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Comparisons Study of S-Lay and J-Lay Methods for Pipeline Installation in Ultra Deep Water

Master Thesis

Marine and Subsea Technology

Jihan Herdiyanti

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Abstract

The pipeline industry has developed its technical capabilities to enable operations in deeper water. In ultra deepwater developments, the offshore industry has been challenged to solve demanding tasks, to develop new and reliable installation technologies for deepwater and uneven seafloor conditions, and to discover technology to deal with harsh environmental conditions.

Pipeline installation in deeper water area needs special considerations regarding the lay vessel capabilities. These capabilities are that the vessel should have enough tension capacity for the deeper water and good dynamic positioning system restricted to small movements only.

Two common methods used to install pipeline are the S-Lay and J-Lay methods. Some parameters need to be considered when choosing the appropriate installation method, therefore limitations for each methods are investigated.

For the S-Lay method, these important parameters Include vessel tension capacity, stinger length, stinger curvature, strain in the overbend region and bending moment in the sagbend region. The maximum depth at which a given pipeline can be laid could be increased with a longer stinger of the lay barge and bigger vessel tension capacity. However, choosing these options may require clamping to pull the pipeline that can cause a heavy mooring system and high risk associated with a very long stinger subject to hydrodynamic forces. In addition, these options also could destroy the pipe coating.

On the contrary with the S-Lay method, the J-Lay method reduces any horizontal reaction on the vessel's equipment, and because of this, the J-Lay technology might be used to meet project requirements in deeper water. However, the capability of the J-Lay method in deep and very deep waters requires barges with dynamic positioning capabilities. This is because positioning by spread mooring with anchors would always be worthless and often unfeasible due to the safety of operations. Under extreme conditions, the loading process induced by the lay barge response to wave actions in deep waters is less severe for J-lay method compared to other methods. However, special attention has to be paid to the complex nature of vortex shedding induced oscillations along the suspended pipeline span.

Considering the aspects mentioned above, studies will be carried out in this master thesis. The thesis will expose two pipeline installation methods, i.e. S-Lay and J-Lay methods for various water depths and pipe sizes. Starting from 800 m to 4000 m water depth, pipe sizes more than 24 inch will be investigated. The effect of increasing strain in the overbend region and effect of reducing the stinger length will be studied to meet these challenges and to improve the laying efficiency especially using the S-lay method. Plot for various water depths and pipeline properties will be presented as the results of this master thesis. The installation analysis will be performed by using computer program SIMLA.

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Jihan Herdiyanti

TABLE OF CONTENTS

Table of Contents

List of Tables

List of Figures

Nomenclature

Symbols

Latin characters

b Pipe buoyancy per unit length

D Outer diameter of the pipe, unless specified otherwise

E Modulus of elasticity of the pipe steel, Young's Modulus

f_o Ovality (out-of-roundness)

f_u Tensile strength

f_y Yield stress

g Gravity acceleration

Ic Cross sectional moment of inertia of the steel pipe

κ Pipe curvature

M Bending moment

M_p Plastic moment capacity

M_{Sd} Design moment

M'_{Sd} Normalized moment (MSd/Mp)

M_y Pipe bending moment at the nominal yield stress; $My = 2\sigma y\ Ic / D$

n Hardening parameter

p_c Characteristic collapse pressure

p_e External pressure

p_{el} Elastic collapse pressure

p_i Internal pressure

p_p Plastic collapse pressure

p_{pr} Propagating pressure

$p_{pr,BA}$ Propagating buckle capacity of an infinite arrestor

p_X Crossover pressure

p_{min} Minimum internal pressure that can be sustained

S_p Plastic axial tension capacity

S_{Sd} Design effective axial force

S'_{Sd} Normalized effective force (SSd/Sp)

T Tension

t Nominal pipe wall thickness (un-corroded)

t_1 Characteristic wall thickness; t-t_{fab} prior to operation. t shall be replaced with t_1 due to possible failure where low capacity- system effects are present

t_2 Characteristic wall thickness; t for pipelines prior to installation

t_{fab} Fabrication thickness tolerance

U_c Mean current velocity normal to the pipe

w_s Pipe submerged weight per unit length

Greek characters

α_{fab} Fabrication factor

α_u Material strength factor

β Factor used in combined loading criteria

γ_c Condition load effect factor

γ_m Material resistance factor

γ_{sc} Safety class resistance factor

γ_w Safety factor for on-bottom-stability

ε Strain

θ Liftoff angle

μ Friction coefficient

ν Poisson's ratio

ρ_w Mass density of water

σ_y Nominal yield stress of the pipe steel

Abbreviations

ALS	Accidental Limit State
CP	Cathodic Protection
CRA	Corrosion Resistant Alloy
CTOD	Crack Tip Opening Displacement
CWC	Concrete Weight Coating
DNV	Det Norske Veritas
DP	Dynamic Positioning
ECA	Engineering Critical Assessment
FLS	Fatigue Limit State
GPS	Global Positioning System
LC	Load Controlled
LRFD	Load and Resistance Factor Design
SMTS	Specified Minimum Tensile Strength
SMYS	Specified Minimum Yield Strength
ULS	Ultimate Limit State
UOE	Pipe fabrication process for welded pipes
UO	Pipe fabrication process for welded pipes
TRB	Three Roll Bending
ERW	Electric Resistance Welding

CHAPTER 1 INTRODUCTION

1.1 Background

Pipelines are major components of the oil and gas production. Both technical and economical challenges should be taken into considerations for pipeline design installations in ultra-deep water.

Pipeline installation methods and selection of pipeline concept are important concerns and set limitations to how deep a pipeline can be laid. Not only limitations to laying vessel tension capacity but also to technical design solutions are important in order to make pipeline installations and operations feasible in deep water depths.

Nowadays, projects have been completed and planned in water depths from more than 2000 meters up to 3500 meters and more. Some examples of deepwater pipeline projects are Medgaz project across Mediterranean Sea that has installed 24 inch pipelines at depths of 2155 meters and Blue Stream project with 24 inch pipeline at depths of 2150 m across the Black Sea. The deepest pipeline project, South Stream has been started in December 2012 in water depths more than 2200 m in the Black Sea, but this water depth record will not last long. A gas pipeline project between Oman and India have for long had plans of installing pipelines at depths of nearly 3500 meters in a 1100 km long crossing of the Arabian Sea to transmit gas from Middle East to India.

In this thesis, the possibilities for pipeline installation in water depths up to 4000 m using pipelay vessels with the biggest tension capacity will be studied. The Allseas Company has decided to build this vessel. This vessel, *Pieter Schelte*, has topside lift capacity of 48000 t, jacket lift capacity of 25000 t and pipelay tension capacity around 2000 t. This tension capacity will be doubling the capacity of Allseas' Solitaire. Pieter Schelte is supposed to be ready for offshore operations in early 2014.

Figure 1-1 : Pieter Schelte Vessel, Ref [1]

1.2 Problem Statement

A marine pipeline is exposed to different loads during installation such as tension, bending, and high external hydrostatic pressures which are becoming greater problems with increasing water depths. The tension applied in the pipe controls the sag-bend curvature while over-bend curvature is controlled by the stinger radius. The required tension depends on water depth, weight of the pipe, acceptable radius of curvature at the over-bend and acceptable stress at the sag-bend. The requirements to the large tension capacity may exceed the capacity of the most powerful S-Lay vessel in combination of very deep waters and thick walled pipes.

Accepting a higher working factor for the pipelines as well as using high steel grade steels will decrease the required wall thicknesses. These conditions lead to a reduction of pipeline weights and can therefore increase the water depth limits for the S-lay method. Some studies to support the idea to exceeding elastic proportionality for stress-strain behavior in the over-bend have been done. However, to extend the achievable water depth by increasing the allowable curvature in the over-bend may cause some crucial issues. Some lay variables such as lay pull, roller reaction, dynamic excitation from vessel motions and hydrodynamic loads need to be investigated. In addition further efforts to predict the historical pipe responses in non-linear behavior must be studied before allowing permanent deformations after installation.

