pipeline spans i.e. unsupported length of pipeline. Further studies can be carried out on the use of residual curvatures to adapt to seabed irregularities. A successful implementation of the method can reduce cost of installation by avoiding the use of the conventional methods of span correction.

- The buckling configuration of the residual curvature section has a shape of Hobbs mode 1. However, the buckling shape can possibly change to a different buckling mode under operational conditions, Ref [12]. This shift in buckling mode can in turn influence the utilization of the pipeline as a result of the variations in residual curvature length as well as residual strain considered. Hence, further studies can be done to investigate the buckling modes and utilization of pipelines.

REFERENCES:

[1] Bai, Y and Bai, Q (2005); Subsea Pipelines and Risers, Elsevier, Kidlington, Oxford. UK.

[2] Berhe, D. (2014); Controlled Lateral Buckling Design of Pipelines, Master thesis at the Department of Mechanical and Structural Engineering and Material Science, the University of Stavanger, Stavanger, Norway, 2014.

[3] Braestrup, M.W., Andersen, J.B., Andersen, L.W., Bryndum, M.B., Christensen, C.J., Nielsen, N.R. (2005); *Design and Installation of Marine Pipelines*, Blackwell Science, Oxford, UK.

[4] Bynum, D. jr. and Havik, K. P. (1981); Marine Pipeline Roll Parameters Studied, Oil & Gas Journal, Aug 24, 1981.

[5] Cooper, C., Aryan, R., Krawczyk, P., Canney, J. and Rabouille, S. (2017); In-Place Analysis of the Edradour Production Pipeline Residual Curvature Buckle Initiator, OPT, March 1 & 2, 2017.

[6] Cooper, P., Zhao, T. and Kortekaas, F. (2017); Residual Curvature Method for Lateral Buckling of Deepwater Flowlines, OPT, March 1 & 2, 2017.

[7] Det Norske Veritas, DNV-OS-F101; Submarine Pipeline Systems, 2007, Oslo, Norway.

[8] Det Norske Veritas, DNV-OS-F201; Dynamic Risers, 2010, Oslo, Norway.

[9] Dixon, D. A. and Rutledge, D.R. (1968); Stiffened Catenary Calculations in Pipeline Laying Problem, Journal of Engineering for Industry, Transactions of the ASME, Vol. 90, no. 1, 153-160, February 1968.

[10] Endal, G. and Egeli, H. (2014); Reel-Lay Method to Control Global Pipeline Buckling Under Operating Loads, OPT, February 26 & 27, 2014.

[11] Endal, G. and Egeli, H. (2014); Reel-Lay Method to Control Pipeline Thermal Expansion During Operation, GvC 2014, OPT, February 26 & 27, 2014.

[12] Endal, G., Giske, S.R., Moen, K. and Sande, S. (2014); Reel-Lay Method to Control Global Pipeline Buckling Under Operating Loads, OMAE2014-24062, June 8-13, 2014, San Francisco, California, USA.

[13] Endal, G., Ness, O.B., Verley, R., Holthe, K. and Remseth, S. (1995); Behavior of Offshore Pipelines Subjected to Residual Curvature During Laying, 1995 OMAE – Volume V, Pipeline Technology.

[14] Endal, G. and Nystrøm, P.R. (2015); Benefits of Generating Pipeline Local Residual Curvature during Reel- and S-lay Installation, OPT, February 25 & 26, 2015.

[15] Endal, G., Ragupathy, P., Rao, V. and Sriskandarajah, T. (2014); Pipeline Roll During Reel-lay Installation Due to Piggyback DEH Cable and Local Residual Curvature, OMAE2014-24484, June 8-13, 2014, San Francisco, California, USA.

[16] Endal, G. and Verley, R. (2000); Cyclic Roll of Large Diameter Pipeline During Laying, OMAE2000/PIPE-5048, February 14-17, 2000, New Orleans, LA, USA.

[17] Gudmestad, O.T. (2015); Marine Technology and Operations, WIT Press, Southampton, UK.

[18] Guo, B., Song, S., Chacko, J., Ghalambor, A. (2005); Offshore Pipelines, Elsevier, Linacre House, Oxford, UK.

[19] Harrison, G. E., BP, Brunner, M.S. (2003), King Flowlines - Thermal Expansion Design and Implementation, OTC 15310, 5-8 May 2003, Houston, Texas, USA.

[20] Herdiyanti, J. (2013); Comparisons Study of S-Lay and J-Lay Methods for Pipeline Installation in Ultra Deep Water, Master thesis at the Department of Mechanical and Structural Engineering and Material Science, the University of Stavanger, Stavanger, Norway, 2013.

[21] Hobbs, R. E. (1984); In-Service Buckling of Heated Pipelines, ASME Journal of Transportation Engineering, Vol. 110, 175-189, March 1984.

[22] Karunakaran, D., (2016); Pipelines and Risers Lecture Note, University of Stavanger, Stavanger, Norway.

[23] Kyriakides, S. and Corona, E. (2007); Mechanics of Offshore Pipelines Volume 1, Elsevier, Oxford. UK.

[24] Mathcad, PTC (2011); User's Guide, Mathcad 15.0 M010, Parametric Technology Corporation, Needham, Massachusetts, USA. Available from: Mathcad Users Guide.pdf

[25] Orcina, OrcaFlex Manual 9.8c. (The versions are updated regularly), Available from: http://www.orcina.com/SfotwareProducts/OrcaFlex/Documentation/index.php

[26] Orimolade, A. P. (2014); Steel Lazy Wave Risers from Turret Moored FPSO, Master thesis at the Department of Mechanical and Structural Engineering and Material Science, the University of Stavanger, Stavanger, Norway, 2014.

[27] Palmer, A.C and King, R. A (2004); Subsea Pipeline Engineering, PennWell Corporation, Tulsa, Oklahoma 74101

[28] Roy, A., Rao, V., Charnaux, C., Ragupathy, P., and Sriskandarajah, T. (2014); Straightener Settings for Under-Straight Residual Curvature of Reel Laid Pipe, OMAE2014-24513, June 8-13, 2014, San Francisco, California, USA.

[29] Statoil Patent WO 02/057674 A1 (2002): Method for Pipelaying from a Coil to the Seabed, Controlling Thermal Expansion.

[30] Subsea7, (2014); Engineering Standard – Rigid Pipelines, Installation Analysis of Rigid Pipelines, ST-GL-ENG-RP-001.

[31] Subsea7, (2016); Engineering Standard – Rigid Pipelines, Lateral Buckling and Pipeline Walking Analysis, ST-GL-ENG-RP-021.

[32] Subsea7, (2015); Engineering Standard – Rigid Pipelines, Reeling and Straightening Analysis of Rigid Pipelines, ST-GL-ENG-RP-010.

[33] Subsea7, (2014); Project Execution Manual – Vigra Spoolbase, MA-NSC-OPS-001.

[34] Subsea7, Seven Oceans. Available from:
http://www.subsea7.com/en/media-centre/image-gallery.html?category=category1

[35] Teigen, M. and Ibrahim, M. (2015); Investigation of the Behavior of the Lateral Buckling Control Method – Reel-lay Induced Imperfection, OMAE2015-41848, May 31-June 5, 2015, St. John’s, Newfoundland, Canada.

[36] Vaughan, N. J. and Nystrøm, P. R., Prediction of Pipeline Rotation During S-lay Installation, IKM Ocean Design AS, Oslo & Stavanger, Norway.

APPENDICES

APPENDIX A: Model I: Short Pipeline Mean Gamma Angles

The mean gamma angle measurements obtained from OrcaFlex for Model I: Short pipeline is given in table A1 below.

Model	Pre-bent Curvature length (m)	Total Length (m)	Mean Gamma results (degree)	% of increase in angle w.r.t. vertical	Maximum vertical sea bed clearance (m)	Remarks
1	15+10+15	40	0^0	-	0.636	No pipe rotation
2	15+20+15	50	36^0	-	0.750	
3	15+30+15	60	55^0	52.78%	0.436	
4	15+40+15	70	69^0	25.45%	0.262	
5	15+50+15	80	73^0	5.80%	0.073	The crown of the under-straightened section touches down the seabed leaving a gap between the seabed and pipeline.
6	15+60+15	90	75^0	2.74%	0.078	
7	15+70+15	100	77^0	2.67%	0.083	
8	15+80+15	110	78^0	1.30%	0.088	
9	15+90+15	120	77.5^0	(0.64%)	0.095	
N.B. 15m transition section is introduced on each side of the residual curvature. The pipeline is short and is rotationally free at the TDP & fixed at the vessel.						

Table A1: Mean gamma values for different under-straightened sections at the seabed (Model I: Short Pipeline)

APPENDIX B: Model II: Long Pipeline Mean Gamma Angles

The mean gamma angle measurements obtained from OrcaFlex for Model II: Long pipeline is given in table A2 below.

<table>
<tr><th>Model</th><th>Curvature length (m)</th><th>Total Length (m)</th><th>Mean Gamma results (degree)</th><th>% of increase in angle w.r.t. vertical</th><th>Maximum vertical sea bed clearance (m)</th><th>Remarks</th></tr>
<tr><td>1</td><td>15+10+15</td><td>40</td><td>0^0</td><td>-</td><td>0.652</td><td>No pipe rotation</td></tr>
<tr><td>2</td><td>15+20+15</td><td>50</td><td>14.3^0</td><td>-</td><td>0.789</td><td></td></tr>
<tr><td>3</td><td>15+30+15</td><td>60</td><td>35.9^0</td><td>151.05%</td><td>0.781</td><td></td></tr>
<tr><td>4</td><td>15+40+15</td><td>70</td><td>43.4^0</td><td>20.89%</td><td>0.528</td><td></td></tr>
<tr><td>5</td><td>15+50+15</td><td>80</td><td>64^0</td><td>47.47%</td><td>0.202</td><td></td></tr>
<tr><td>6</td><td>15+60+15</td><td>90</td><td>67.2^0</td><td>5%</td><td>0.116</td><td rowspan="5">The crown of the under-straightened section touches the seabed while creating a gap between the seabed and pipeline.</td></tr>
<tr><td>7</td><td>15+70+15</td><td>100</td><td>75.7^0</td><td>12.65%</td><td>0.115</td></tr>
<tr><td>8</td><td>15+80+15</td><td>110</td><td>77.8^0</td><td>2.77%</td><td>0.122</td></tr>
<tr><td>9</td><td>15+90+15</td><td>120</td><td>82^0</td><td>5.40%</td><td>0.126</td></tr>
<tr><td>10</td><td>15+100+15</td><td>130</td><td>83.5^0</td><td>1.83%</td><td>0.128</td></tr>
<tr><td colspan="7">N.B. 15m transition section is introduced on each side of the residual curvature.
The pipeline is long and is rotationally fixed at both the vessel and TDP.</td></tr>
</table>

Table A2: Mean gamma values for different under-straightened sections at the seabed (Model II: Long Pipeline)

APPENDIX C: Results for Sensitivity test of pipe OD

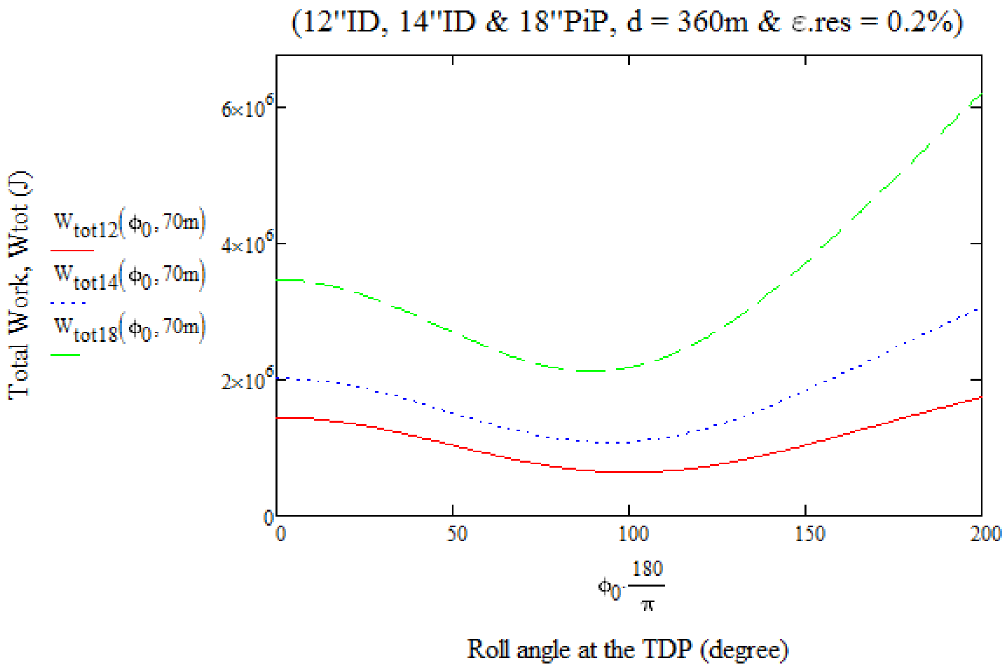


Figure A1: Comparison of the predicted pipeline roll angle for 12" ID, 14" ID and 18" pipe-in-pipe (water depth 360m & residual strain 0.2%)

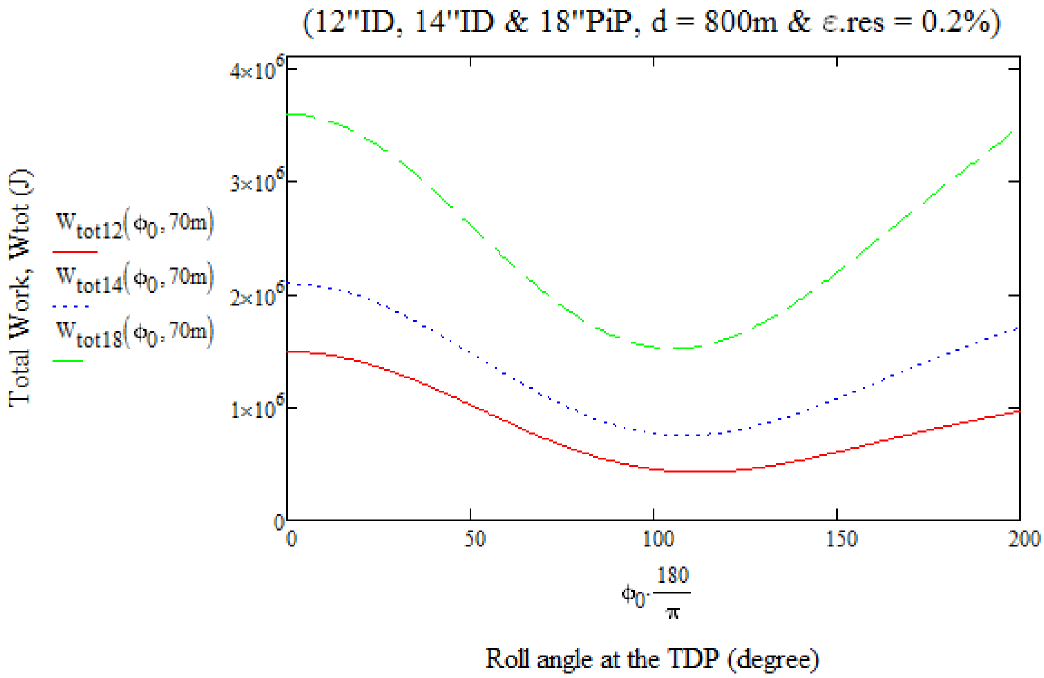


Figure A2: Comparison of the predicted pipeline roll angle for 12" ID, 14" ID and 18" pipe-in-pipe (water depth 800m & residual strain 0.2%)

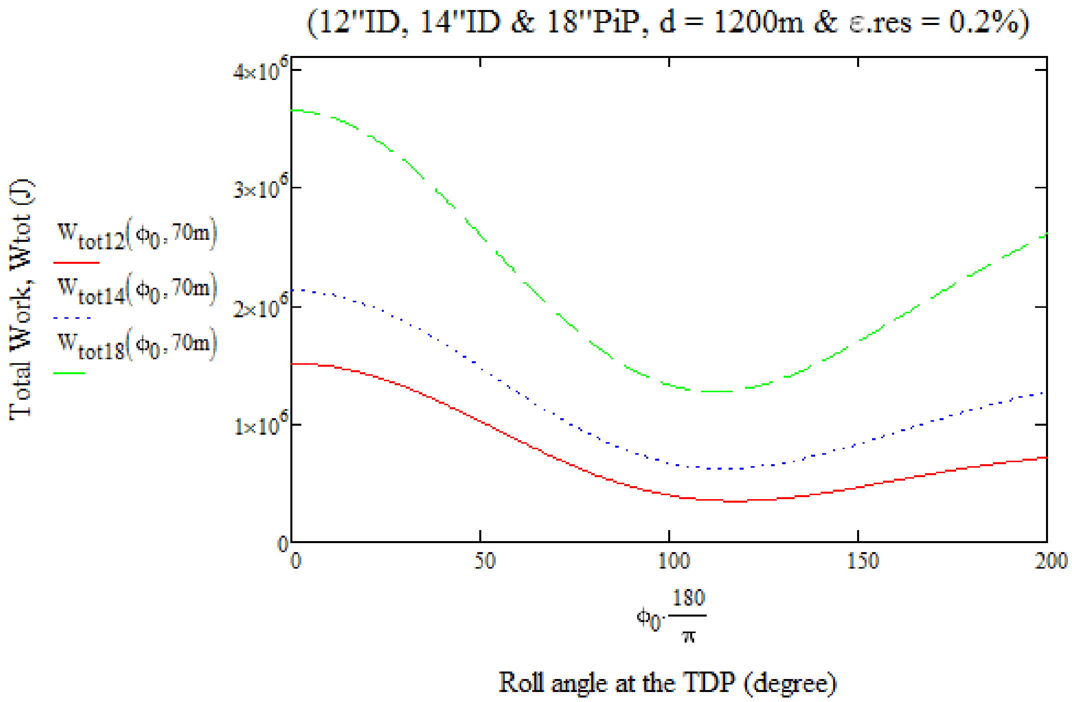


Figure A3: Comparison of the predicted pipeline roll angle for 12" ID, 14" ID and 18" pipe-in-pipe (water depth 1200m & residual strain 0.2%)

APPENDIX D: Results for Sensitivity test of pipe D_0/t ratio

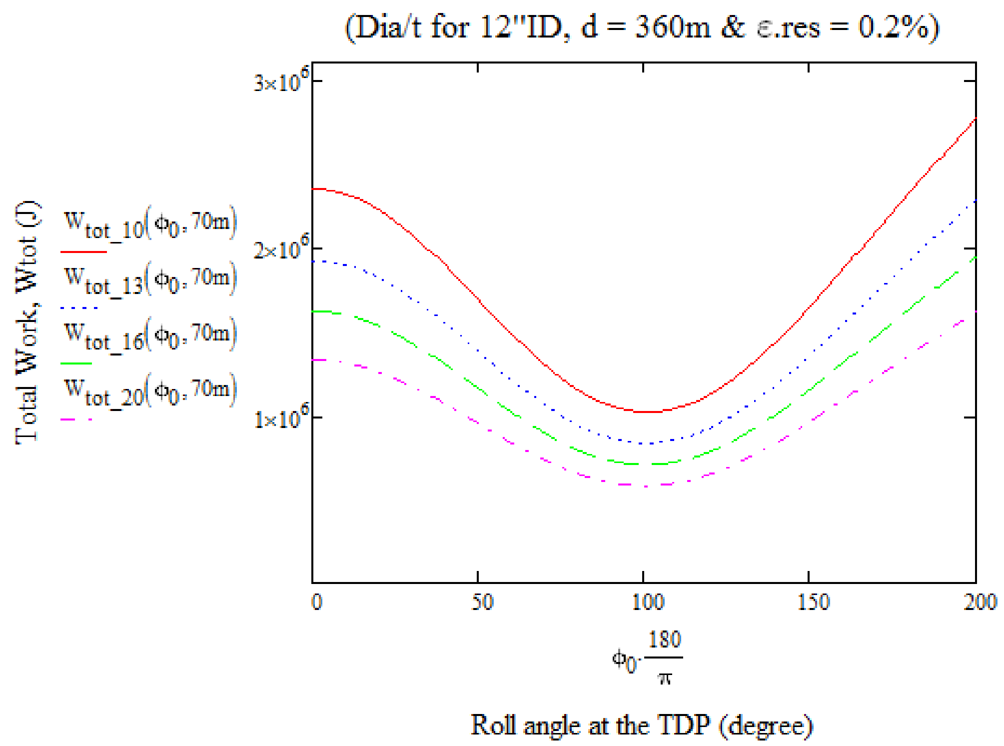


Figure A4: 12" ID predicted pipeline roll for different D0/t ratios (water depth 360m & residual strain 0.20%)

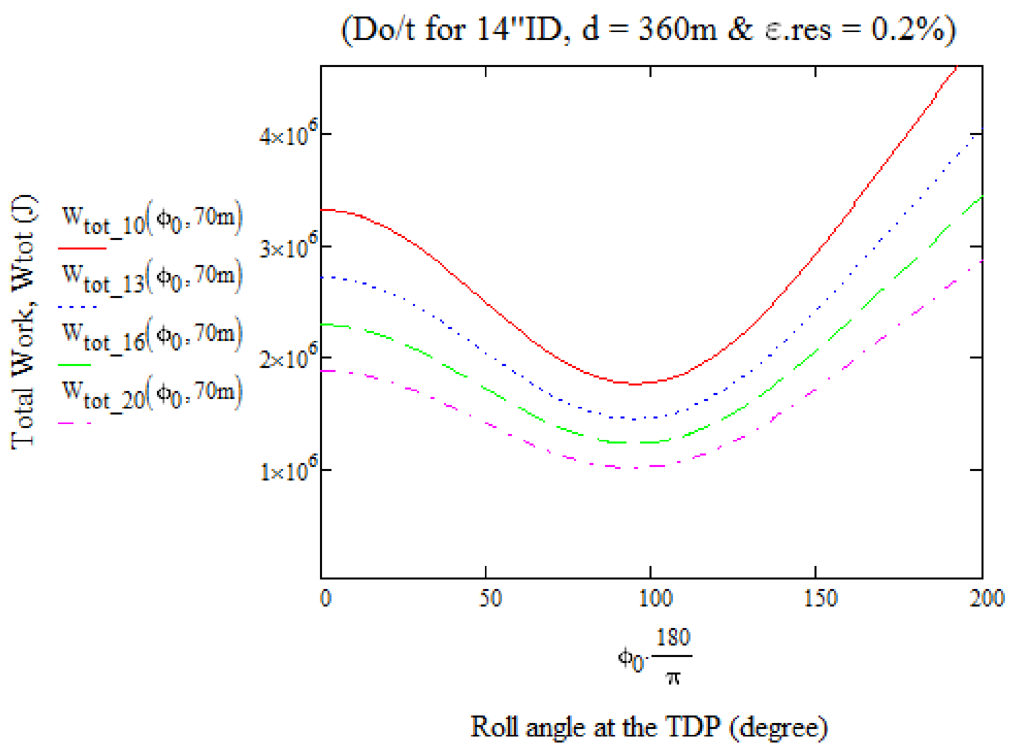


Figure A5: 14" ID predicted pipeline roll for different D0/t ratios (water depth 360m, residual strain 0.20%)

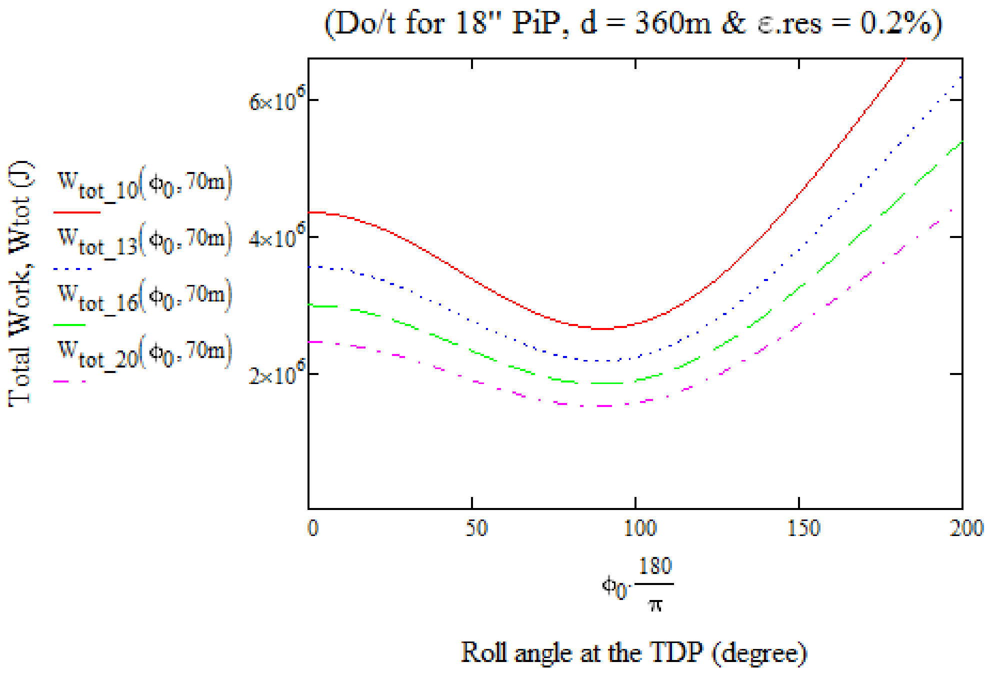


Figure A6: 18" OD pipe-in-pipe predicted pipeline roll for different D0/t ratios (water depth 360m & residual strain 0.20%)

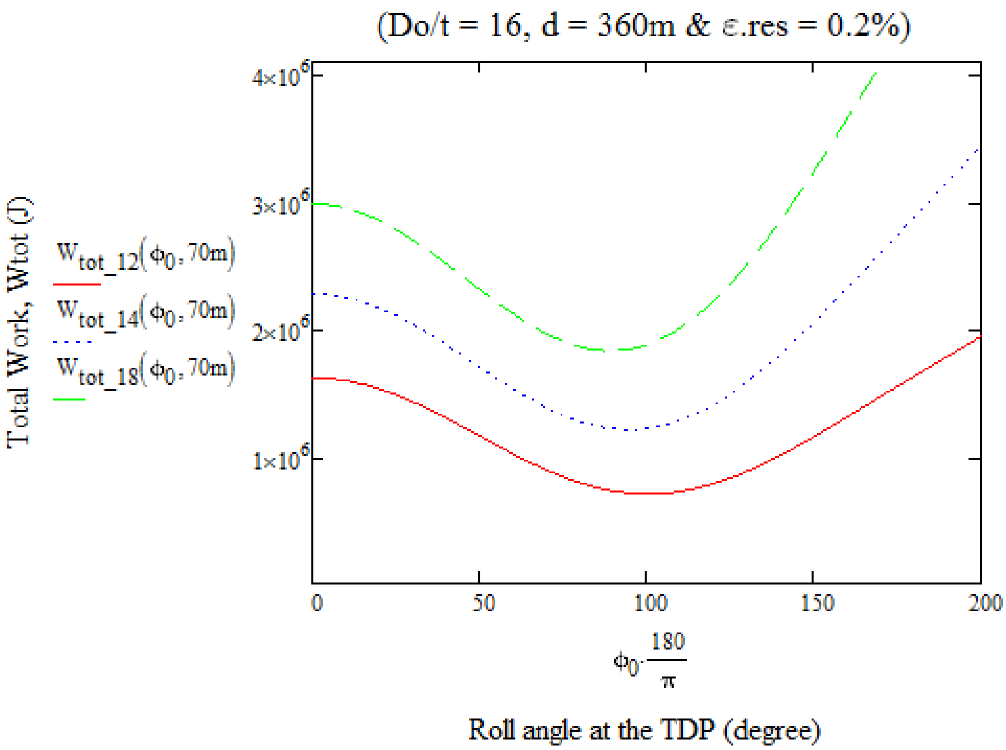


Figure A7: Comparison of the predicted pipeline roll angle at TDP for 12" ID, 14" ID and 18" pipe-in-pipe for $D_0/t=16$ (water depth 360m & residual strain 0.20%)

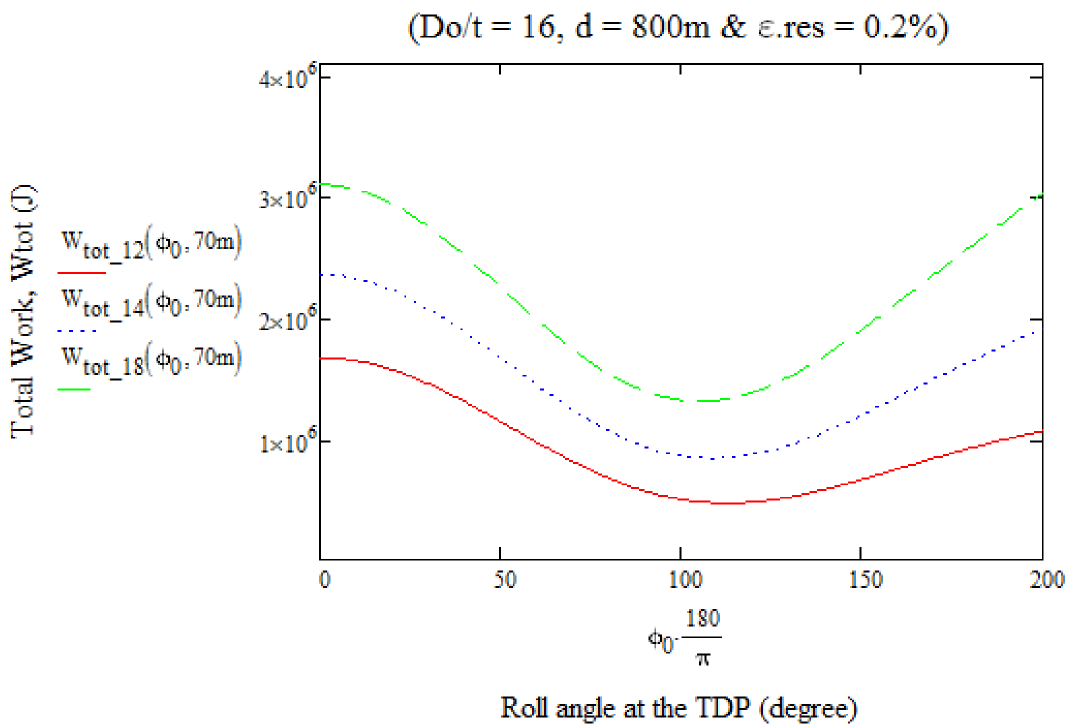


Figure A8: Comparison of the predicted pipeline roll angle at TDP for 12" ID, 14" ID and 18" pipe-in-pipe for $D_0/t=16$ (water depth 800m & residual strain 0.20%)

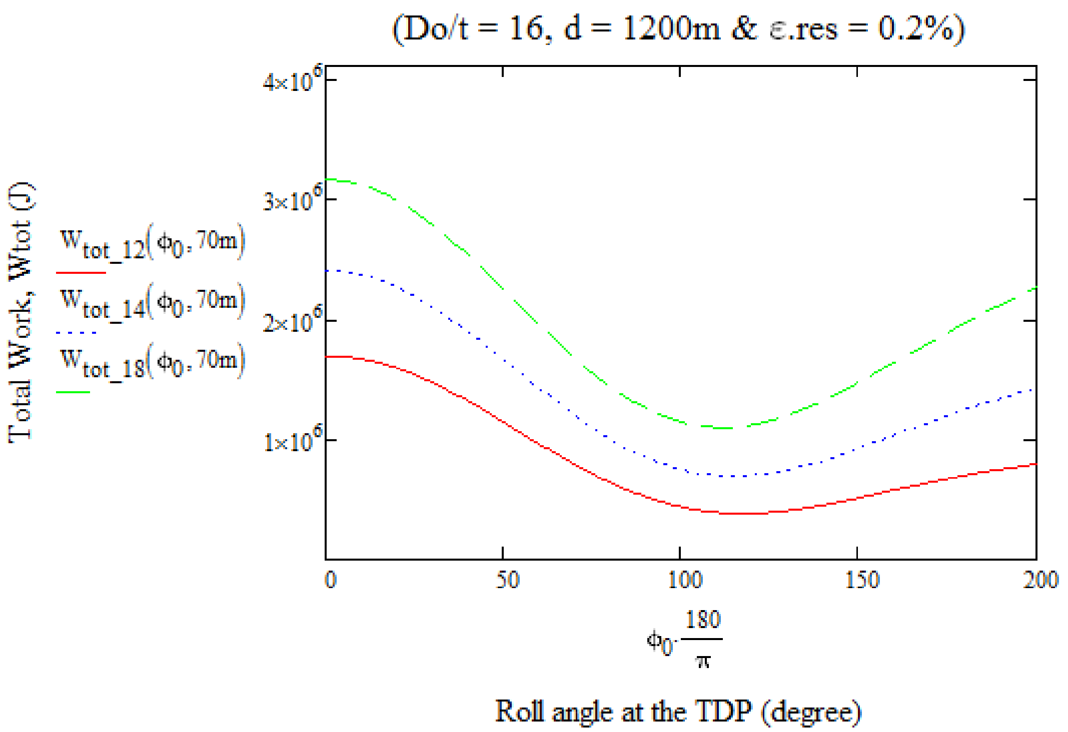


Figure A9: Comparison of the predicted pipeline roll angle at TDP for 12" ID, 14" ID and 18" pipe-in-pipe for $D_0/t=16$ (water depth 1200m & residual strain 0.20%)

APPENDIX E: Results for Sensitivity test of Horizontal Component of lay tension

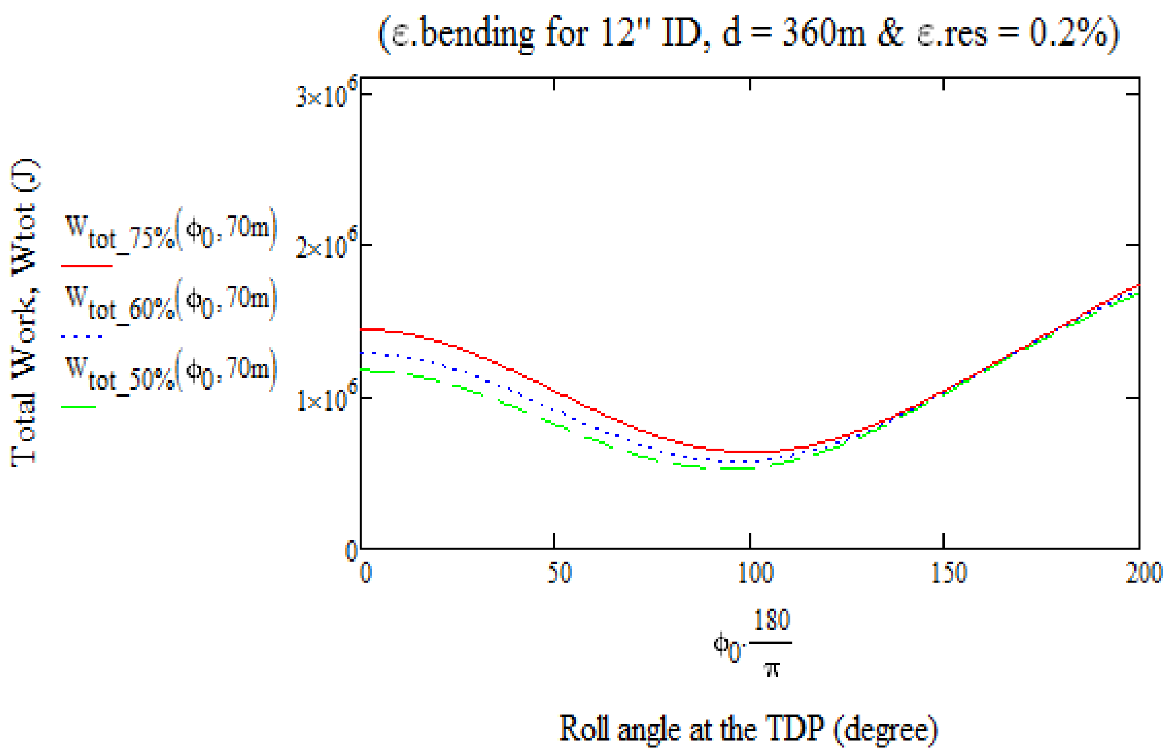


Figure A10: 12" ID predicted pipeline roll for different allowable bending strains (water depth 360m & residual strain 0.20%)