The J-Lay method is another alternative to install pipelines in deeper water depths and larger diameters. In the J-Lay method, the requirements of curvature in the over-bend can be reduced; therefore only a short stinger is required to withstand the load from the lay span and to assist the pipe coming out from the vessel. The requirements of horizontal tension are smaller compared to the S-Lay method, only simply to withstand the submerged weight of the pipes, to control stresses, and to maintain a satisfactory curvature in the sag-bend. However, the J-Lay method does not allow more than one welding and NDT station, causing the welding process to be much slower than the S-Lay method. In addition, the availability of welding and NDT technology for thick pipes may aggravate this situation.

A very long free span of pipe sections from the barge to the seafloor is exposed to loads caused by vessel responses and vortex shedding due to marine currents in ultra deep waters. In fact, severe currents may cause vibrations and involve high Eigen-modes, therefore high dynamic stresses may happen as consequences. This phenomena combined with long time required for a pipe to reach the sea bottom can accumulate intolerable fatigue damage during installations, causing very small or even no margin for the on-bottom operating life.

1.3 Purpose and Scope

The purpose of this thesis is to study the possibilities of pipeline installations in water depth up to 4000 m using pipelay vessel with the biggest tension capacity available and using appropriate technical solutions. This tension capacity will be 2000 t and the vessel will be ready for offshore operations in early 2014.

Scope of this thesis:

- Comprises development of 14 inch, 20 inch, 28 inch, and 30 inch steel pipelines for installation at water depths 800 m, 1300 m, 2000 m, 2500 m, 3000 m, 3500 m, and 4000 m;
- Comparison between the S-Lay and J-Lay methods for various pipeline sizes and water depths as mentioned above;
- Identify main challenges for pipeline installations in ultra deep water;
- Perform analysis for pipeline installation using software SIMLA and compare the results with ORCAFLEX, OFFPIPE, and manual calculations;
- Study the effect wall thickness requirements using the higher steel grades (X65, X70, X80, X100) for the case of combination of bending and external pressure;
- Study the effect of plastic strains in the over bend;
- Study the effect of changing in ovality;
- Study the effect of increasing of allowable strain in overbent up to 0.5%;
- Study the effect of reducing the length of stinger.

1.4 Thesis Organization

The remaining chapters in this thesis are organized as follows:

Chapter 2 (Basic Theory) presents the pipeline laying methods relevant for deep waters and discusses the main challenges related to developments of pipeline concepts at these water depths. The chapter also presents a discussion of the advantages and disadvantages of the different concepts. In addition, theoretical studies about pipe material and possibilities to exceed the elastic proportionality for stress-strain behavior are included in this chapter to establish a layable and operative pipeline at deep waters.

Chapter 3 (Design Criteria &Methodology) presents the design criteria for the pipelines being studied as part of the case studies, including pipeline properties, material data, data about the physical environmental and design criteria, as well as design methodology applied in the thesis.

Chapter 4 (Analysis Study) presents the S-Lay and J-Lay analysis for various water depths and pipeline sizes. The pipe laying systems modeled with the finite element software SIMLA, is explained.

Chapter 5 (Results and Discussions) presents results and evaluations regarding pipe layability studies of S-lay and J-lay methods in water depths up to 4000 m. The results and discussions of sensitivity studies such as the effect of changing in ovality, the effect of increasing material grade, the effect of increasing allowable strain in the overbend region and the effect of reducing the length of stinger are also presented. In addition in this chapter, SIMLA results are compared to corresponding results obtained from OFFPIPE, ORCAFLEX and manual callculations.

Chapter 6 (Conclusion and Further Studies) presents conclusions and recommendations for further studies.

CHAPTER 2 BASIC THEORY

2.1 Pipeline Installation

Pipeline installation is one of the most challenging offshore operations. A high level of engineering design is required to determine the required diameter of pipe, type of material, and installation method that are suitable for certain locations. Furthermore these criteria will be used for choosing installation vessel and determine the estimated cost.

This chapter outlines two common methods used to install pipeline, i.e:

- S-lay;
- J-lay.

2.1.1 S-Lay Method

S-lay is one of the pipes installation methods which is characterized by "S" curve during laying to the seabed. Before laying to the seabed, the pipes are stored and assembled on the vessel. The pipe leaves the vessel at the stern part through a sloping ramp (see ***Figure 2-1***). The stinger is located at the end of the ramp. It is used to support the pipelines, to control the curvature, and to prevent massive deflections in the overbend region. With the choosen angle, segments of the stinger can be set to determine its shape. Stinger length depends on water depth and submerged weight of the pipes. Sufficient length of the stinger is required to avoid excessive bending that may cause the pipelines to buckle. Tensioners are located on the ramp; it has the function to hold the suspended length of the pipeline.

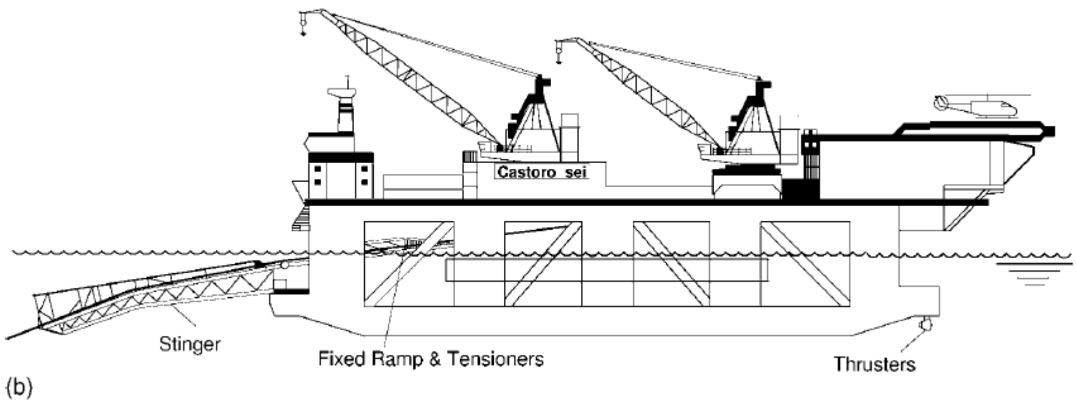

Figure 2-1: Schematic of Saipem's Castoro Sei Semi-Submersible S-Lay Vessel, Ref [26]

The upper curved part of the pipeline is known as the *overbend* or upper generator convex, Ref [26]. The pipeline will lose contacts with the stinger at a chosen angle and go downward straightly and then gradually bends in the opposite direction known as the sagbend area. From the sagbend area, the suspended pipe continues to reach the seabed at the touchdown point. The detail of the S-lay configuration is shown in Figure 2-2. In the sagbend area (or known also as lower generator concave), the combination of bending and pressure loads are must safely be sustained.

The tension applied at the top is used to control the curvature in the sagbend region. Excessive bending, local buckling and collapse could happen if the tension in the top is lost due to sudden movements of the ship or any others reasons. A schematic showing initial buckle propagation from local collapse during S-Lay installation is presented in Figure 2-3.

The main function of the lay vessel is to provide tension to holds the suspended line pipes and to control its shape. The behavior of the long suspended pipeline is more like a cable rather than a beam. The water depth will determine the length of pipe, the tension required, as well as the curvature in the sagbend area. The deeper water, the bigger tension is required and this comes at a significant cost to the operations by requiring a modern installation vessel, Figure 2-4.

The objectives of installation design are:

- To avoid buckling failures in the overbend and the sagbend area;
- To keep the pipeline in the elastic regime.