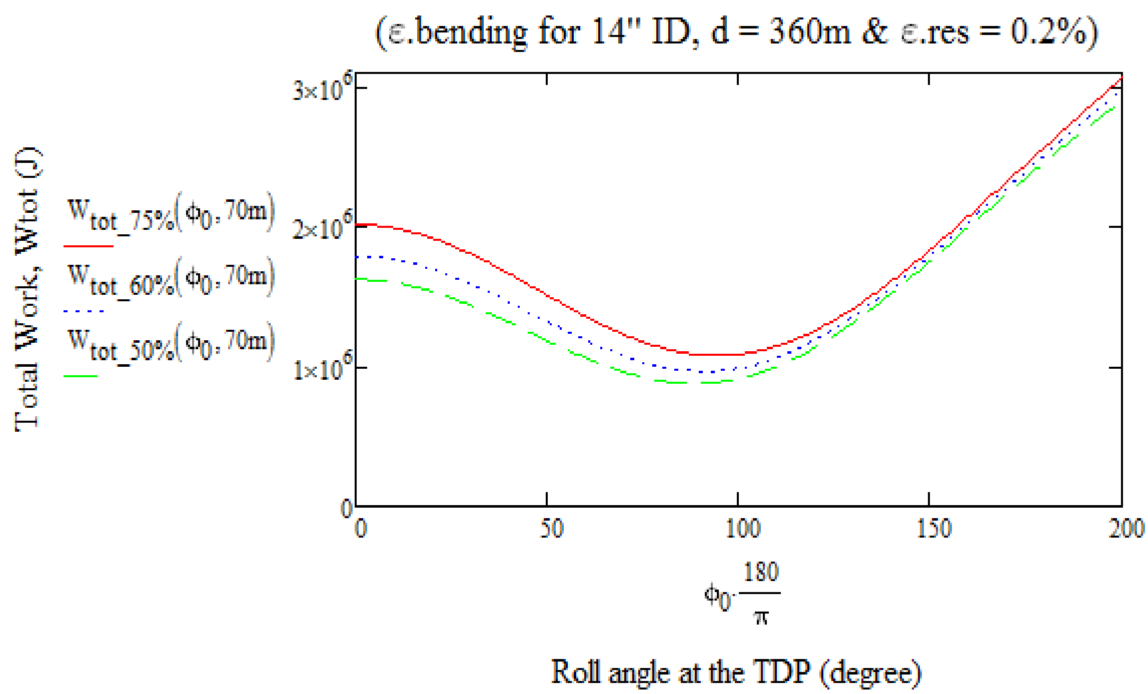


Figure A11: 14" ID predicted pipeline roll for different allowable bending strains (water depth 360m, residual strain 0.20%)

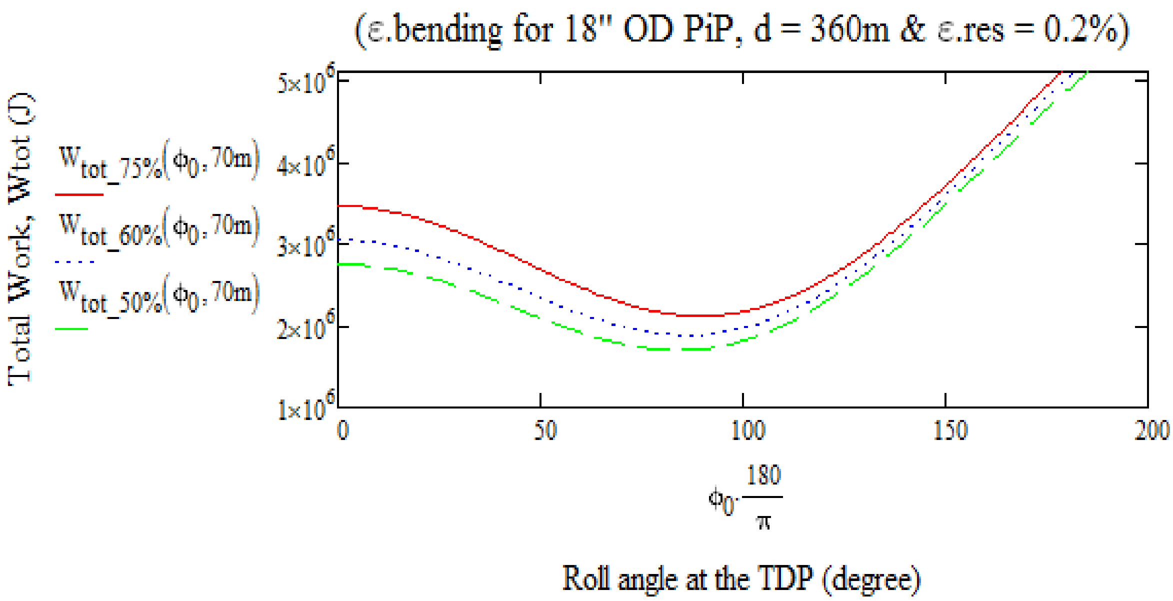


Figure A12: 18" OD pipe-in-pipe predicted pipeline roll for different allowable bending strains (water depth 360m, residual strain 0.20%)

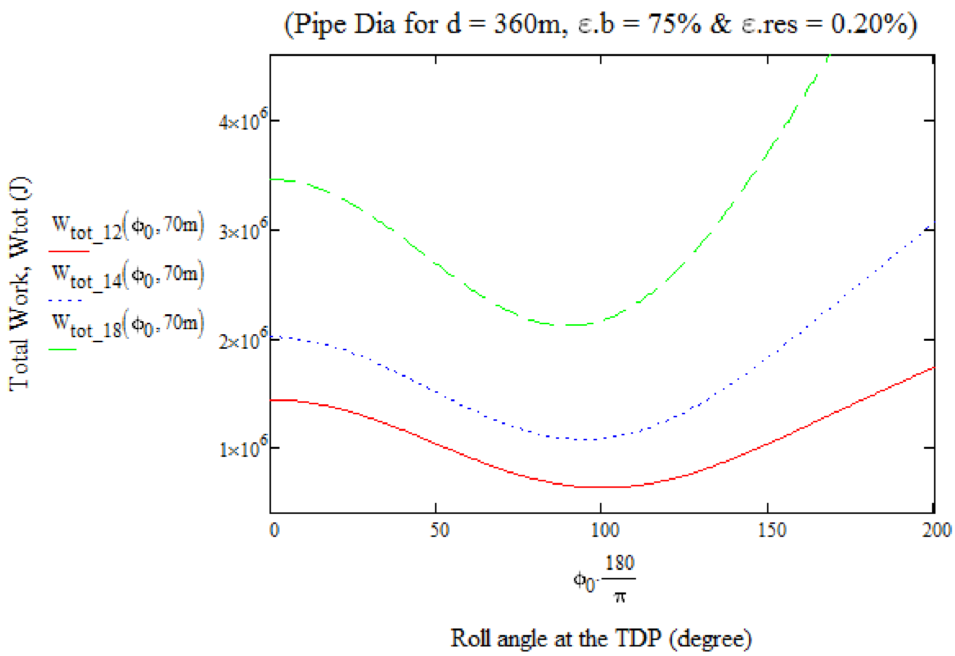


*Figure A13: Comparison of the predicted pipeline roll angle at TDP for 12" ID, 14" ID and 18" pipe-in-pipe for allowable bending strain corresponding to 75%*SMYS/E (Water depth 360m & residual strain 0.20%)*

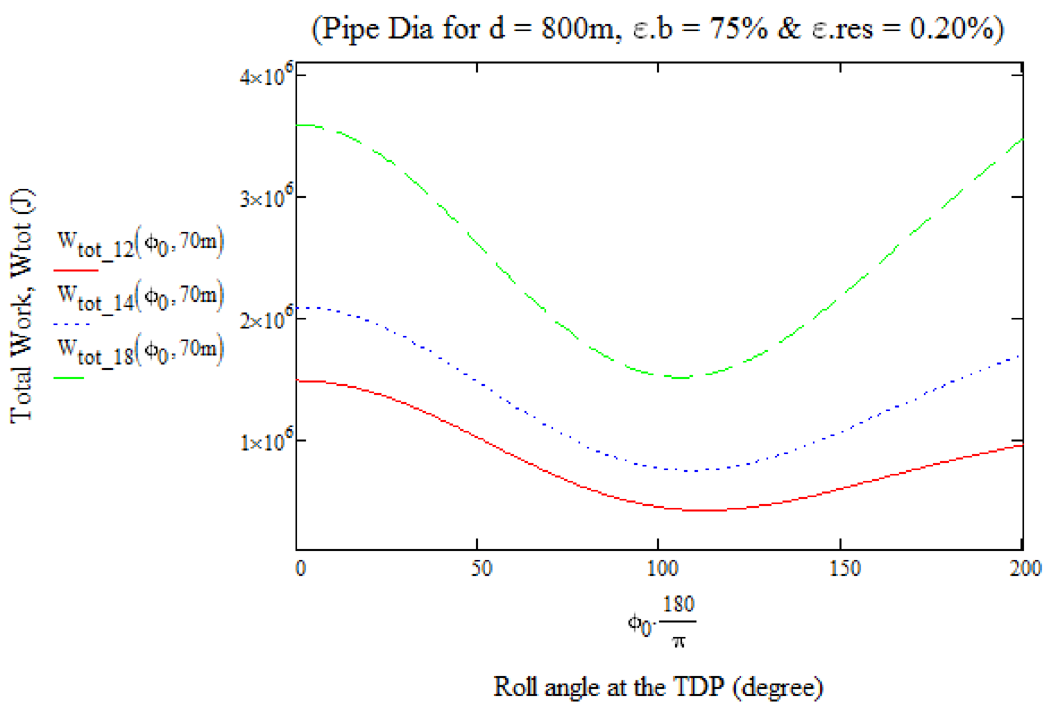


*Figure A14: Comparison of the predicted pipeline roll angle at TDP for 12" ID, 14" ID & 18" OD pipe-in-pipe for allowable bending strain corresponding to 75%*SMYS/E (Water depth 800m & residual strain 0.20%)*

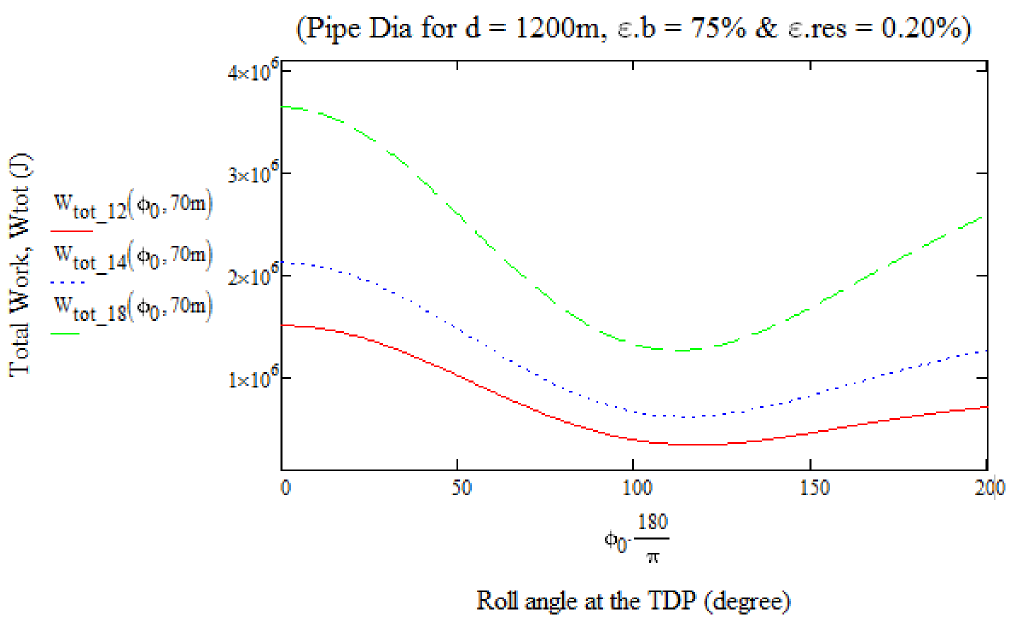


*Figure A15: Comparison of the predicted pipeline roll angle at TDP for 12" ID, 14" ID & 18" OD pipe-in-pipe for allowable bending strain corresponding to 75%*SMYS/E (Water depth 1200m & residual strain 0.20%)*

Nominal Curvatures for various allowable bending strains

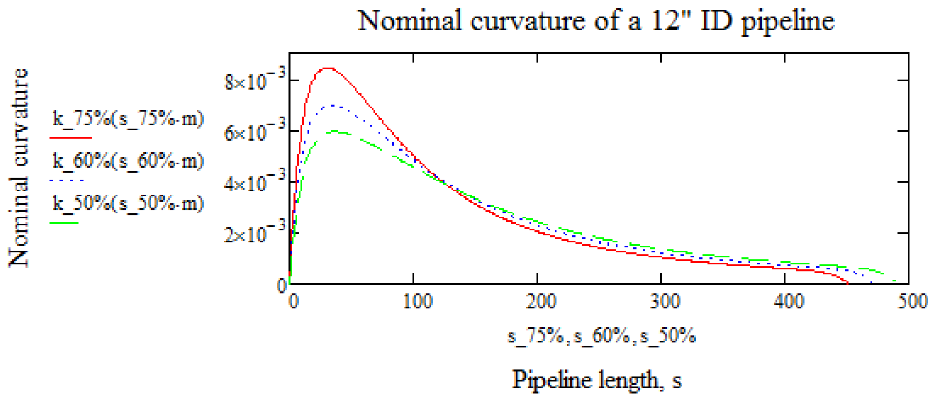


Figure A16: Nominal curvature for bending strains 50%, 60% and 75% of SMYS/E in a single pipe of 12" ID

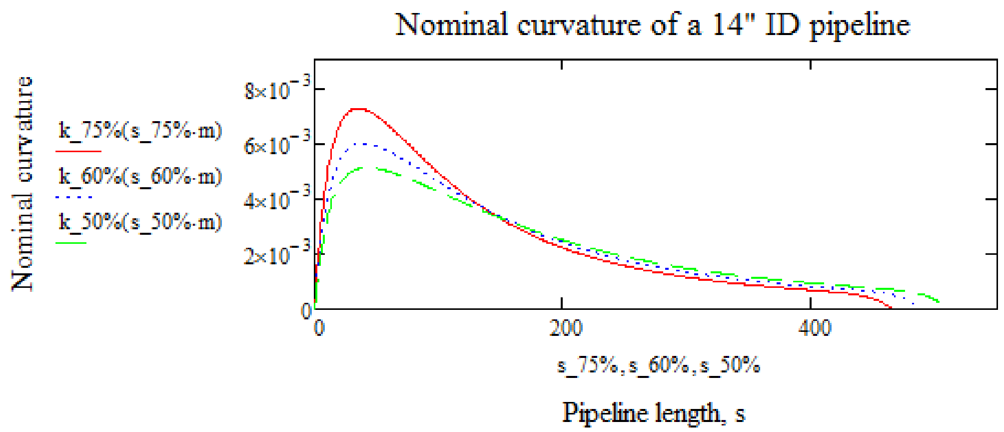


Figure A17: Nominal curvature for bending strains 50%, 60% and 75% of SMYS/E in a single pipe of 14" ID

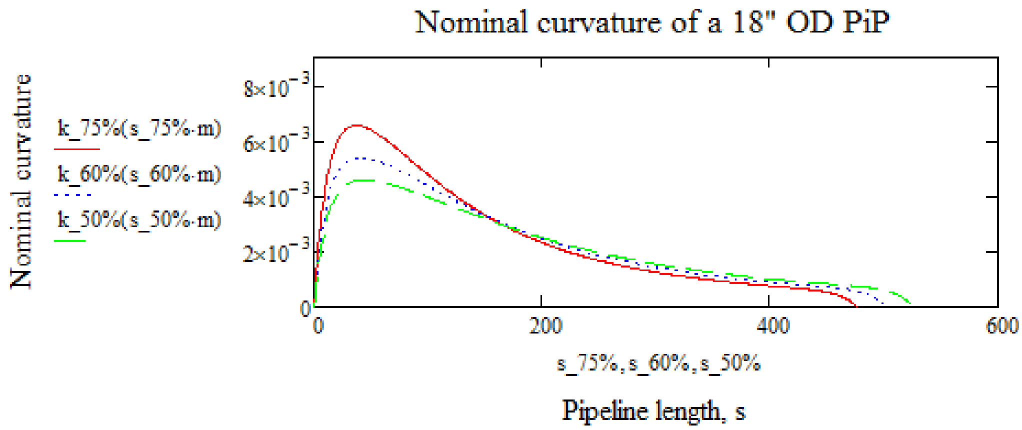


Figure A18: Nominal curvature for bending strains 50%, 60% and 75% of SMYS/E in an 18" OD PiP

APPENDIX F: Results for Sensitivity test of Residual Strain

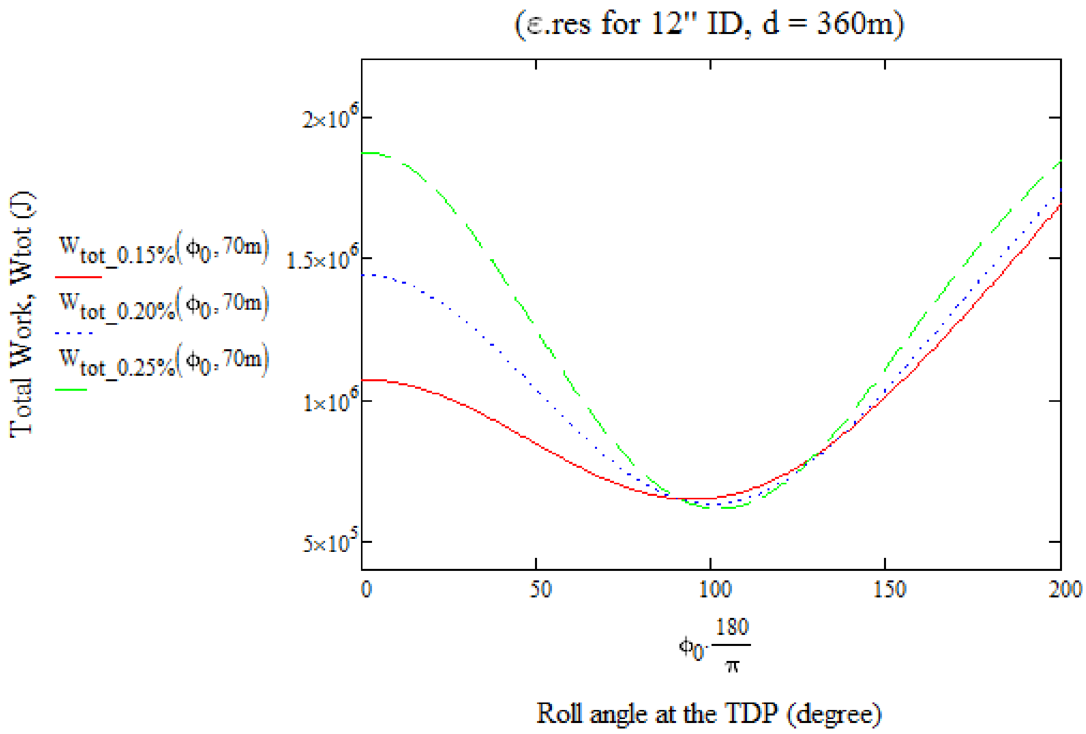


Figure A19: 12" ID predicted pipeline roll for different residual strains of 0.15%, 0.20% and 0.25% (water depth 360m)

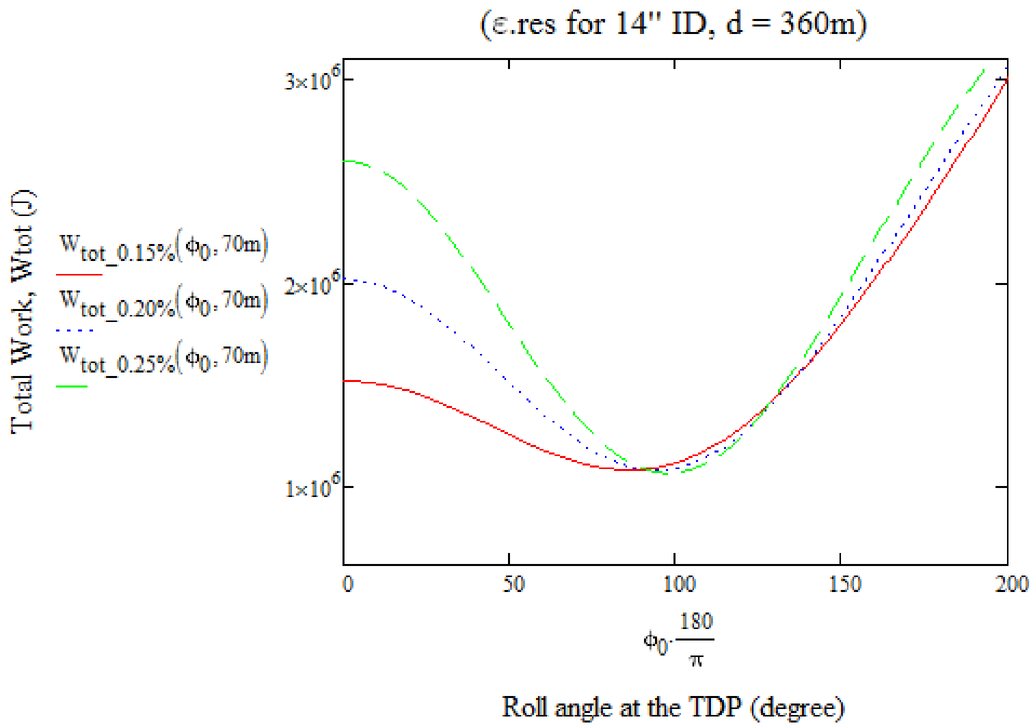


Figure A20: 14" ID predicted pipeline roll for different residual strains of 0.15%, 0.20% and 0.25% (water depth 360m)

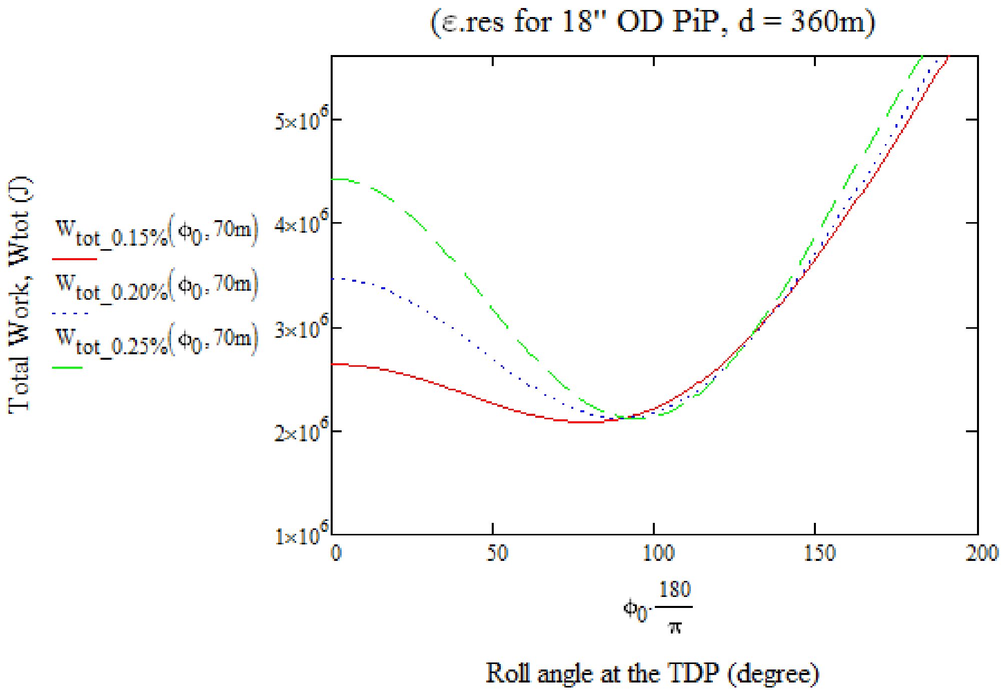


Figure A21: 18" OD pipe-in-pipe predicted pipeline roll for different residual strains of 0.15%, 0.20% and 0.25% (water depth 360m)

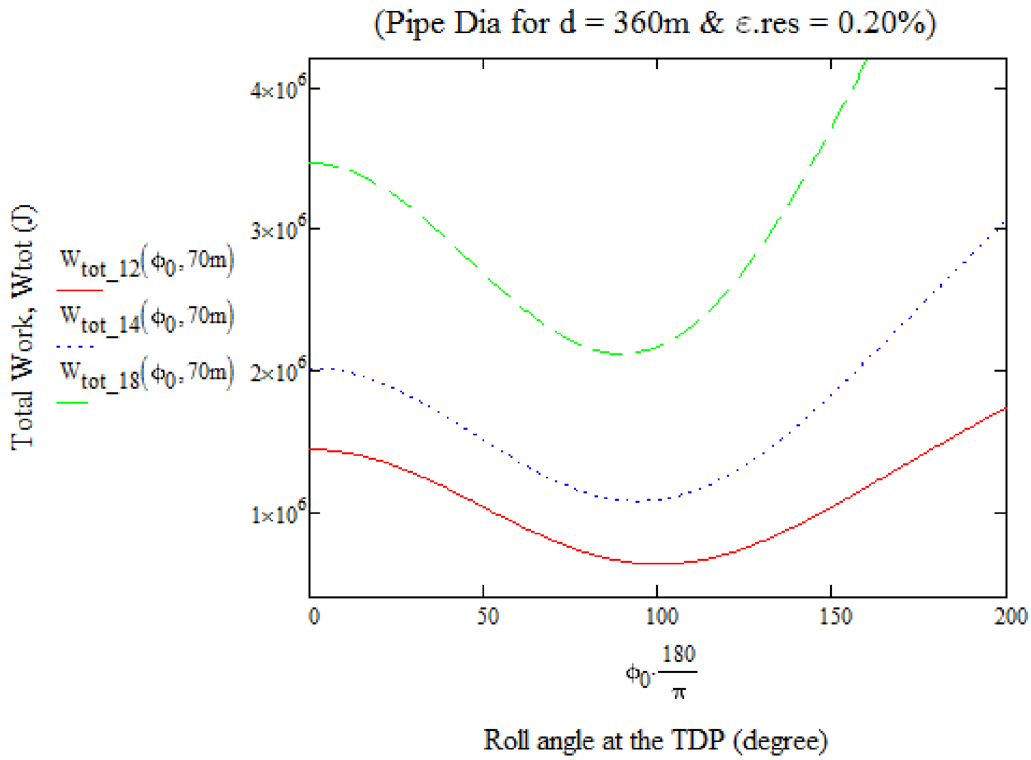


Figure A22: Comparison of the predicted pipeline roll angle at TDP for 12"ID, 14"ID & 18" OD pipe-in-pipe for residual strain 0.20% (water depth 360m)

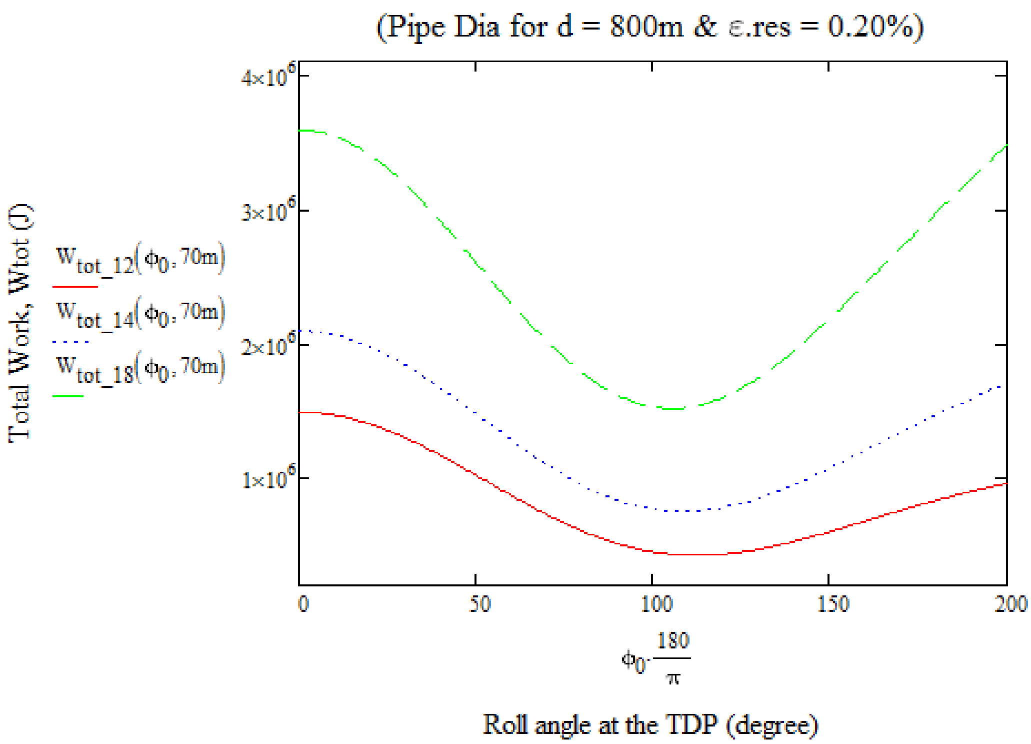


Figure A23: Comparison of the predicted pipeline roll angle for 12"ID, 14"ID & 18" OD pipe-in-pipe for residual strain 0.20% (water depth 800m)

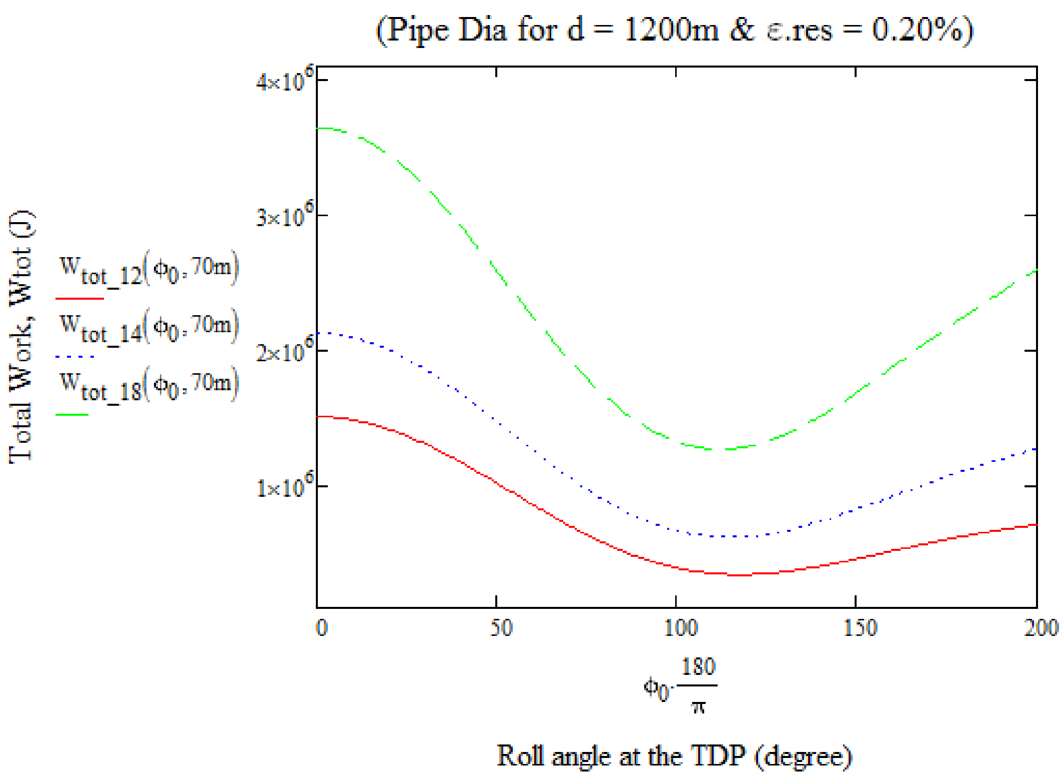


Figure A24: Comparison of the predicted pipeline roll angle for 12"ID, 14"ID & 18" OD pipe-in-pipe for residual strain 0.20% (water depth 1200m)

Total Curvatures for various residual strains

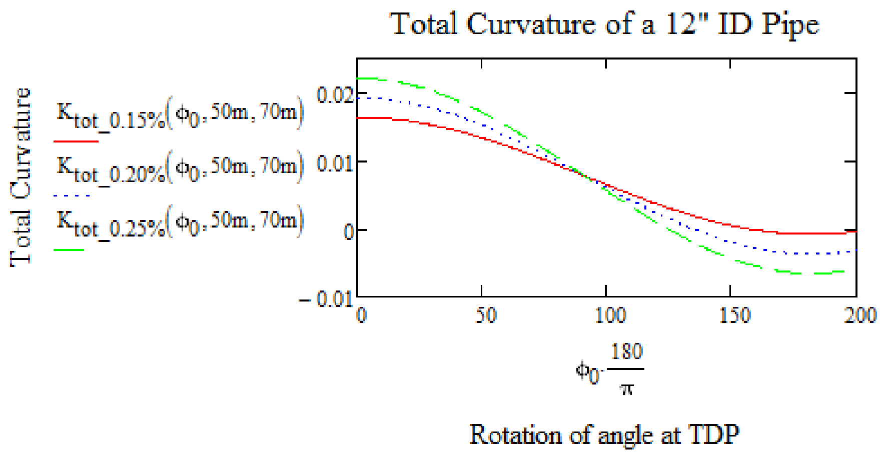


Figure A25: Total curvature for residual strains 0.15%, 0.20% and 0.25% in a single pipe of 12" ID

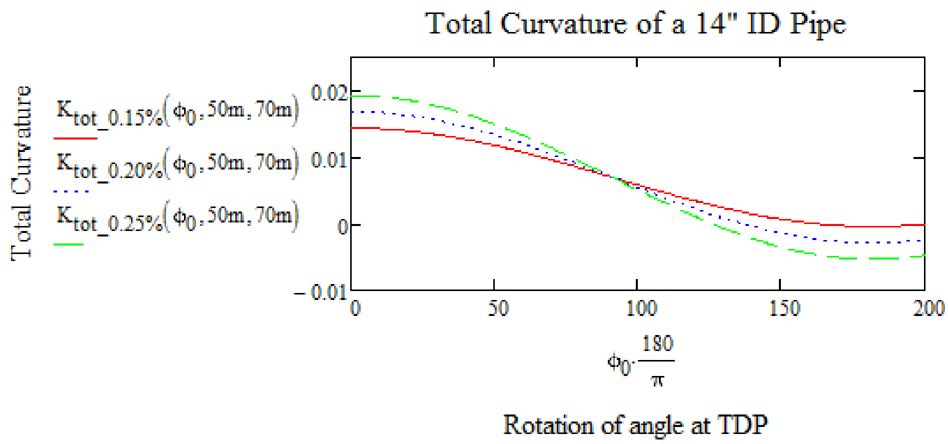


Figure A26: Total curvature for residual strains 0.15%, 0.20% and 0.25% in a single pipe of 14" ID

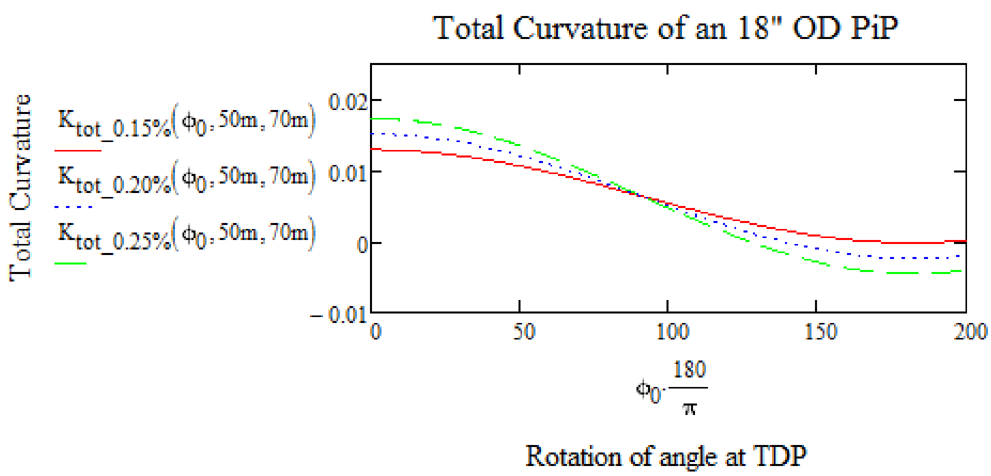


Figure A27: Total curvature for residual strains 0.15%, 0.20% and 0.25% in a pipe in pipe of 18" OD