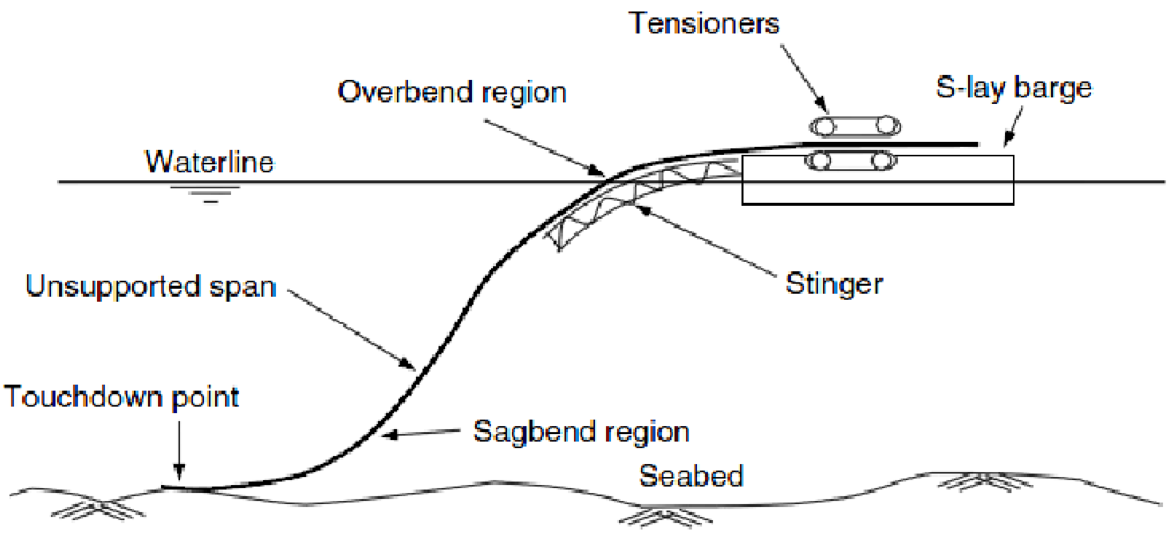

Figure 2-2: Pipe Laying Configuration Using the S-Lay Method, Ref [4]

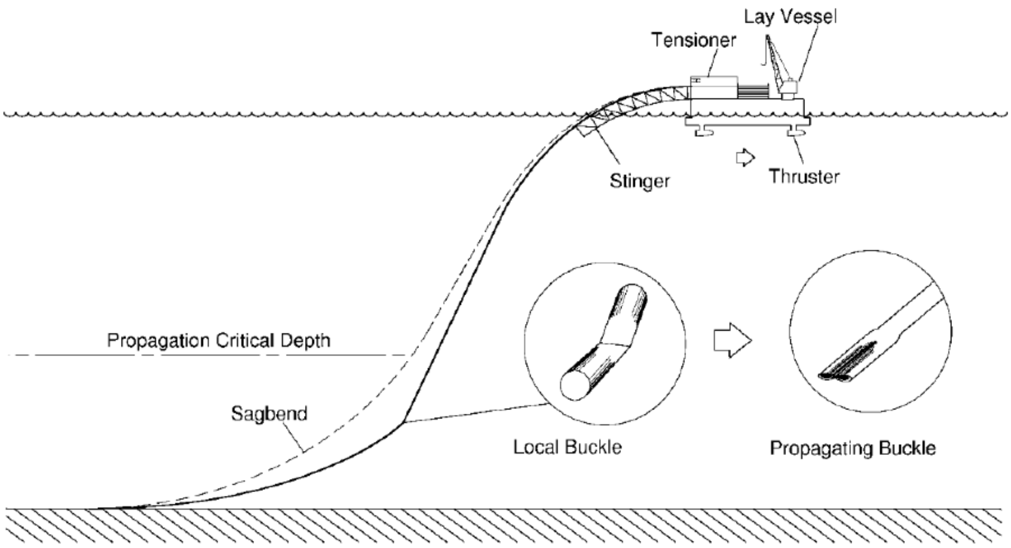

Figure 2-3: Buckling during S-Lay, Ref [26]

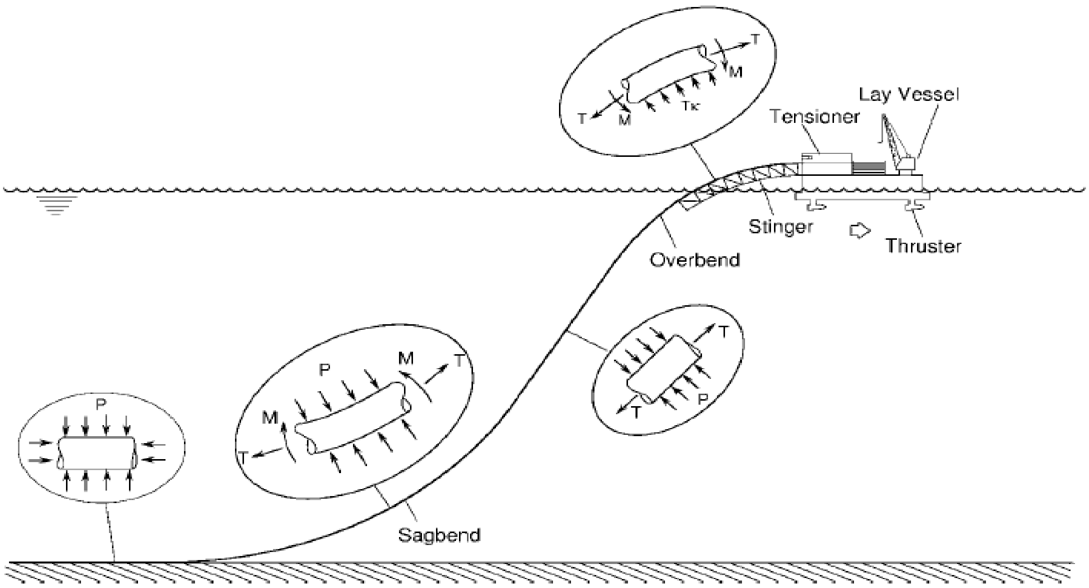

Figure 2-4: Schematic Representation of S-Lay Pipeline Installation and Associate Pipeline Loadings, Ref [26]

Some concerns for S-Lay method are the allowable strain in the overbend and the allowable bending moments in the sagbend region. The important parameters that control the maximum strain and maximum bending moment in the pipeline during installation are stinger length, stinger radius, tensioning capacity, and longitudinal trim of the vessel, Ref [18]. These parameters will control water depth at which a given pipeline can be laid.

Advantages

- The vessels have capability to instal pipelines with various diameters. No limitations to pipeline diameter and length;
- Minimum on-shore support required after the installation has begun;
- With the S-Lay method, some tasks such as welding, inspections, and field joint applications can be performed at the same time;
- Some contractors have good experiences with S-Lay method which is good for technical and economical aspects;
- Laying speed is quite high, even for large diameter pipelines, typically around 2 to 6 km/day, Ref [18]. The laying rate depends on seabed topography and waterdepth.

Disadvantages

- Limited installation depth due to limited vessel tension capacity;
- Long stinger is susceptible to hydrodynamic forces;
- Require clamping to pull the pipeline that can necessitate a heavy mooring system and high risk associated with a very long stinger subject to hydrodynamic forces. In addition, these options also could destroy the pipe coating;
- High probability of exceeding allowable strain in overbend area.

2.1.1.1 S- Lay Main Installation Component

Typically, S-Lay method is done by the following main installation equipments.

Tensioners

Tensioners are normally located close to the stern. The friction between rubber pads in the tensioning machines gives a tension on the pipe to control the curvature during laying down and to securing the integrity of the pipe. The required tension depends on water depth, length of the stinger, stinger radius, pipe size and weight. As the length and weight increase with increasing water depth, the required tension also increases. The tension capacity of the installation vessel will set a limitation to how deep the pipeline can be laid.