APPENDIX G: Results for Sensitivity test of water depth

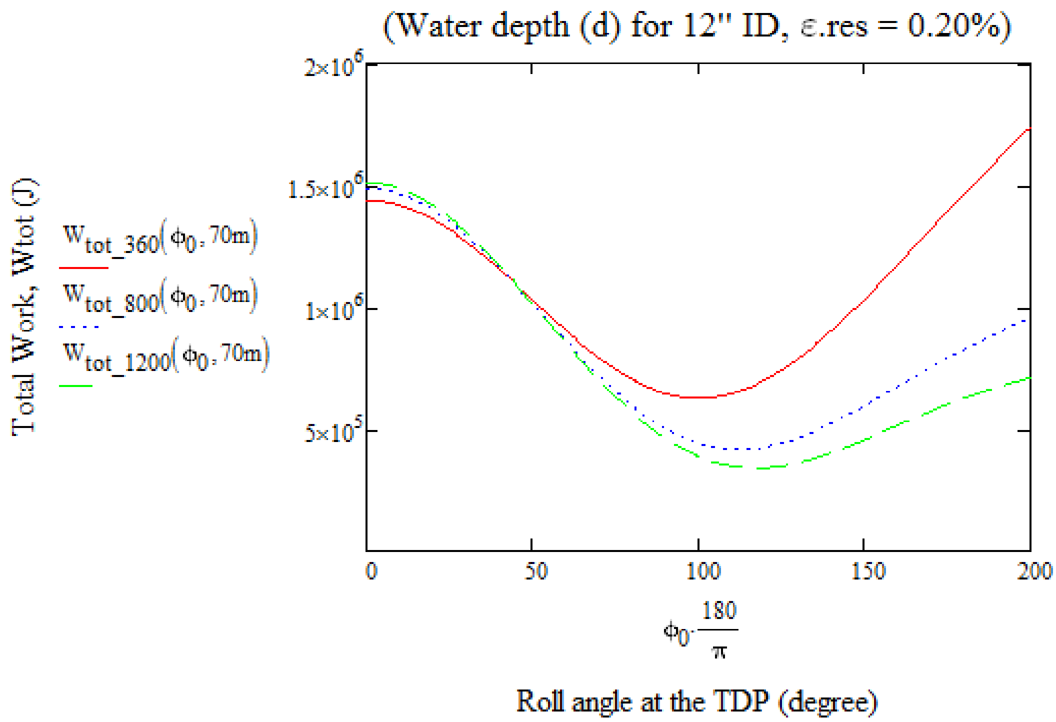


Figure A28: 12" ID predicted pipeline roll for different water depths 360m, 800m and 1200m (residual strain 0.20%)

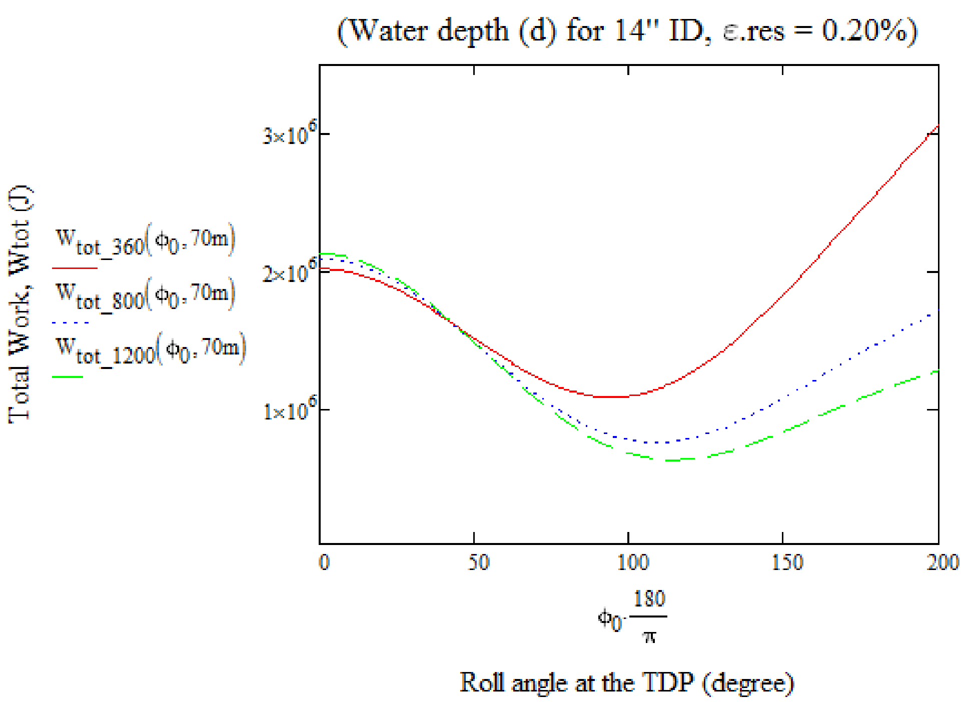


Figure A29: 14" ID predicted pipeline roll for different water depths 360m, 800m and 1200m (residual strain 0.20%)

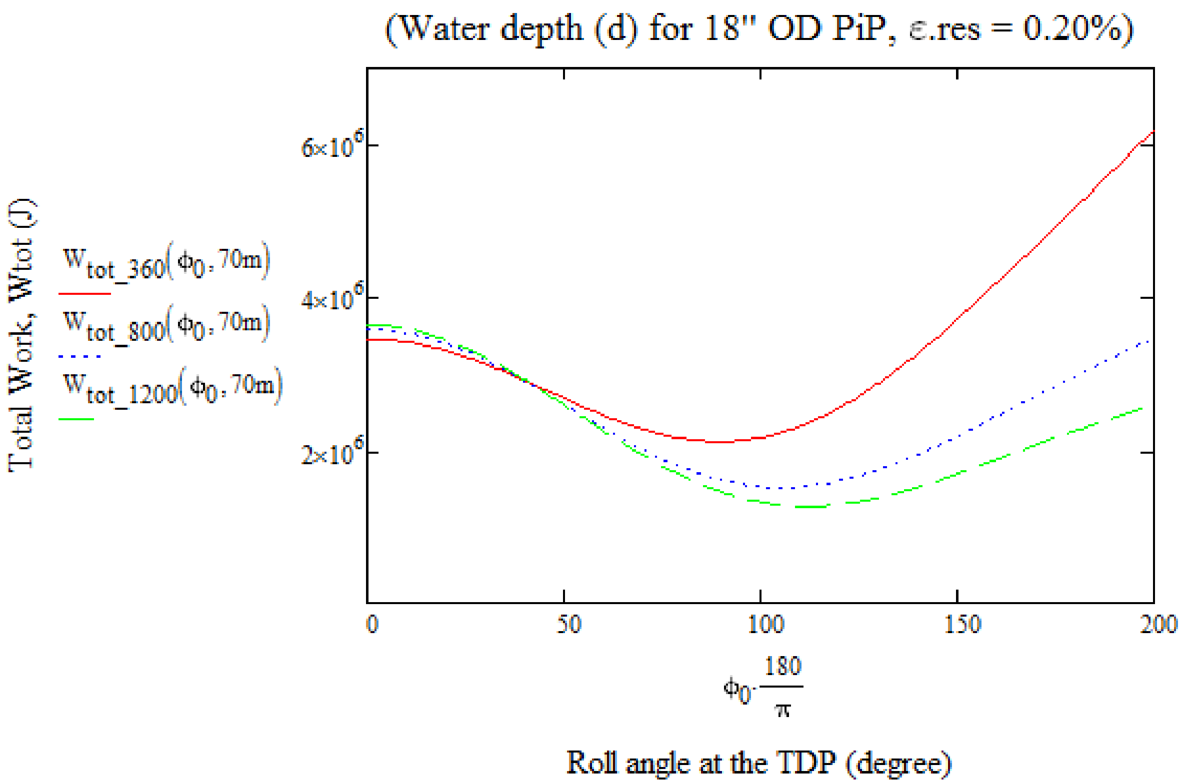


Figure A30: 18" OD pipe-in-pipe predicted pipeline roll for different water depths 360m, 800m and 1200m (residual strain 0.20%)

APPENDIX H: Sample of analytical calculation in Mathcad

PREDICTION OF PIPE ROLL WITH RESIDUAL CURVATURE FOR 12" ID

Water depth: $d := 360m$

Out side diameter: $D_0 := 0.3488m$

Pipe thickness: $t := 0.019m$

Descity of Steel: $\rho_{steel} := 7850 \frac{kg}{m^3}$

Density of sea water: $\rho_{sea} := 1025 \frac{kg}{m^3}$

Gravitational acceleration: $g = 9.807 \frac{m}{s^2}$

Cladding thickness: $t_c := 0.003m$ $\quad t_c = 3 \cdot mm$

Descity of cladding: $\rho_{clad} := 8000 \frac{kg}{m^3}$

Submerged Pipe Weight: $W_s := \pi \cdot (D_0 - t) \cdot t \cdot g \cdot \rho_{steel} + \pi (D_0 - 2 \cdot t - t_c) \cdot t_c \cdot g \cdot \rho_{clad} - \pi \, \rho_{sea} \cdot g \cdot \frac{D_0^2}{4}$

$W_s = 782.571 \cdot \frac{N}{m}$

Modulus of Elasticity: $E := 200 \cdot 10^9 \frac{N}{m^2}$

Shear / modulus of rigidity: $G := 80 \cdot 10^9 \frac{N}{m^2}$

Specified minimum Yield Strength: $SMYS := 450 \cdot 10^6 \frac{N}{m^2}$

Maximum allowable bending strain: $\varepsilon_b := \frac{75\% \cdot SMYS}{E}$ $\quad \varepsilon_b = 1.688 \times 10^{-3}$

Horizontal component of lay tension:

$$H_{comp} := \frac{\frac{D_0}{2} \cdot W_s}{\varepsilon_b} \qquad H_{comp} = 8.088 \times 10^4 \cdot N$$

Horizontal Length of pipe line:

$$l := \frac{H_{comp}}{W_s} \cdot \mathrm{acosh}\left(W_s \cdot \frac{d}{H_{comp}} + 1\right)$$

$$l = 225\,m$$

Pipe line length, L

$$L := \frac{H_{comp}}{W_s} \cdot \left(\sinh\left(\frac{W_s \cdot l}{H_{comp}}\right)\right)$$

$$L = 452\,m$$

Residual Strain 0.2%:

$$\varepsilon_{res} := 0.002$$

Residual Curvature:

$$K_{res} := \frac{\varepsilon_{res}}{\left(\frac{D_0}{2}\right)} \qquad K_{res} = 0.011\,\frac{1}{m}$$

Horizontal lay tension divided by pipe's submerged weight:

$$A := \frac{H_{comp}}{W_s} \qquad A = 103.348\,m$$

Second Moment of Area:

$$I := \pi \cdot \frac{\left[D_0^{\ 4} - (D_0 - 2 \cdot t)^4\right]}{64} \qquad I = 2.685 \times 10^{-4}\,m^4$$

Polar second Moment of Area:

$$I_t := \pi \cdot \frac{\left[D_0^{\ 4} - (D_0 - 2 \cdot t)^4\right]}{32} \qquad I_t = 5.371 \times 10^{-4}\,m^4$$

Pipeline Top Tension during installation

$$T := \sqrt{H_{comp}^{\ 2} + (W_s \cdot L)^2} \qquad T = 3.626 \times 10^5\,N$$

Define γ as:

$$\gamma := \sqrt{E \cdot \frac{I}{T}} \qquad \gamma = 12.17\,m$$

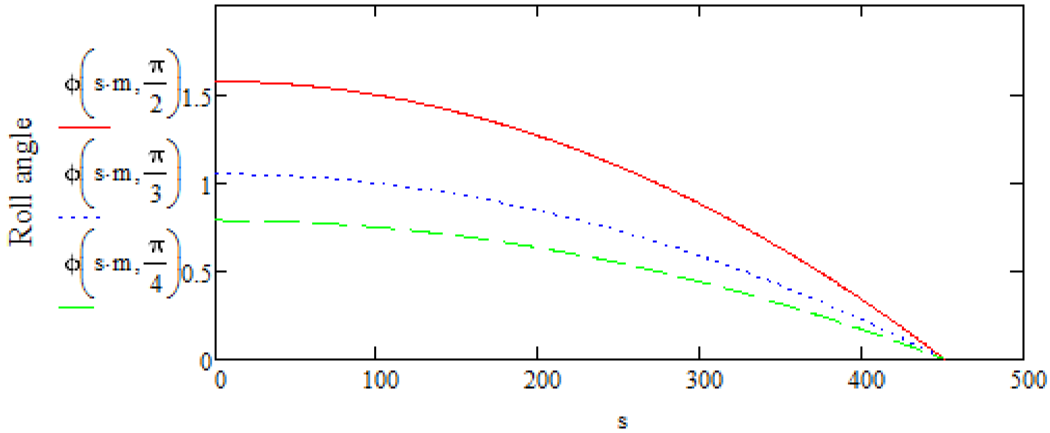
Assume s is the distance from TDP to L: $s := 0, 1 .. 452$

Assign ϕ0 rotation angle of the touch down: $\phi_0 := 0, 0.01 .. 4$

The length of curvature in the pipeline: $L_{curv} := 0, 25 .. 150$

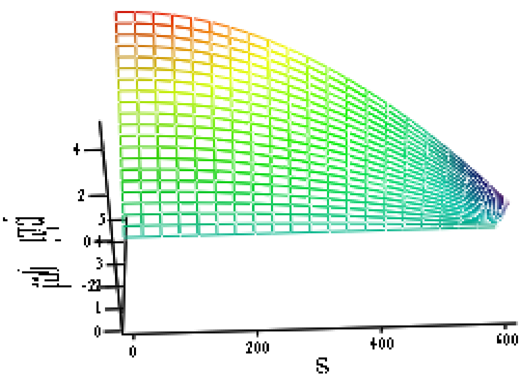
The roll angle: $\phi(s, \phi_0) := \phi_0 - \phi_0 \cdot \frac{s^2}{L^2}$

The roll angle in a pipeline



Pipeline length, s

Surface Plot of the roll angle, ϕ

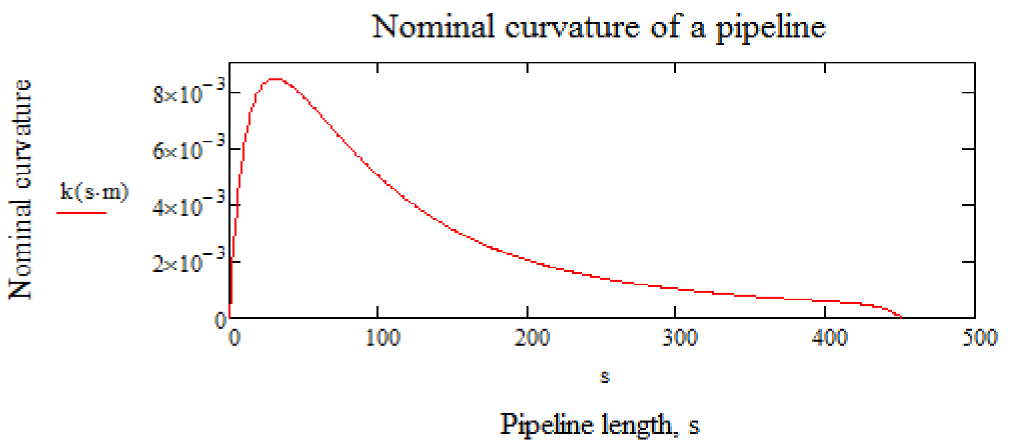


The roll angle phi in pipeline

ϕ

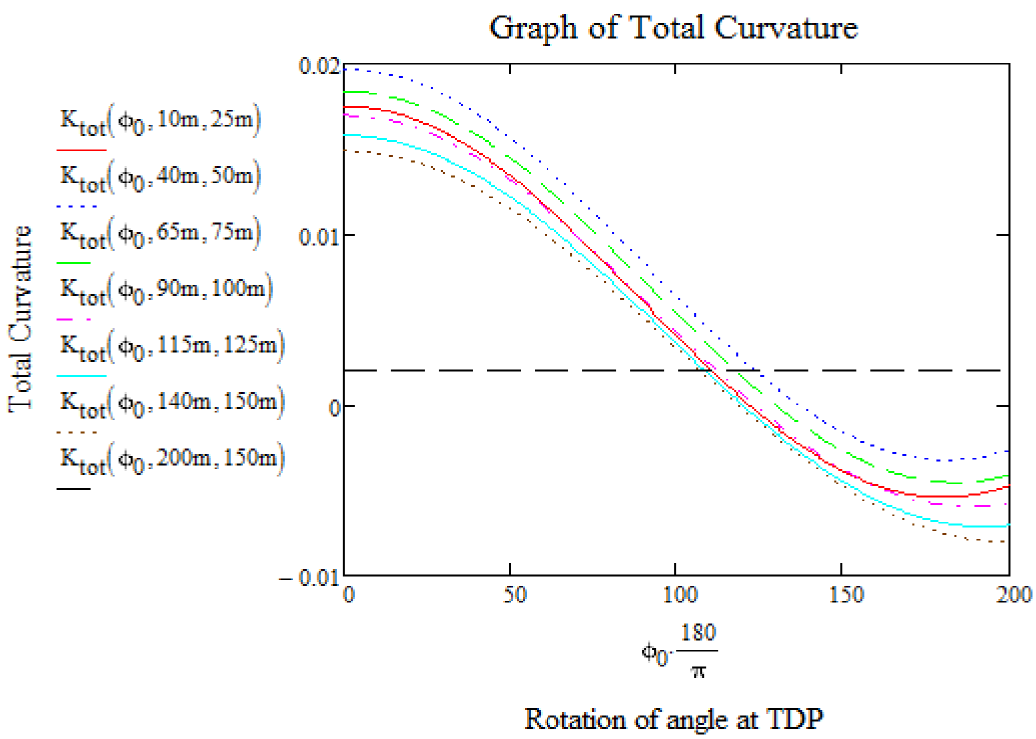
Nominal curvature k(s):

$$k(s) := \frac{A}{\left(A^2 + s^2\right)} - \frac{A}{(A+d)^2} \cdot e^{\left(\frac{s}{\gamma} - \frac{L}{\gamma}\right)} - \frac{A}{(A+s)^2} \cdot \frac{e^{\left(\frac{L}{\gamma} - \frac{s}{\gamma}\right)}}{e^{\left(\frac{L}{\gamma}\right)}}$$