Transfer of tension between tensioner device and pipe is the most critical issue for some pipelay techniques, Ref [37]. The three methods for transfer of tension are:

- Long tensioners and low squeeze;
- Short tensioners and high squeeze;
- Shoulders with collars on the pipe.

The pipe coating area that is exposed to friction must be large enough in order to avoid damage; large tensioners with low squeeze can be used for this purpose.

In order to increase the possibility of pipeline installation in deeper water, tensioners can be applied after the overbend section. The benefit of this method is that lower strain will occur in the overbend areasince the combination of the tensioner force and bending effect can be avoided, Ref [37].

Stinger

The stinger is a frame structure with roller to support the pipelines during installation and create the pipe's curvature in the overbend area. Typically, some hinged members are built in the stinger to adjust the stinger curvature. Different type of vessels has different length of stinger, but for installation vessels in deepwater the length could be more than 100 m. For example Solitaire has a 140 m stinger length and the new S-lay vessel, Pieter Schelte has 170 m stinger length. In deeper water, a longer stinger length is required to maintain the strain less than the maximum acceptable limit criteria for the overbend section. Using short stinger can cause higher bending and pipeline damage during pipeline installation. The stinger should be able to withstand all the forces acting during operation, such as:

- Hydrodynamic forces due to waves and currents;
- Load from laying the pipeline;
- The stinger self weight;
- Load acting on the stinger due to vessel movements.

There are two types of stinger configurations that commonly used nowadays:

- Rigid stingers

This type of stinger have fixed configuration with certain length and an un-adjustable angle of curvature. The stinger is connected rigidly to the vessel, restricted to small movements only.

- Articulated stingers joined by hinges

Since this stinger uses hinge joints in each segment, the angle of its curvature radius can be adjusted as per required. An articulated stinger is more flexible for pipeline installation in deeper water by setting the curvature angle close to a vertical position. With this vertical position, the free span length can be reduced and furthermore this can decrease the stresses on the pipelines.

2.1.2 J-Lay Method

The suspended pipe length increases in deeper water conditions, and as a result an increasing tension requirement can not be avoided. This tough requirement is solved with the J-Lay method. This method is characterized by the pipeline leaving the vessel from nearly a vertical position and has J-shape on the way down to the sea floor. In the J-Lay method, the requirement to curvature in the over-bend can be reduced; therefore only a short stinger is required to withstand the load from the lay span. The horizontal tension required is smaller compared to the S-Lay method; its role is only simply to withstand the submerged weight of the pipes, to control stresses, and to maintain a satisfactory curvature in the sag-bend. In addition, the shorter suspended length in the J-Lay method can cause a significant reductions in the thruster power requirements.

However, due to the near vertical installation, the J-Lay method does not allow more than one welding and NDT station. To solve these limitations, longer pipe section are prepared to increase the efficiency of the operation. For this purpose, around four to six 12 m sections are welded on shore. After inspection, coating and the welding proceses, the long section of the pipe is lowered to sea bottom. Because of these aspects, the J-lay method has a slow production rate and the availability of welding and NDT technology for thick pipes may aggravate this situation.

In the J-Lay method, the pipeline must be designed to withstand the load condition that is illustrated schematically in Figure 2-5. From this figure, we can see that the pipe is exposed to high tension and reatively small external pressure in the surface area, and further down, the pressure increases and the tension decreases progresively. Furthermore, a propagation buckle also needs to be taken into considerations and it is necessary to install buckle arrestors to eliminate this problem.

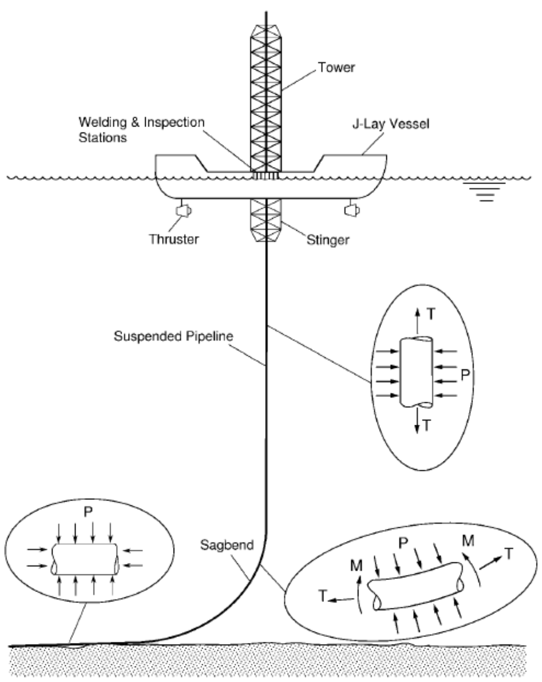

Figure 2-5: Schematic representation of J-lay pipeline installation and associated pipeline loading, Ref [26]

Advantages

- The required tension can be reduced as the pipe leaves the vessel near to vertical position. The tensionis only required to maintain bending at acceptable criteria for the sagbend region;
- No stingeris required. No overbend, therefore the limit criteria for this region can be eliminated;

- The free span is shorter compared to S-Lay method because lower lay tensions are resulting in reduced bottom tension in the pipe;
- Compared to S-Lay method, the J-lay method pipeline laying is more accurate because the location of the touchdown point is near to the vessel;
- Less vulnerable to the weather conditions due to a decreased area of interaction with the waves. Only a short length of the line close to the surface is exposed to wave motions because the pipelines are installed nearly atvertical position;
- Fast and relatively safe abandonment and recovery turn around.

Disadvantages

- The J-Lay method does not allow more than one welding and NDT station, causing the welding process to be much slower than the S-Lay method. In addition, the availability of welding and NDT technology for thick pipes may aggravate this situation;
- The effect of the weight and the height of the tower are needed to be taken into consideration for stability issues;
- The method is not suitable for installation in shallow water. In shallow water the pipe bend at the seafloor will be too sharp and cause pipeline damage;
- The capability of the J-Lay method in deep and very deep waters requires barges with dynamic positioning capabilities.

2.1.2.1 J-Lay Main Installation Equipment

Typically, the J-Lay method is carried out by the following main installation equipment:

Towers

The tower is a nearly vertical frame that supports the pipeline during J-Lay operations and consists of tensioners and work stations. The tower's orientation is normally between 0^o and 15^o relative to the vertical position. The location of J-Lay towers is close to the middle of the vessel for the DB 50 (McDermott's) or at the stern for S-7000 (Saipem), as shown in Figure 2-6, Ref [21].

Tensioners

For the J-Lay method, sufficient tension must be provided by the tensioner to avoid buckling in the sagbend area during installation. The submerged weight controls the required tension and the tension controls the curvature in the sagbend region. Some methods have been adopted by the J-Lay vessel owners to maintain a high tension. For example S-7000 has 525 t tension capacity using friction claps. Another system has been used by the Balder vessel to get 1050 t capacity. This system uses a collar that is welded to the upper end of the pipe and is held by the clamp at the end of the tower.