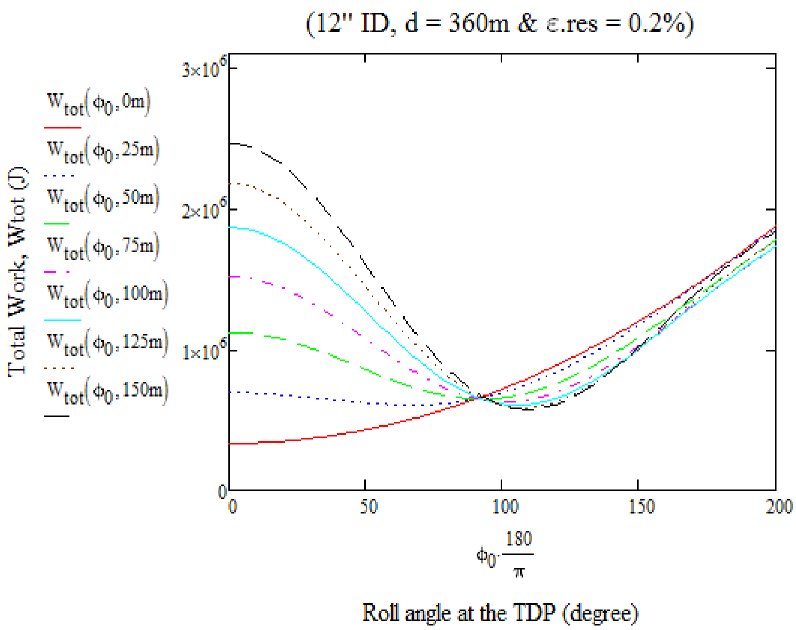
The total curvature ktot(s,ϕ0):

$$K_{tot}\left(\phi_0, s, L_{curv}\right) := \begin{cases} k(s) + K_{res} \cdot \cos\left(\phi\left(s, \phi_0\right)\right) & \text{if } s \le L_{curv} \\ k(s) & \text{otherwise} \end{cases}$$



The total work Wtot(ϕ0) from the surface to the seabed is assumed to consist of a bending contribution Wb(ϕ0) and a roll contribution Wr(ϕ0):

$$W_{tot}(\phi_0, L_{curv}) := \begin{cases} \left[\int_0^{L_{curv}} E\cdot I\cdot\left(k(s) + K_{res}\cdot\cos(\phi(s,\phi_0))\right)^2 ds + \int_{L_{curv}}^{L} E\cdot I\cdot(k(s))^2 ds + \int_0^L G\cdot I_t\cdot\left(\frac{d}{ds}\phi(s,\phi_0)\right)^2 ds\right] & \text{if } L_{curv} < L \\ \left[\int_0^{L_{curv}} E\cdot I\cdot\left(k(s) + K_{res}\cdot\cos(\phi(s,\phi_0))\right)^2 ds + \int_0^L G\cdot I_t\cdot\left(\frac{d}{ds}\phi(s,\phi_0)\right)^2 ds\right] & \text{otherwise} \end{cases}$$



PREDICTION OF PIPE ROLL WITH RESIDUAL CURVATURE FOR 14" ID

Water depth: $d := 360m$

Out side diameter: $D_0 := 0.4056m$

Pipe thickness: $t := 0.022m$

Density of Steel: $\rho_{steel} := 7850 \frac{kg}{m^3}$

Density of sea water: $\rho_{sea} := 1025 \frac{kg}{m^3}$

Gravitational acceleration: $g = 9.807 \frac{m}{s^2}$

Cladding thickness: $t_c := 0.003m$ $\qquad t_c = 3 \cdot mm$

Descity of cladding: $\rho_{clad} := 8000 \frac{kg}{m^3}$

Submerged Pipe Weight: $W_s := \pi \cdot (D_0 - t) \cdot t \cdot g \cdot \rho_{steel} + \pi (D_0 - 2 \cdot t - t_c) \cdot t_c \cdot g \cdot \rho_{clad} - \pi \rho_{sea} \cdot g \cdot \frac{D_0^2}{4}$

$$W_s = 1.007 \times 10^3 \cdot \frac{N}{m}$$

Modulus of Elasticity: $E := 200 \cdot 10^9 \frac{N}{m^2}$

Shear / modulus of rigidity: $G := 80 \cdot 10^9 \frac{N}{m^2}$

Specified minimum Yield Strength: $SMYS := 450 \cdot 10^6 \frac{N}{m^2}$

Maximum allowable bending strain: $\varepsilon_b := \frac{75\% \cdot SMYS}{E}$ $\qquad \varepsilon_b = 1.688 \times 10^{-3}$

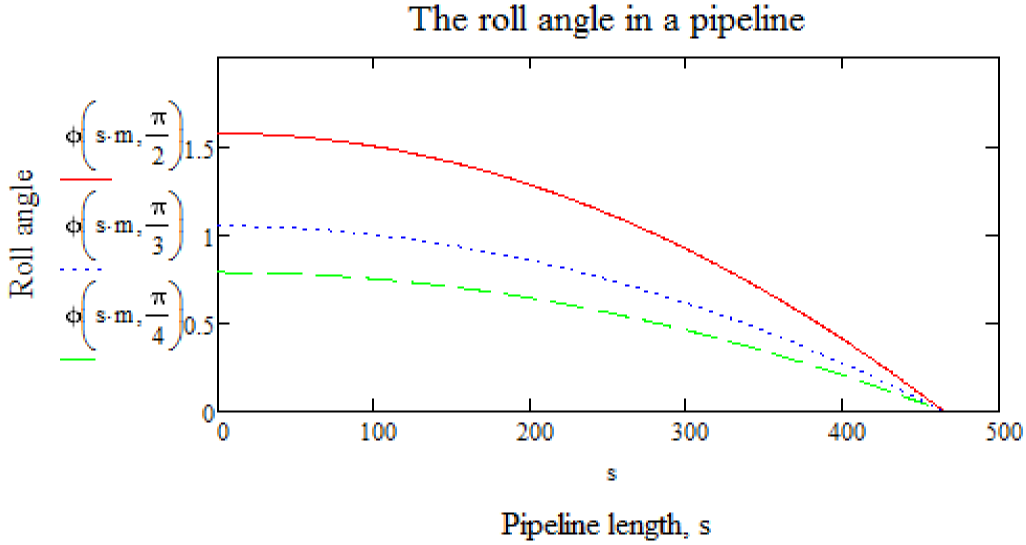
Horizontal component of lay tension:	$H_{comp} := \dfrac{\dfrac{D_0}{2} \cdot W_s}{\varepsilon_b}$	$H_{comp} = 1.211 \times 10^5 \cdot N$
Horizontal Length of pipe line:	$l := \dfrac{H_{comp}}{W_s} \cdot \operatorname{acosh}\left(W_s \cdot \dfrac{d}{H_{comp}} + 1\right)$ $l = 248\,m$	
Pipe line length, L	$L := \dfrac{H_{comp}}{W_s} \cdot \left(\sinh\left(\dfrac{W_s \cdot l}{H_{comp}}\right)\right)$ $L = 465\,m$	
Residual Strain 0.2%:	$\varepsilon_{res} := 0.002$	
Residual Curvature:	$K_{res} := \dfrac{\varepsilon_{res}}{\left(\dfrac{D_0}{2}\right)}$	$K_{res} = 9.862 \times 10^{-3} \dfrac{1}{m}$
Horizontal lay tension divided by pipe's submerged weight:	$A := \dfrac{H_{comp}}{W_s}$	$A = 120.178\,m$
Second Moment of Area:	$I := \pi \cdot \dfrac{\left[D_0^{\ 4} - (D_0 - 2 \cdot t)^4\right]}{64}$	$I = 4.893 \times 10^{-4}\,m^4$
Polar second Moment of Area:	$I_t := \pi \cdot \dfrac{\left[D_0^{\ 4} - (D_0 - 2 \cdot t)^4\right]}{32}$	$I_t = 9.785 \times 10^{-4}\,m^4$
Pipeline Top Tension during installation	$T := \sqrt{H_{comp}^{\ 2} + (W_s \cdot L)^2}$	$T = 4.837 \times 10^5\,N$
Define γ as:	$\gamma := \sqrt{E \cdot \dfrac{I}{T}}$	$\gamma = 14.223\,m$

Assume s is the distance from TDP to L: $s := 0, 1 .. 465$

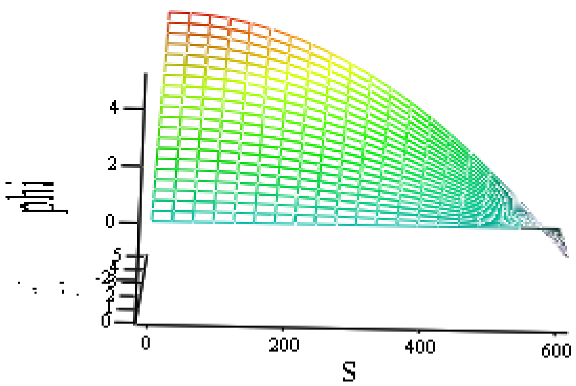
Assign ϕ0 rotation angle of the touch down: $\phi_0 := 0, 0.01 .. 4$

The length of curvature in the pipeline: $L_{curv} := 0, 25 .. 150$

The roll angle is given by: $\phi(s, \phi_0) := \phi_0 - \phi_0 \cdot \frac{s^2}{L^2}$



Surface Plot of the roll angle, ϕ

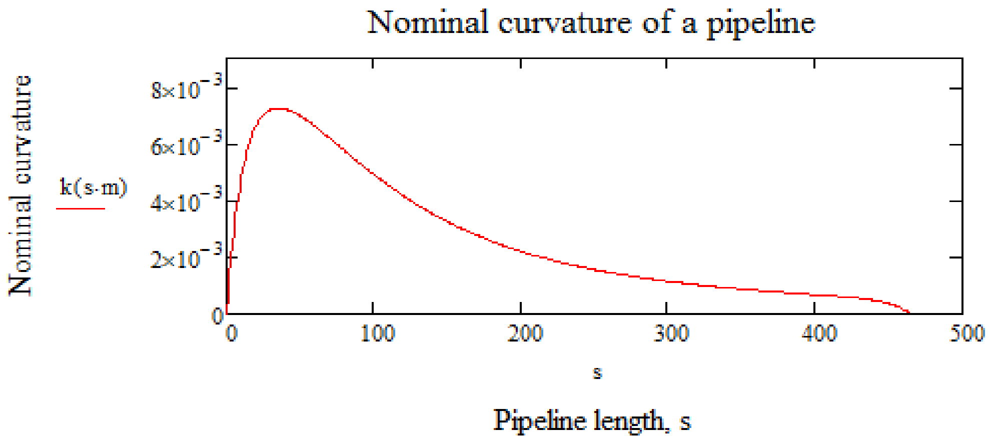


The roll angle phi in pipeline

ϕ

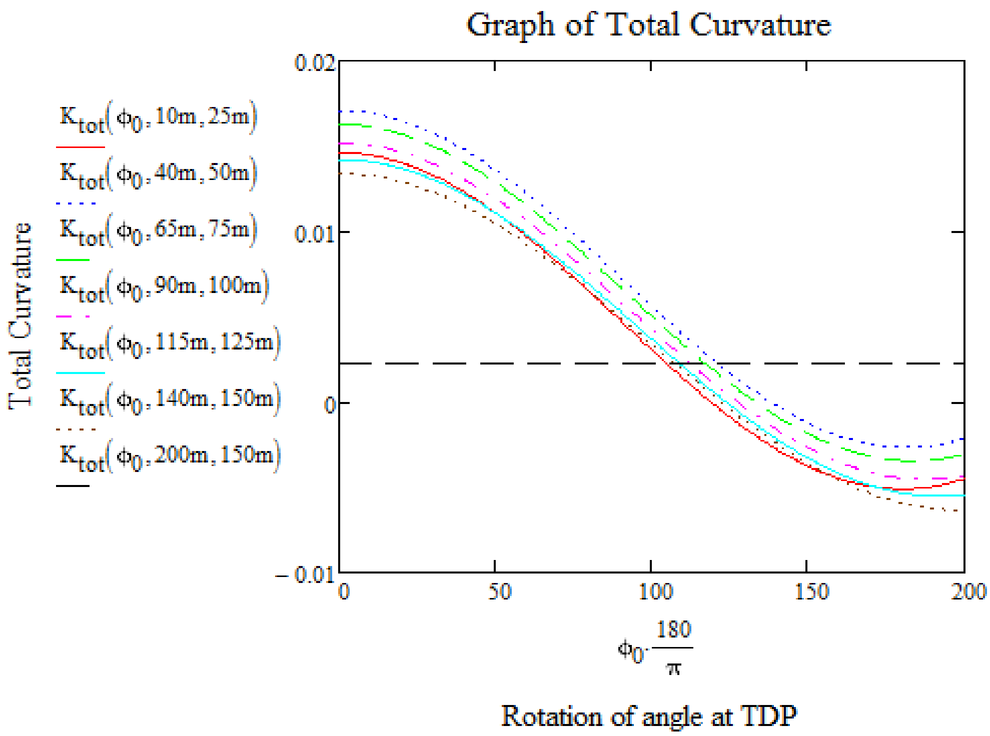
Nominal curvature k(s):

$$k(s) := \frac{A}{\left(A^2 + s^2\right)} - \frac{A}{(A+d)^2} \cdot e^{\left(\frac{s}{\gamma} - \frac{L}{\gamma}\right)} - \frac{A}{(A+s)^2} \cdot \frac{e^{\left(\frac{L}{\gamma} - \frac{s}{\gamma}\right)}}{e^{\left(\frac{L}{\gamma}\right)}}$$



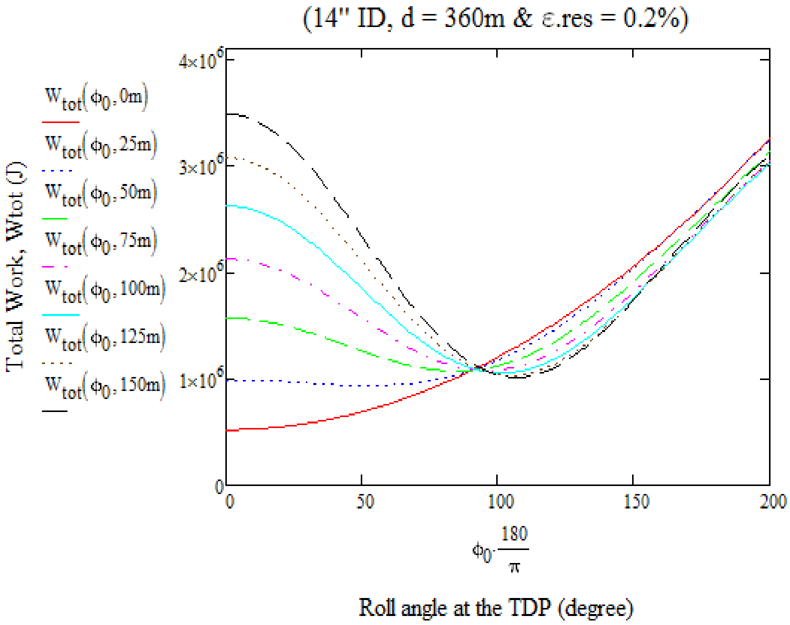
The total curvature ktot(s,ϕ0):

$$K_{tot}\left(\phi_0, s, L_{curv}\right) := \begin{cases} k(s) + K_{res} \cdot \cos\left(\phi\left(s, \phi_0\right)\right) & \text{if } s \le L_{curv} \\ k(s) & \text{otherwise} \end{cases}$$



The total work Wtot(ϕ0) from the surface to the seabed is assumed to consist of a bending contribution Wb(ϕ0) and a roll contribution Wr(ϕ0):

$$W_{tot}(\phi_0, L_{curv}) := \begin{cases} \left[\int_0^{L_{curv}} E\cdot I\cdot\left(k(s) + K_{res}\cdot\cos(\phi(s,\phi_0))\right)^2 ds + \int_{L_{curv}}^{L} E\cdot I\cdot(k(s))^2 ds + \int_0^L G\cdot I_t\cdot\left(\frac{d}{ds}\phi(s,\phi_0)\right)^2 ds\right] & \text{if } L_{curv} < L \\ \left[\int_0^{L_{curv}} E\cdot I\cdot\left(k(s) + K_{res}\cdot\cos(\phi(s,\phi_0))\right)^2 ds + \int_0^L G\cdot I_t\cdot\left(\frac{d}{ds}\phi(s,\phi_0)\right)^2 ds\right] & \text{otherwise} \end{cases}$$



PREDICTION OF PIPE ROLL WITH RESIDUAL CURVATURE FOR 18" OD PIPE-IN-PIPE

Water depth: $d := 360m$

OUTER PIPE

Pipe diameter: $D_{01} := 18in$ $D_{01} = 0.457\,m$

Pipe wall thickness: $w_{t1} := 22.2mm$ $w_{t1} = 0.022\,m$

INNER PIPE

Pipe diameter: $D_{02} := 12.75in$ $D_{02} = 0.324\,m$

Pipe wall thickness: $w_{t2} := 20.6mm$ $w_{t2} = 0.021\,m$

Specified Minimum Yield Strength $SMYS := 450 \cdot 10^{6} \frac{N}{m^{2}}$

MOMENT CAPACITY OF SECTION:

Plastic Moment Capacity:

$$M_{pi} := \frac{1}{6} \cdot SMYS \cdot \left[D_{01}^{3} - \left(D_{01} - 2 \cdot w_{t1}\right)^{3} + D_{02}^{3} - \left(D_{02} - 2 \cdot w_{t2}\right)^{3}\right]$$

$$M_{pi} = 2.746 \times 10^{6} \cdot N \cdot m$$

EQUIVALENT SINGLE PIPE SECTION:

Wall thickness for an equivalent single pipe

$$w_{te} := \frac{1}{2} \cdot \left(D_{01} - \sqrt[3]{D_{01}^{3} - \frac{6 \cdot M_{pi}}{SMYS}}\right)$$

$$w_{te} = 0.034\,m$$

Descity of Steel: $\rho_{steel} := 7851 \frac{kg}{m^3}$

Density of sea water: $\rho_{sea} := 1025 \frac{kg}{m^3}$

Gravitational acceleration: $g = 9.807 \frac{m}{s^2}$

Cladding thickness $t_c := 0.003m$ $t_c = 3 \cdot mm$

Descity of cladding $\rho_{clad} := 8000 \frac{kg}{m^3}$

Submerged Weight

$$W_s := \pi \cdot g \cdot \rho_{steel} \cdot (D_{01} - w_{te}) \cdot w_{te} + \pi \cdot (D_{01} - 2 \cdot w_{te} - t_c) \cdot t_c \cdot g \cdot \rho_{clad} - \pi \rho_{sea} \cdot g \cdot \frac{D_{01}^2}{4}$$

$$W_s = 2.115 \times 10^3 \cdot \frac{N}{m}$$

Modulus of Elasticity: $E := 200 \cdot 10^9 \cdot \frac{N}{m^2}$

Shear / modulus of rigidity: $G := 80 \cdot 10^9 \cdot \frac{N}{m^2}$

Maximum allowable bending strain $\varepsilon_b := \frac{75\% \cdot SMYS}{E}$ $\varepsilon_b = 1.688 \times 10^{-3}$