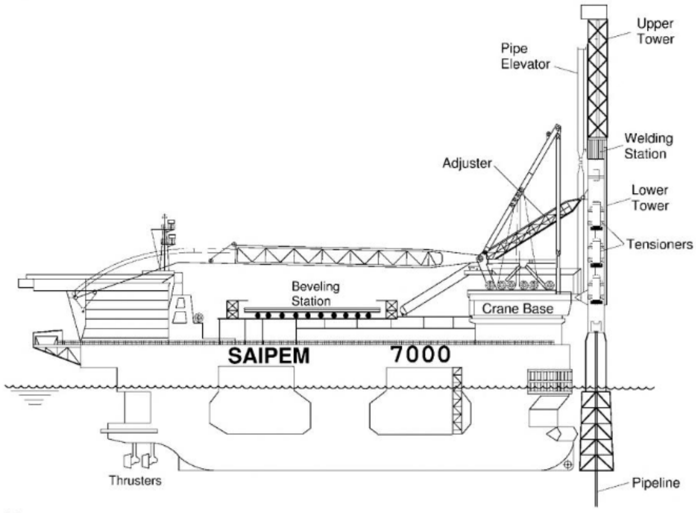

Figure 2-6: Installation Equipment on S-7000, Ref [26]

2.1.3 **Comparison between S-Lay and J-Lay**

Different pipelay configurations will cause different required top tension and critical area. For example, the required top tension for S-lay configuration is higher compared to J-Lay configuration. The critical area that becomes most concern for J-Lay configuration is the sagbend region while for S-Lay, the overbend region will become more critical than the sagbend. In the overbend region, the strain should satisfy the criteria stated in DNV-OS-F101 (2007). And for J-Lay, bending moment in the sagbend area should be less than allowable bending moments for appropriate water depth.

Comparison of S-Lay and J-Lay configuration is shown in Figure 2-7. Let's consider two pipelines with same properties and same liftoff angles being installed using S-Lay and J-lay method respectively. In these cases, the differences of required top tension for both methods can be calculated.

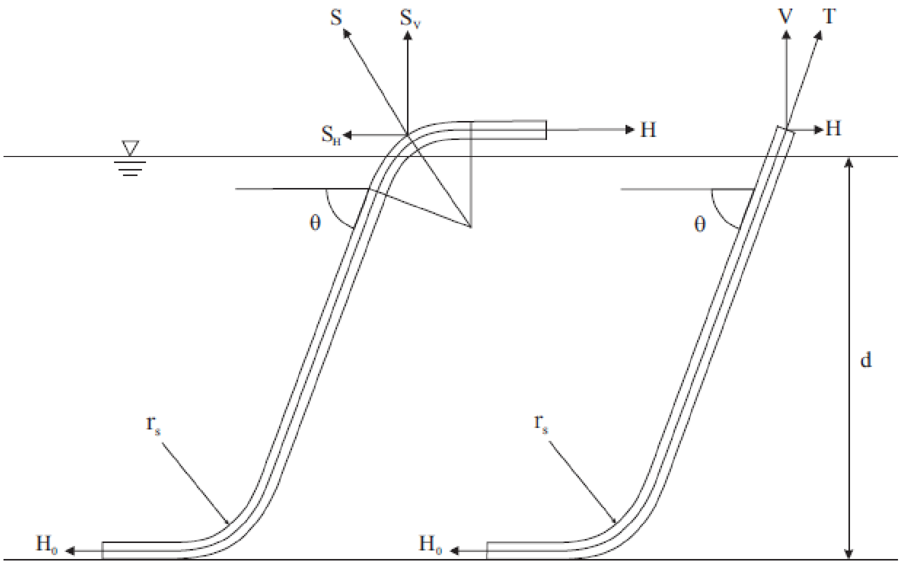

Figure 2-7: Comparison Tension for S-Lay and J-Lay Configurations, Ref [26]

Based on Figure 2-7, using static equilibrium method, the horizontal and vertical forces can be found:

$$H = T\cos\theta \tag{2.1}$$

$$V = T\sin\theta \tag{2.2}$$

And the required top tension is:

$$T = \sqrt{H^2 + V^2} \tag{2.3}$$

Since the submerged weight "w_s" is known based on pipe diameter and thickness, and the suspended length of pipe "s" is also known, the vertical tension can be calculated using the following formula:

$$V = w_s s \tag{2.4}$$

In the J-Lay case, horizontal forces "H" is only required to counteract horizontal tension at the touchdown point "H_o". And for the S-Lay case, the horizontal forces are required to counteract the combination of horizontal tension at touchdown point "H_o" and the horizontal component of stinger reaction forces "S_H". Therefore, since the horizontal forces for the S-Lay method are higher than for the J-Lay method, the required top tension for S-Lay is also higher than for J-Lay.

2.2 Catenary Analysis

The objective of introducing the catenary equation is to provide a validation of the model developed in this master thesis. The equation for the catenary is derived in this section.

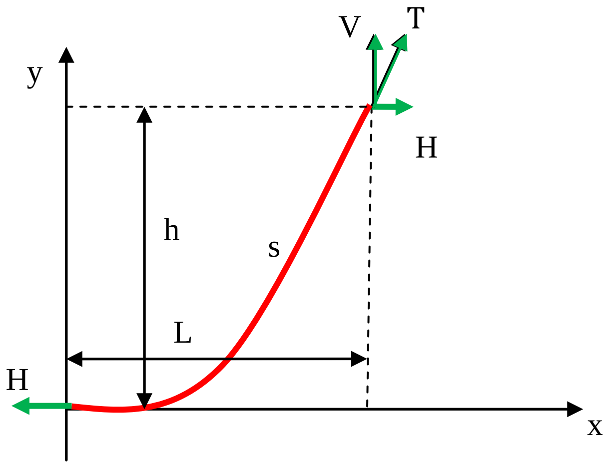

Figure 2-8 : The hanging chain, the catenary, Ref [14]

Based on information presented in Figure 2-8, the relation for distance to touchdown point "L"can be developed as follow:

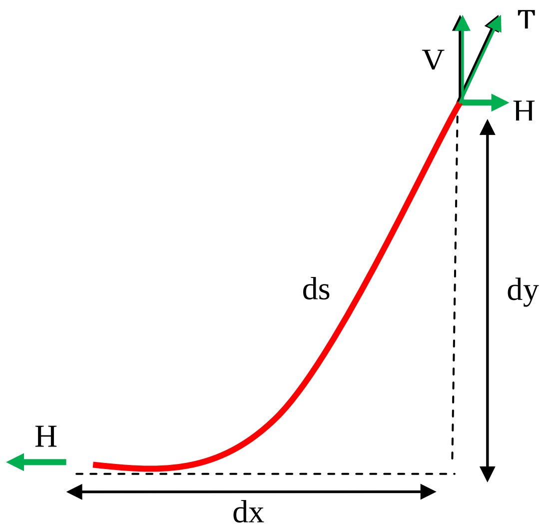

Figure 2-9 : The hanging chain, the catenary, Ref [14]

$$ds = \sqrt{dx^2 + dy^2}$$

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

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

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

And

$$dV = w_s ds$$

$$\frac{dV}{dx} = w_s \frac{ds}{dx}$$

Then :

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

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

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

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

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

$$\int_0^x \frac{w_s}{H} dx = \int_0^{y'} \frac{d(y')}{\sqrt{1 + (y')^2}} dx$$

$$\frac{w_s}{H} x = \text{arcsinh}(y')$$

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

The formula for the caternary is:

$$y = \frac{H}{w_s}\left(cosh \frac{w_s}{H} x - 1\right) \tag{2.5}$$

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

$$h = \frac{H}{w_s}\left(cosh \frac{w_s}{H} L - 1\right) \tag{2.6}$$

$$\frac{hw_s}{H} + 1 = cosh\left(\frac{w_s}{H} L\right)$$

$$\frac{w_s}{H}L = arccosh\left[\frac{hw_s}{H} + 1\right]$$

Therefore:

$$L = \frac{H}{w_s} arccosh\left[\frac{hw_s}{H} + 1\right] \tag{2.7}$$

From the previous page, we know that:

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

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

$$s = \frac{H}{w_s}\left(sinh\frac{w_s}{H}L\right) \tag{2.8}$$

Using equation (2.6) and (2.8) we can develop the formula to get equation (2.9) :

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

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

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

We know that :

$$sinh^2\alpha - cosh^2\alpha = -1$$

Hence :

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

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

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

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

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

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

And the equation for horizontal tension is :

$$H = \frac{w_s}{2h}(s^2 - h^2) \tag{2.9}$$

Therefore, the required top tension as found in the computer analysis can be compared with results of hand calculation using equation 2.9, equation 2.4 and equation 2.3.

The bending strain can be calculated with the following equation, Ref [32] :

$$\varepsilon = \frac{D}{2R} \tag{2.10}$$

Where :

ε Bending strain

D Outer Pipe Diameter

R Bending radius of the pipeline

The minimum over-bend radius is given by the equation, Ref [32] :

$$R = \frac{E.D}{2\sigma_0 DF} \tag{2.11}$$

Where,

σ_0 Minimum specified yield stress

DF Design factor, usually 0.85

E Elastic modulus of the pipeline

D Outside pipe steel diameter

According to equation (2.11) the bigger pipe diameter requires a larger stinger radius to avoid plastic deformation.

2.3 Pipe Material

Material type is determined based on various factors such as:

- Water depth;
- External hydrostatic pressure;
- Internal pressure;
- Fluid characteristics;

• Environmental conditions;

• Weight requirements;

• Installation analysis;

• Seabed topography;

• Cost

According to DNV-OS-F101 (2007), the following material characteristics shall be considered:

- Mechanical properties;
- Hardness;
- Fracture toughness;
- Fatigue resistance;
- Weldability;
- Corrosion resistance.

In order to ensure the compatibility of the pipeline, the following supplementary requirements are need to be identified in materials selection, Ref [13]:

1. Supplementary requirement S, sour service

A pipeline that transports fluid with hydrogen sulphide (H_2S) contents shall be evaluated for ‘sour service’ according to ISO 15156. For materials specified for sour service in ISO 15156, specific hardness requirements always apply, Ref [13].

2. Supplementary requirement F, fracture arrest properties

Supplementary requirements to fracture arrest properties are given in Sec.7 I200 DNV-OS-F101 (2007) and are valid for gas pipelines carrying essentially pure methane up to 80% usage factor, up to a pressure of 15 MPa, 30 mm wall thickness and 1120 mm diameter, Ref [13].

For conditions beyond these limitations, the calculation reflecting the actual conditions or full-scale test should be considered to determine the required fracture arrest properties.

3. Supplementary requirement P, Plastic Deformation

According to DNV-OS-F101 (2007), supplementary requirement (P) is applicable to linepipe when the total nominal strain in any direction from a single event is exceeding 1.0% or accumulated nominal plastic strainis are exceeding 2.0%.

For pipes that require supplementary requirement (P), tensile testing should be carried out in the longitudinal direction to satisfy DNV requirements.

4. Supplementary requirement D, Dimensional Requirements

Requirements for tolerances should be selected considering the influence of dimensions and tolerances on the subsequent fabrication/installation activities and the welding facilities to be used, Ref [13].

5. Supplementary requirement U, Utilization

The Purchaser may in retrospect upgrade a pipe delivery to be in accordance with Supplementary requirement U. Incase of more than 50 test units it must be demonstrated that the actual average yield stress is at least two (2.0) standard deviations above the SMYS. If the number of test units is between 10 and 20 the actual average yield stress shall as a minimum be 2.3 standard deviations above SMYS, and 2.1 if the number oftest units are between 21 and 49, Ref [13].

2.3.1 Material Grade

The steel should strong enough to withstand transverse tensile and longitudinal forces during operation and installation. Besides that, the pipelines should also be constructed by materials with sufficient toughness to resist impact loads and to tolerate defects. Weldability is critical problem, it is important to make sure that the pipeline is possible to be welded with the same strength and toughness as the rest of the pipe, and also due to economical reasons, Ref [36].

The properties mentioned above are determinied by the steel grades. Different steel grades will have different strength and characteristics.

For pipeline design, steel grade X65, from API 5L (2004) are normally used. X70 steel grade has been used in offshore projects, i.e. for the planned Oman India Gas Pipeline project and the installed Medgaz pipeline at 2155 m water depth, Ref [10]. This project used 24 inch pipe diameter with constant internal diameter. Steel grades higher than X70 are only used in onshore project so far. There are around five onshore projects that are identified using X80 steel grade, i.e. Ref [6]:

- Germany, Mega II Pipeline (1985);
- Czechoslovakia (1986);
- Alberta Canada, Empress East Compressor Station (1990);
- Germany Schlüchtern to Wetter, Ruhrgas (1993);
- Alberta Canada, Mitzihwin Project (1994).

Higher grades are currently under active development. X100 grades are being actively developed by several companies, Ref [6].

Carbon Steel

The carbon steel pipelines are alloyed with various elements such as carbon, manganese, silicon, phosphorus and sulphur. For modern pipelines the amount of carbon are varying from 0.10% to 0.15%, between 0.80% and 1.60% manganese, under 0.40% silicon, less than 0.20% and 0.10% phosphorus and sulphur content, and under 0.5% copper, nickel and chromium, Ref [8]. The effect of alloying elements with certain composition into the steel material will determine the steel grade, and hereby the strength, weldability, toughness and ductility of the pipe.

Increasing the material resistances to corrosions can be done by applying corrosion resistant materials such as martensitic stainless steels, duplex stainless steels, super duplex stainless steels, (super) austenitic stainless steels and nickel alloys. These are known as Corrosion Resistant Alloys (CRA). The CRA are used for internal corrosion resitence while Cathodic Protection (CP) and external coating are acting as external corrosion resistances. The CRA that is used in one location could be different from another location and depends on the type of transported fluid.

2.3.1.1 Advantages of High Strength Steel

The following lists are described the advantages of using high strength steel in pipeline industry.

1. Potential Cost Reduction

Higher wall thickness is required to withstand internal and external pressure especially in deep and ultra deep water conditions. Using high strength material grade can reduce the required wall thickness and can hereby increase the chance to reduce the overall cost of the project. This cost reduction due to decreasing of wall thickness can be achieved because of the pipe manufacturing and construction processes. Furthermore, some aspects such as transportation, welding consumables, welding equipment rental and overall lay time could possibly give contribution to reduce the cost.

Price (1993), Ref [39], considered both the direct and indirect consequences of using a high strength steel, and estimated a 7.5% overall project saving for a 42-inch offshore line laid with X80 instead of X65.

Using non standard pipeline diameter and thickness can also be considered as one of alternative solutions to reduce the cost. The optimum pipe diameter and thickness based on design calculation or modeling is more effective to be choosen instead of selecting the larger standard size.

2. Wall Thickness and Construction

As mentioned above, using higher steel grade will reduce the wall thickness requirement. Thinner wall thickness will reduce construction/lay time because a thinner wall requires less field welding. Further impact on reducing wall thickness is the lay barge requirement. This is related to weight of the pipe and availability of vessel with enough tension capacity.

3. Weldability

Higher wall thickness gives some difficulties related to weldability. The cooling rate of weld will increase for higher wall thickness. The increasing of the cooling rate causes potensial problems with hardness, fracture toughness, and cold cracking (if non-hydrogen controlled welding processes are used). In other words, the effect of increasing the material grade will reduce the cooling rate of the weld.

4. Pigging Requirements

It is required to have enough space for the pigging purpose especially in deep water developments. Some types of pigging tools will limit the possibility to use thicker wall thickness. Therefore, using thinner wall thickness as the impact of higher strength material will give advantages for pigging operations.

2.3.1.2 Disadvantages of High Strength Steel

The disadvantages of using high strength steel in the pipeline industry are:

1. Increase in material cost per volume

The higher strength material is more expensive than ordinary material grade. Therefore it is important to compare the increasing cost due to the increase in material grade with cost reductions due to decreasing in total required wall thickness.

2. Limited Suppliers

Using material grades above X70 represents challenges to the pipeline industry because of the limitations of proven suppliers available in the world.