Horizontal component of lay tension: $H_{comp} := \frac{\frac{D_{01}}{2} \cdot W_s}{\varepsilon_b}$ $H_{comp} = 2.865 \times 10^5 \cdot N$

Horizontal Pipe line length, l:	$l := \frac{H_{comp}}{W_s} \cdot \left(\operatorname{acosh}\left(\frac{W_s}{H_{comp}} \cdot d + 1\right)\right)$ $l = 267\,m$	
Overall Pipe line length, L	$L := \frac{H_{comp}}{W_s} \cdot \left(\sinh\left(\frac{W_s \cdot l}{H_{comp}}\right)\right)$ $L = 477\,m$	
Residual Strain 0.2%:	$\varepsilon_{res} := 0.002$	
Residual Curvature:	$K_{res} := \frac{\varepsilon_{res}}{\left(\frac{D_{01}}{2}\right)}$	$K_{res} = 8.749 \times 10^{-3}\,\frac{1}{m}$
Horizontal lay tension divided by pipe's submerged weight:	$A := \frac{H_{comp}}{W_s}$	$A = 135.467\,m$
Second Moment of Area:	$I := \frac{\pi}{64} \cdot \left[D_{01}{}^4 - \left(D_{01} - 2 \cdot w_{te}\right)^4\right]$ $I = 1.018 \times 10^{-3}\,m^4$	
Polar second Moment of Area:	$I_t := \frac{\pi}{32} \cdot \left[D_{01}{}^4 - \left(D_{01} - 2 \cdot w_{te}\right)^4\right]$ $I_t = 2.037 \times 10^{-3}\,m^4$	
Pipeline Top Tension during installation	$T := \sqrt{H_{comp}{}^2 + \left(W_s \cdot L\right)^2}$	$T = 1.048 \times 10^6\,N$
Define γ as:	$\gamma := \sqrt{\frac{(E \cdot I)}{T}}$	$\gamma = 13.941\,m$

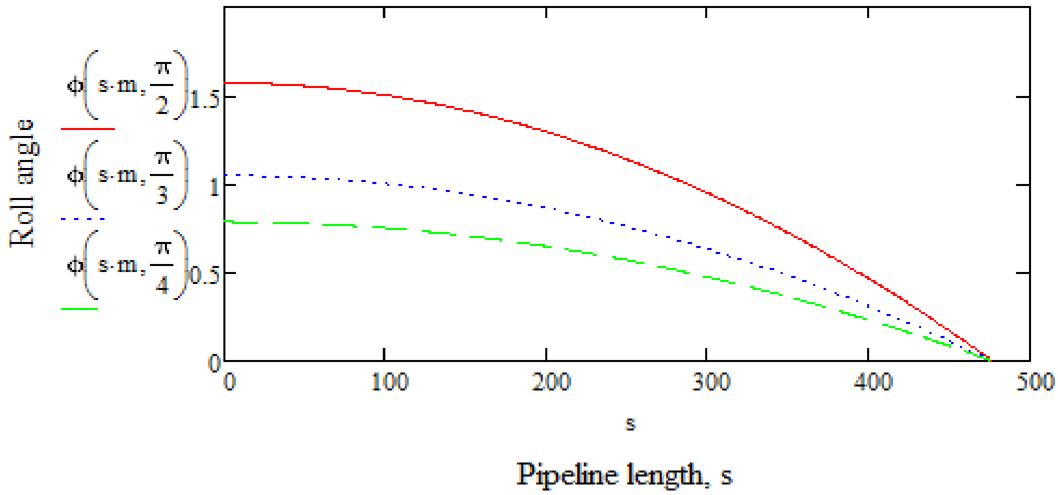
Assume s is the distance from TDP to L: $s := 0, 1 .. 477$

Assign $\phi 0$ rotation angle of the touch down: $\phi_0 := 0, 0.01 .. 4$

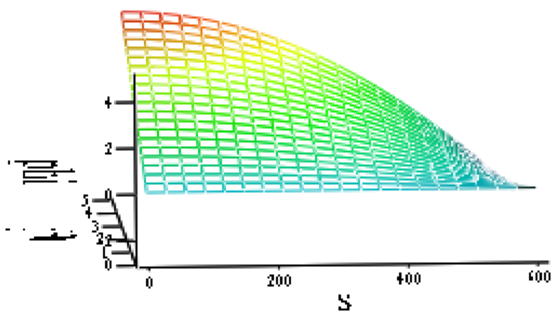
The length of curvature in the pipeline: $L_{curv} := 0, 25 .. 150$

The roll angle is given by: $\phi(s, \phi_0) := \phi_0 - \phi_0 \cdot \frac{s^2}{L^2}$

The roll angle in a pipeline



Surface Plot of the roll angle, ϕ



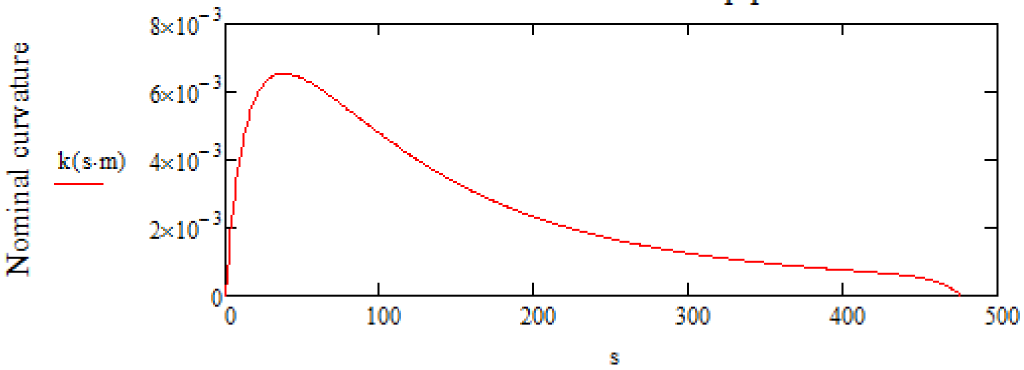
The roll angle phi in pipeline

ϕ

Nominal curvature k(s):

$$k(s) := \frac{A}{\left(A^2+s^2\right)} - \frac{A}{(A+d)^2}\cdot e^{\left(\frac{s}{\gamma}-\frac{L}{\gamma}\right)} - \frac{A}{(A+s)^2}\cdot\frac{e^{\left(\frac{L}{\gamma}-\frac{s}{\gamma}\right)}}{e^{\left(\frac{L}{\gamma}\right)}}$$

Nominal curvature of a pipeline

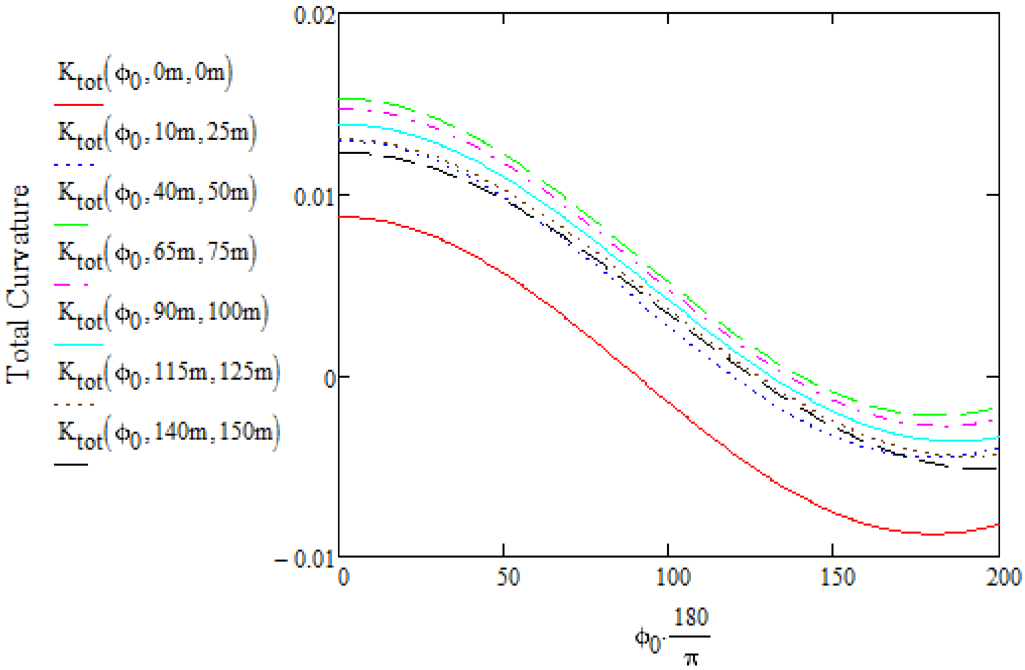


Pipeline length, s

The total curvature ktot(s,ϕ0):

$$K_{tot}\left(\phi_0, s, L_{curv}\right) := \begin{cases} k(s) + K_{res}\cdot\cos\left(\phi\left(s,\phi_0\right)\right) & \text{if } s \le L_{curv} \\ k(s) & \text{otherwise} \end{cases}$$

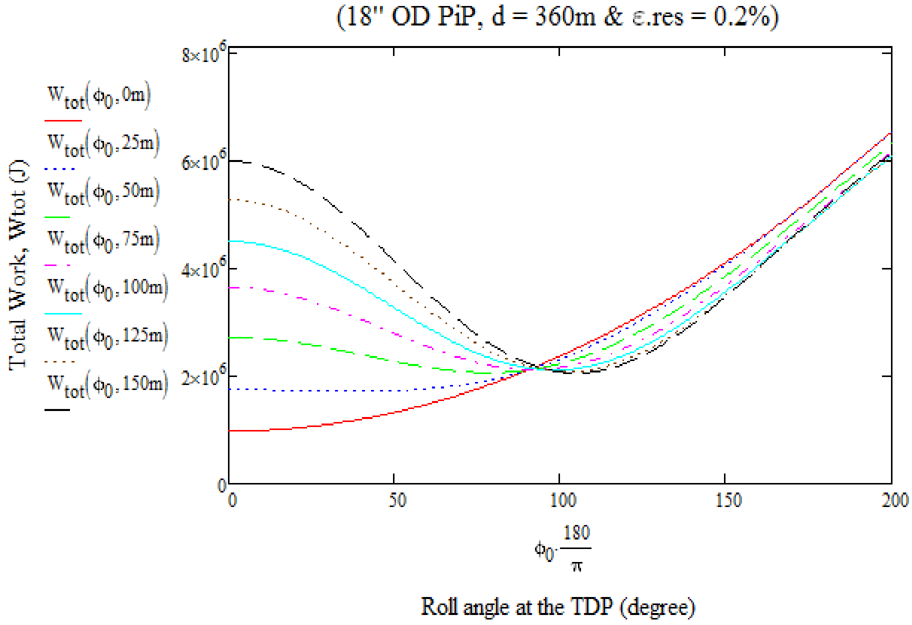
Graph of Total Curvature



Rotation of angle at TDP

The total work Wtot(ϕ0) from the surface to the seabed is assumed to consist of a bending contribution Wb(ϕ0) and a roll contribution Wr(ϕ0):

$$W_{tot}(\phi_0, L_{curv}) := \begin{cases} \int_0^{L_{curv}} E\cdot I\cdot(k(s) + K_{res}\cdot\cos(\phi(s,\phi_0)))^2\, ds + \int_{L_{curv}}^{L} E\cdot I\cdot(k(s))^2\, ds + \int_0^L G\cdot I_t\cdot\left(\frac{d}{ds}\phi(s,\phi_0)\right)^2 ds & \text{if } L_{curv} < L \\ \int_0^{L_{curv}} E\cdot I\cdot(k(s) + K_{res}\cdot\cos(\phi(s,\phi_0)))^2\, ds + \int_0^L G\cdot I_t\cdot\left(\frac{d}{ds}\phi(s,\phi_0)\right)^2 ds & \text{otherwise} \end{cases}$$



APPENDIX I: Brief Description of Software Programs used

I.1 Mathcad

A) Introduction

Mathcad is the industry standard technical calculation tool for engineers worldwide. Mathcad delivers all the solving capabilities, functionalities, and robustness needed for calculation, data manipulation, and engineering design work. Mathcad is a user-friendly software where equations are written as mathematical functions. It always provides an up-to-date numerical results and graphs. You can use Mathcad equations to solve both symbolical and numerical equations. Mathcad is a product of Parametric Technology Corporation's (PTC) and more information about the software can be found on their website (www.ptc.com). A short and brief description of the software is presented based on PTC user's guide manual, Ref [24].

B) Overview of the software

The Mathcad Workspace

When you start Mathcad, you see a window as shown in figure A31.

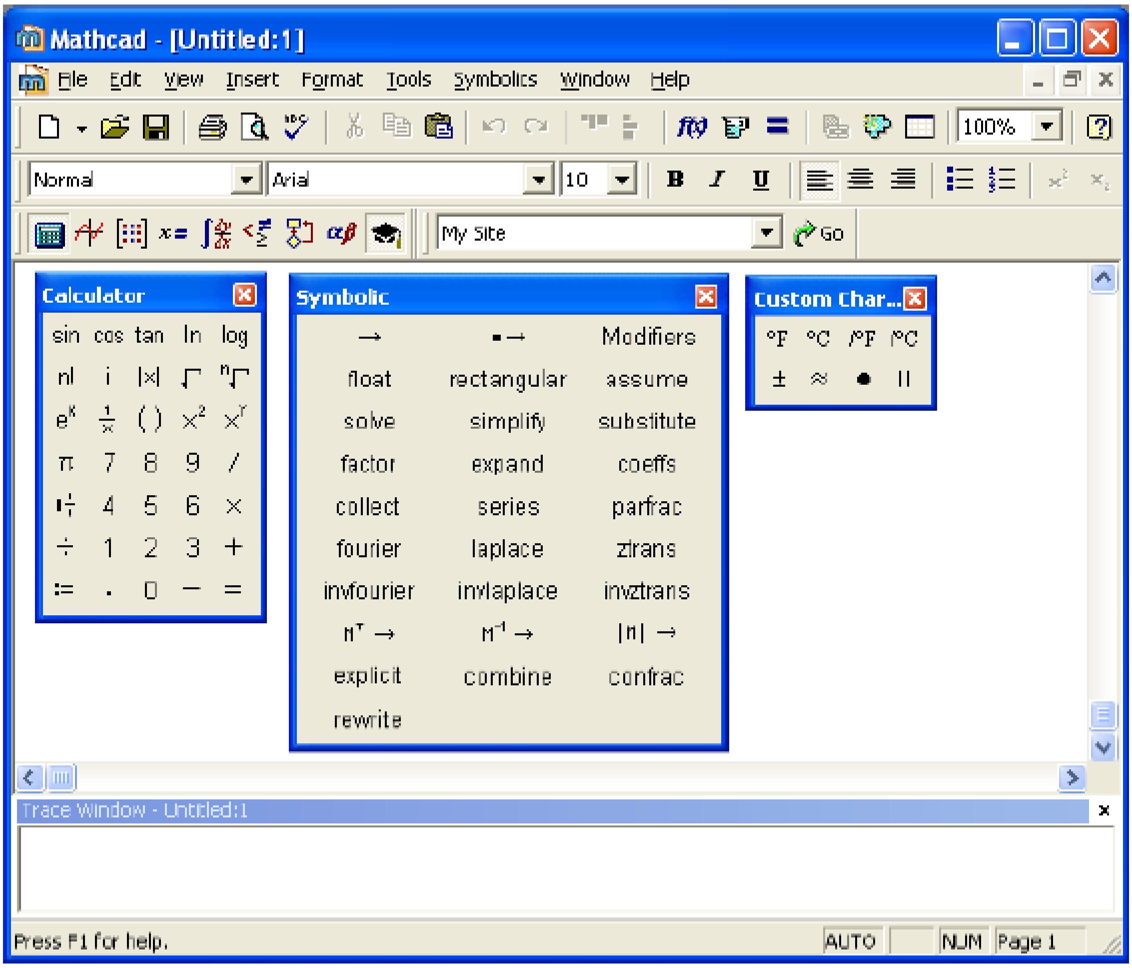


Figure A31: Mathcad with various toolbars displayed, Ref [24]

Each button in the Math toolbar opens another toolbar of operators or symbols. You can insert many operators, Greek letters, and plots by clicking these buttons. Figure 32 shows the nine buttons in Math toolbar.

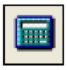
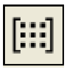
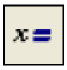
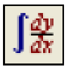
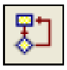
Button	Toolbar
	**Calculator**: Arithmetic operators.
	**Graph**: Two- and three-dimensional plot types and graph tools.
	**Matrix**: Matrix and vector operators.
	**Evaluation**: Equal signs for evaluation and definition.
	**Calculus**: Derivatives, integrals, limits, and iterated sums and products.
	**Boolean**: Comparative and logical operators for Boolean expression.
	**Programming**: Programming constructs.
	**Greek**: Greek letters.
	**Symbolic**: Symbolic keywords and modifiers.

Figure A32: Math tool bar buttons in Mathcad, Ref [24]

The standard toolbar provides quick access to many menu commands. The formatting toolbar contains scrolling lists and buttons to specify font characteristics for both equations and text. To learn what a button on any toolbar does, hover the mouse over the button until a tooltip appears with a brief description.

Working with worksheets: when you start Mathcad, you open a Mathcad worksheet. You can have as many worksheets open as your available system resources allow.

Regions

Mathcad lets you enter equations, text, and plots anywhere in the worksheet. Each equation, piece of text, or other elements are region. A Mathcad worksheet is a collection of such regions. To start a new region in Mathcad:

1. Click anywhere in a blank area of the worksheet. You see a small crosshair. Anything you type appears at the crosshair.
2. If the region you want to create is a math region, just start typing anywhere you put the crosshair. By default, Mathcad understands what you type as mathematics.
3. To create a text region, choose Text Region from the Insert menu and then start typing.