3. Welding Restrictions

Welding to achieve the best quality may be takes some times due to some restriction and complex control for higher material grade. Besides that, limited experience of welding high material grade especially for offshore project also need to be considered if selecting higher material grade.

4. Limited Offshore Installation Capabilities

The limited number of pipelay installation contractor with proven experience of welding X70 represents another challenge to choose higher material grade.

5. Repair Problems

There is no experience for pipeline repair using hyperbaric welding for higher material grade so far. Therefore some studies are required in order to get better understanding of this issue. Another alternative to repair a pipeline is using the hot tap method, but same problem as with the first alternative is present; there is no experience for high strength material in offshore developments.

2.4 Plasticity during Installation

Some studies to support the idea to exceeding elastic proportionality for stress-strain behavior in the over-bend have been done. In some circumstances, this can be done safely.

Strain based design is one method allowing the pipe to go beyond yield. The following lists are strain criteria based on DNV-OS-F101 (2007):

- Strain requirements
  - If total nominal strain ≤ 0.4 %, there is no additional requirement
  - If total nominal strain > 0.4 %, ECA should be implemented
  - If total nominal strain > 1.0 %, additional material tests, i.e. supplement requirement P is required
- Plastic Strain degrades the fracture resistance of material each time the pipe is yielded. Additional material tests are also required if the accumulated plastic strain exceeds 2.0 %.
- Reeling requires ECA and additional testing.

Strain based design can be shown graphically in Figure 2-10.

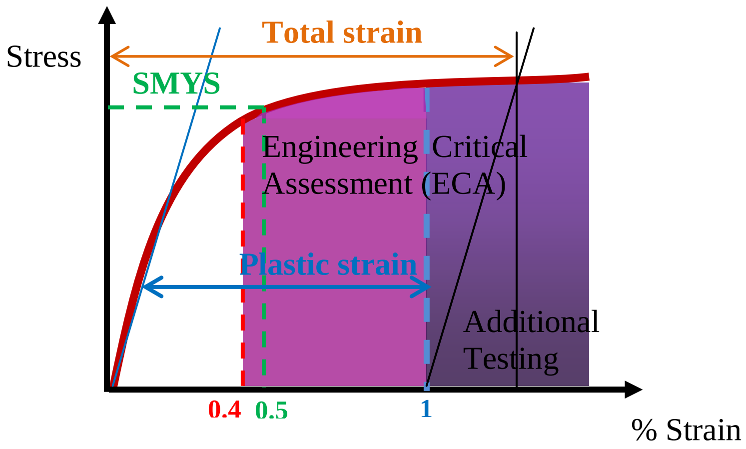

Figure 2-10: Stress and Strain Diagram, Ref [20]

The process of strain based design is shown in the following flow chart, Figure 2-11.

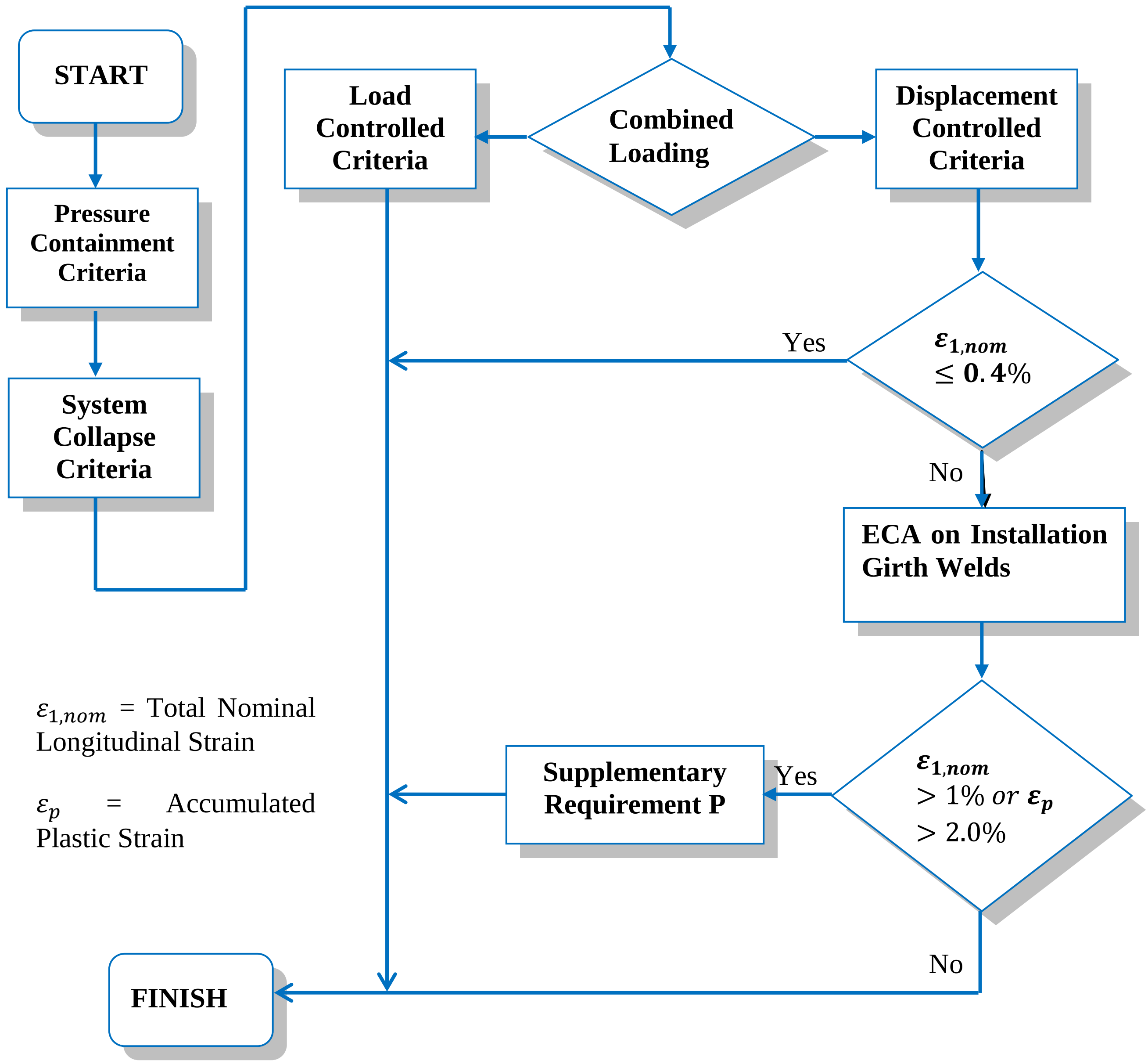

Figure 2-11: Flow Chart of Strain Based Design, Ref [20]

When the pipe yields plastically, the effect due to that strain will be cumulative. Permaent deformation will happen. If the total nominal longitudinal strain exceeds 0.4 % an engineering critical assessment (ECA) must be performed.

Furthermore, if the total nominal strain exceed 1.0 % or if the accumulated plastic strain more than 2 %, the additional requirements, i.e. supplementary requirement P need to be satisfied. This supplementary requirement determines the fracture toughness of the material and particularly the welds. Additional test need to be carried out. The tests include crack tip opening displacement (CTOD) on specimens of the weld. The test is based on the largest weld defects allowed by the welding specification.

With reeled pipe, the accumulated plastic strain always exceeds 2.0%. Usually, the accumulated plastic strain is close to 10%. But for the S-Lay and J-Lay method, it is very rare to reach plastic limits. The reason is because the local buckling due to combination of external pressure and bending moment is happened before the plastic limit can be achieved.