C) Definitions and Variables

Mathcad's power and versatility quickly become apparent once you begin to use variables and functions. By defining variables and functions, you can link equations together and use intermediate results in further calculations.

Defining Variables: To define a variable the following steps are followed

1. Type the variable name.
2. Type the colon key or click the symbol colon with equal sign on the Calculator tool bar to insert the definition symbol.
3. Type the value to be assigned to the variable. The value can be a single number or a more complicated combination of numbers and previously defined variables.

If you make a mistake, click on the equation and press [**space**] until the entire expression is between the two blue editing lines. Then delete it by choosing Cut from the Edit menu ([**Ctrl**]X). Or use Mathcad's Undo [**Ctrl**] Z command from the Edit menu to step back through the equation.

Variable in Mathcad worksheets are defined from top to bottom and left to right on a page. Once you have defined a variable like *t*, you can compute with it anywhere below and to the right of the definition.

Mathcad updates results as soon as you make changes. For example, if you click on a value on your screen and change it to another number, Mathcad changes the result as soon as you press [**Enter**] or click outside of the equation.

D) Functions

Defining a function: To add a function definition to your worksheet:

1. First define the function *f(t)* by typing **f(t)**
2. Complete the definition by typing the expression fully

The definition you type defines a function. The function name is *f*, and the argument of the function is *t*. You can use this function to evaluate the expression for different values of *t*. To do so, simply replace *t* with an appropriate number. For example, to evaluate the function at a particular value, such as 5, type **f(5)**=. Mathcad returns the correct value.

Formatting a Result: The display format can be set for any number that Mathcad calculates and displays. To change the result so it is displayed differently:

1. Click in the result
2. Choose Result from the Format menu to open the Result Format dialog box. These dialog settings affect how results are displayed, including the number of decimal places, the use of exponential notation and trailing zeros, and so on. Figure A33 shows the Result Format dialog box.

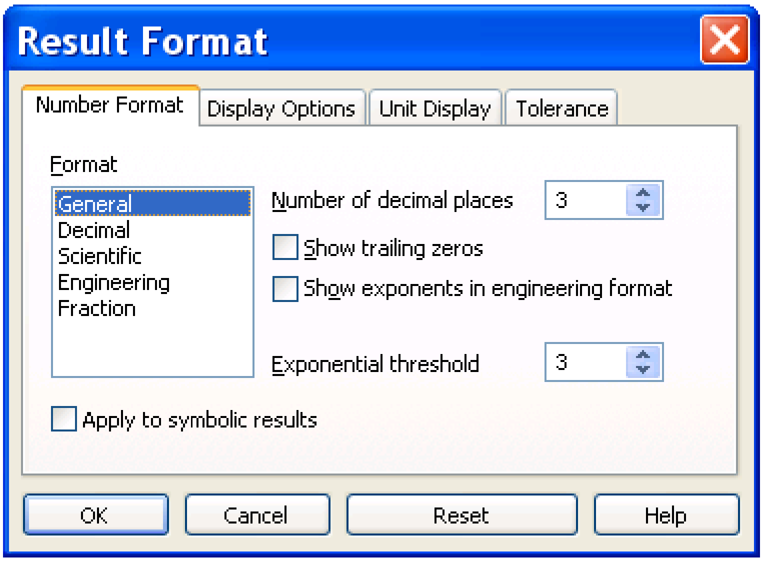


Figure A33: Result Format dialog box in Mathcad, Ref [24]

3. The default format scheme is 'Genera' with 'Exponential Threshold' set to 3. Only number greater than or equal to 10^3 are displayed in exponential notation. Click the arrows to the right of the 3 to increase the Exponential Threshold to 6.

4. After finishing click 'OK,' the number changes to reflect the new result format.

It should be noted that when you format a result, only the display of the result is affected. Mathcad maintains full precision internally (up to 16 digits)

E) Graphs

Mathcad provides a variety of two-dimensional X-Y and polar graphs plus three-dimensional contour, scatter, and surface plots. This section describes how to create a simple two-dimensional graph.

Creating a Basic Graph: To create and X-Y plot:

1. Click in a blank area of worksheet.

2. Choose **Graph > X-Y Plot** from the **Insert** menu or click X-Y plot button on the **Graph** tool bar. Or type [@]. Mathcad inserts a blank X-Y plot.

3. Fill in the *x*-axis placeholder (bottom center) with variable t, and the *y*-axis placeholder (left center) with f(t). These placeholders can contain a function, an expression, or a variable name.

4. Click outside the plot or press [**Enter**]

Mathcad automatically chooses axis limits for the function. To specify the axis limits yourself, click in the plot and type over the numbers in the placeholders at the ends of the axes. Mathcad also creates the plot over a default range.

Formatting a Graph: The *default* characteristics of a Mathcad graph are numbered linear axes, no grid lines, and points connected with solid lines. One can change these characteristics by formatting the graph. To format a graph:

1. Double –click the graph to bring up the Formatting dialog box.
2. Click the Traces tab.
3. Double-click 'trace 1' in the table cell under 'Legend Label.' Type a name for the trace, for example, Displacement.
4. Click the table cell in the 'Line' column and choose a dotted line. Choose a line weight of 3 from the next column, and the color blue in the 'Color' column.
5. Uncheck the 'Hide Legend' check box, & select the 'Bottom-left' position for the legend and click 'OK'
6. Mathcad shows the graph as a dotted line. Note that the sample line under the f(t) now reflects the new formatting, as does the legend.
7. Click outside the graph to deselect it.

F) Saving, Printing, and Exiting

After creating a worksheet, the next step is to save or print it.

Saving a Worksheet: To save a worksheet

1. Choose **Save** from the **File** menu, [**Ctrl**] S. If the file has never been saved before the Save As dialog box appears.
2. Type the name of the file in the text box provide. To save to another folder, located the folder using the Save As dialog box.

By default, Mathcad saves the file in a native Mathcad format – Mathcad XML (.XMCD) or compressed Mathcad XML (XMCDZ). There is an option of saving in other formats – HTML, RTF for Microsoft Word, or XMCT as templates for new Mathcad worksheets.

Printing: To print, choose **Print** from the **File** menu or click the printer button on the **Standard** toolbar. To preview the printed page, choose **Print Preview** from the **File** menu or click the print preview button on the **Standard** toolbar.

Exiting Mathcad: To quit Mathcad, Choose **Exit** from the **File** menu. If you have moved any toolbars, Mathcad remembers their locations for the next time you open the application.

I.2 OrcaFlex

A) Introduction

OrcaFlex is a software program primarily designed for static and dynamic analysis of a number of Offshore structures i.e. rigid and flexible risers, mooring system and installation. OrcaFlex is a product of Orcina Ltd and more information about the software can be found on their website (www.orcina.com). A short description of the software is presented here based on the software's user manual and Gudmestad's book, Ref [17].

B) Overview of the software program

The software program is started on a computer in which it is installed in a similar manner to other basic software. This can be done from the desktop, from the start menu, or through other available shortcuts. It is a user-friendly software with good features and pictorial representation of models.

A 3-D view representing the marine environment is presented to the user when the program starts; the view shows the sea surface, the seabed, and a dark empty space representing the surrounding environment. A pictorial representation of this main window is as shown in figure A34, where the blue line represents the sea surface, and the brown line represents the seabed.

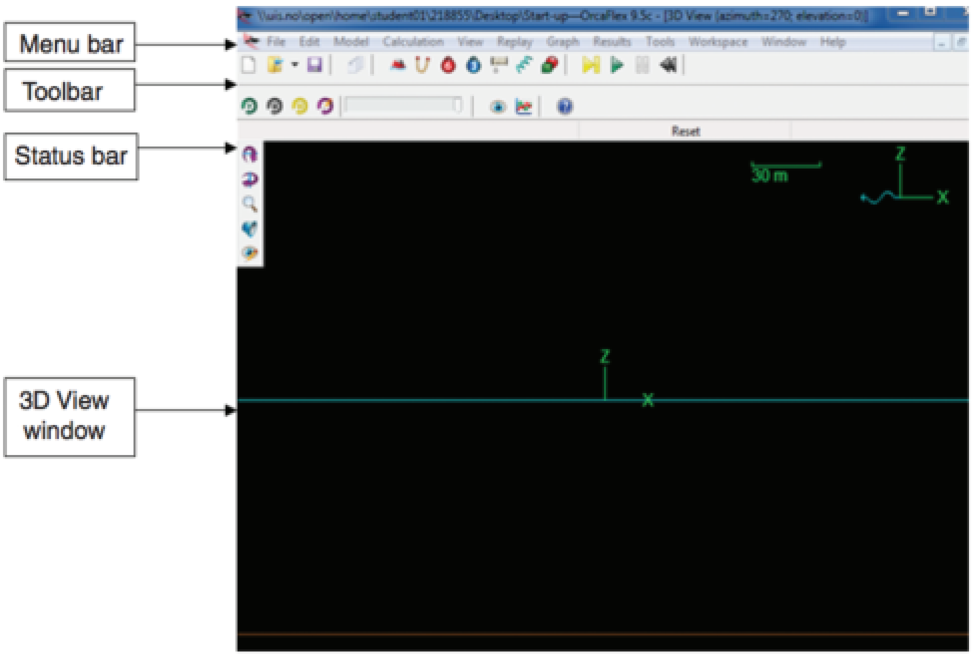


Figure A34: OrcaFlex main window, Ref [17]

Menu bar: The menu bar has various commands including commands for opening, saving, printing and exporting. It has data and object editing facilities. It provides access to facilities that are used for modeling, starting, stopping, and replaying analyses. It can be used when accessing different views of the model. It provides commands used in obtaining analyses results, and can be used to access multiple windows and workspace.

Tool bar: The tool bar can be described as a shortcut to the menu bar, it provides a shortcut to access most of the commands that are found in the menu bar. In other words, it provides for a quick access to most of the commands used in modeling, analyses, and obtaining results.

Status bar: The status bar provides information about how current action is progressing, and is divided into message box, state indicator, and information box.

3D view: The 3D view window shows the current model in a pictorial form, and provides good pictorial representation of each part of a system. The main window can also be divided into sub-windows, showing graphs, spreadsheets, and texts.

C) Modeling and analysis

The sequence of analysis in OrcaFlex, following the creation of a model of the marine structure, is as shown in figure A35. If the static analysis does not converge it is impossible to perform a dynamic analysis, and this will require the user to modify the configuration, or time steps.

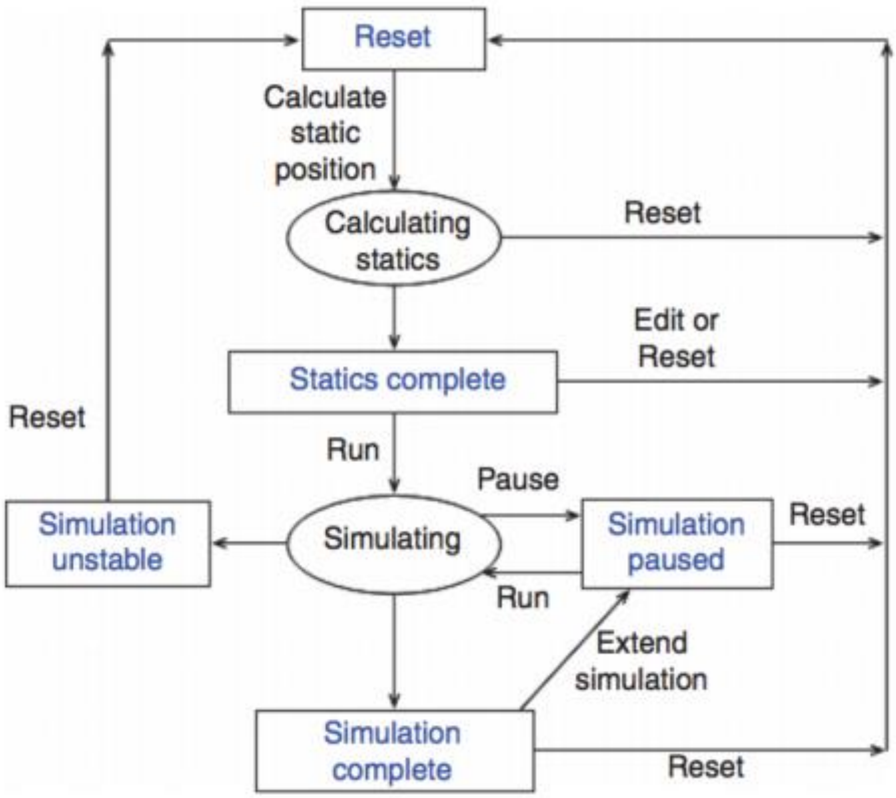


Figure A35: Model states, Ref [17]

The coordinate system in OrcaFlex is as shown in figure A36, this comprises of a general global coordinate system, denoted GXYZ and local coordinate systems (*Vxyz*) for each of the modeled objects.

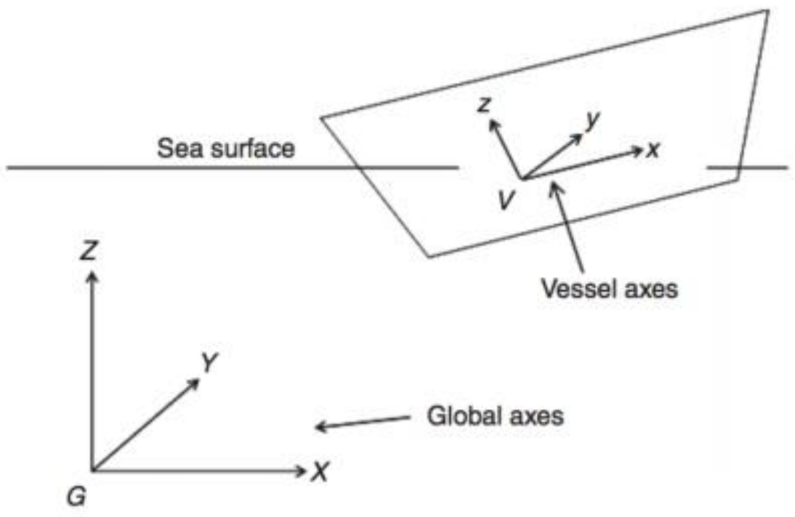


Figure A36: OrcaFlex coordinate systems, Ref [17]

The various headings and directions in OrcaFlex is as shown in figure A37, they are specified by providing the azimuth angle for a direction, measured counter-clockwise.

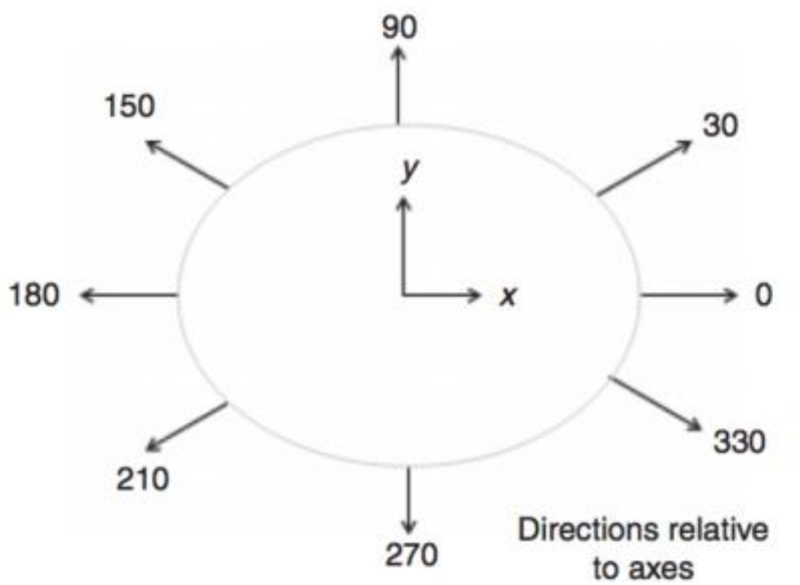


Figure A37: OrcaFlex headings and directions, Ref [17]

A description of how the simulation time is specified and how this can be divided into different stages is shown in figure A38; this information is particularly useful if one wants to capture part of simulation rather than the entire simulation period.

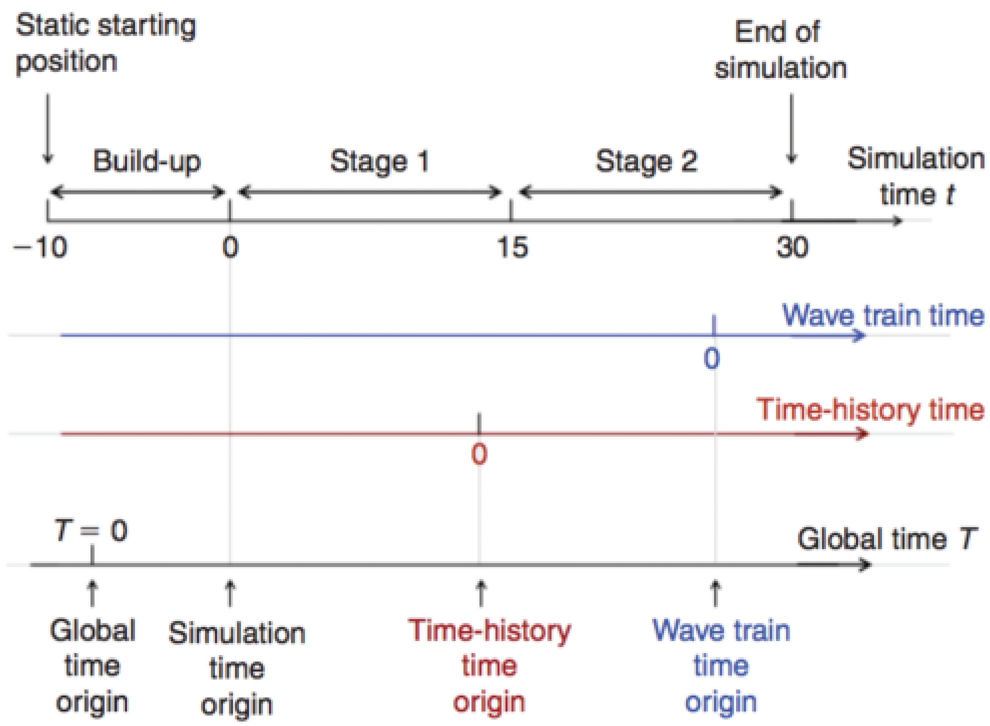


Figure A38: Setting up simulation time and stages, Ref [17]