2.4.1 **Allowable Strain of a pipeline**

Some experiences have proven that the steel pipeline is able to bend exceeding the yield stress without reducing the capacity to withstand internal pressure. These experiences can be seen in the reeling process where the strain can reach 2-3%. The yielding point for pipelines is defined as the stresses at which the total strain is 0.5%, Ref [34]. The total strain is a combination of elastic and plastic strain. Based on DNV OS F-101, the total strain of 0.5% for 415 grade C-Mn Steel consist of 0.2% elastic strain and 0.3% plastic strain, Ref [34].

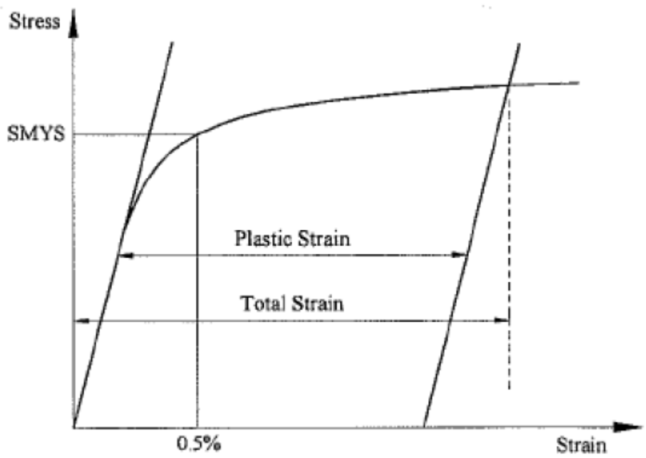

Figure 2-12: Reference for Plastic Strain Calculation, Ref [13]

Normally the proportional limit for pipeline is about 75% yield stress and it is tolerated up to 85% the yield stress. Because of this, even in normal laying condition, it is normal if the pipeline experience plastic deformation. This is the reason that in practice it is common to base the criteria for dimensioning of laying parameters on accepted strains and not on stresses, Ref [34].

2.4.2 **Special Strength Conditions during Pipeline Laying**

In S-Lay method, the pipeline doesn't contact directly to the stinger but will rest on some rollers. Because of this the friction force between the pipeline and the stinger is decreased and the bending moment will be highest in the roller positions and minimum in the mid span between two rollers. Figure 2-13 presents the moment diagram in the rollers position. The strain in the roller position might be exceed the proportional limit and causes plastic deformation on the pipeline.

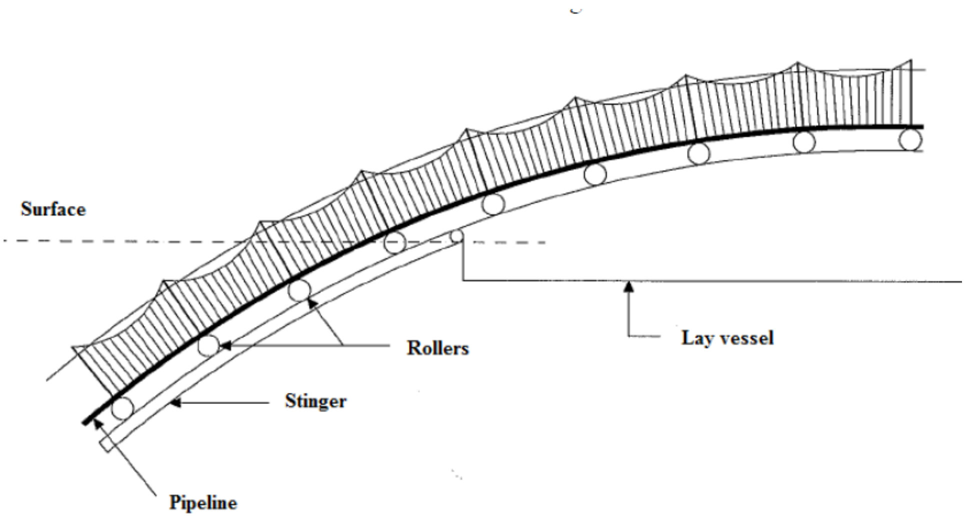

Figure 2-13: Moments as the Pipeline Passes Rollers on the Stinger, Ref [34]

2.4.3 Exceeding the Bending Strength

High external pressure at pipelines which are installed in deep water, lead to the requirement of thicker wall thickness. 'Thick walled pipelines' terms is usually used for pipeline with less than 40-50 of diameter/wall thickness ratio. A 'thick walled pipelines' typical moment - curvature diagram is shown in Figure 2-14.

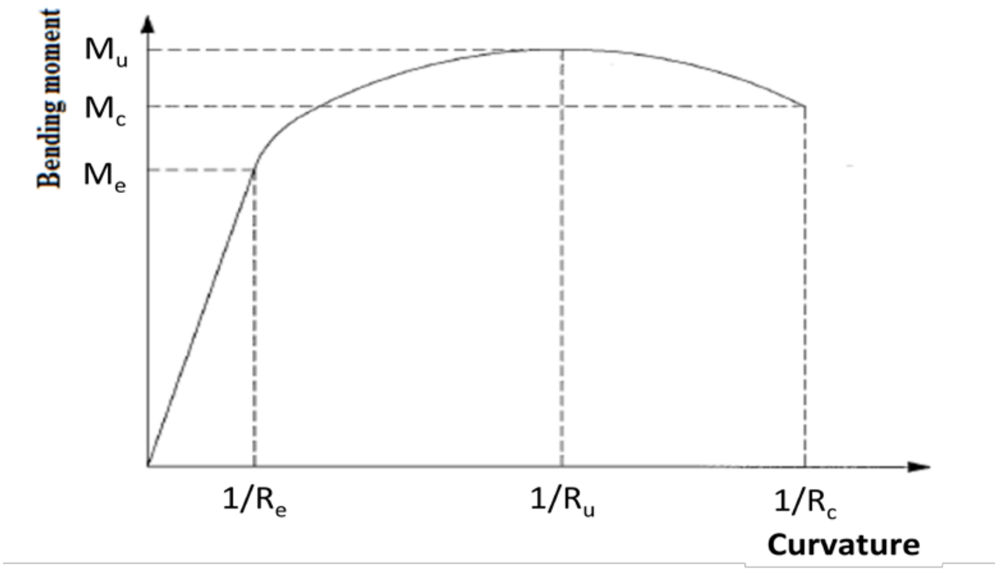

Figure 2-14: Typical Moment – Bending Curvature Diagram, Ref [34]

Figure above shows R_e as the bending radius and $1/R_e$ as bending curvature where the plastic deformation started. Ovalization will be occured to the pipelines' cross section when the pipeline is bent even bigger. If it continues, the maximum moment (M_u) will be reached with R_u as the correspond bending radius. The curvature of the pipeline capacity will be reached if the bending radius is further reduced with R_c as the correspond bending radius. Once this degree of curvature achieved, local buckling will occur at the compressive side of the pipelines. For ‘thin wall thickness’ pipeline’s cross section with ratio of diameter / wall thickness greater than 250 to 300, the local buckling is happened in the elastic zone, Ref [34].

Curvature correspond to R_c does not always have to be larger than the curvature correspond to R_u. To avoid local buckling, the smallest curvature of these two should be considered, Ref [34].

The bending radius in overbend and sagbend are important to be kept large enough as this will increase the safety to avoid local bukcling , Ref [34].

2.4.4 **Residual Curvature**

Most of the time the pipeline will not rest on the seabed in perfectly flat condition due to surface unevenness, etc. The residual curvature after installation might be tolerated due to this uneven condition.

When laying on the seabed, the pipeline has axial force similar to installation horizontal tensile force. If there is residual curvature, this axial force will help to straighten the pipeline. Nevertheless, during pipeline repair operation, this axial force might cause some problems.

Theoretically, pipeline can be straightened using the bending forces in the sagbend if plastic deformation occurs in the overbend.

The relation of moment and strain in the pipeline from the stinger to the seabed that is experiencing plastic deformation is presented in Figure 2-15.

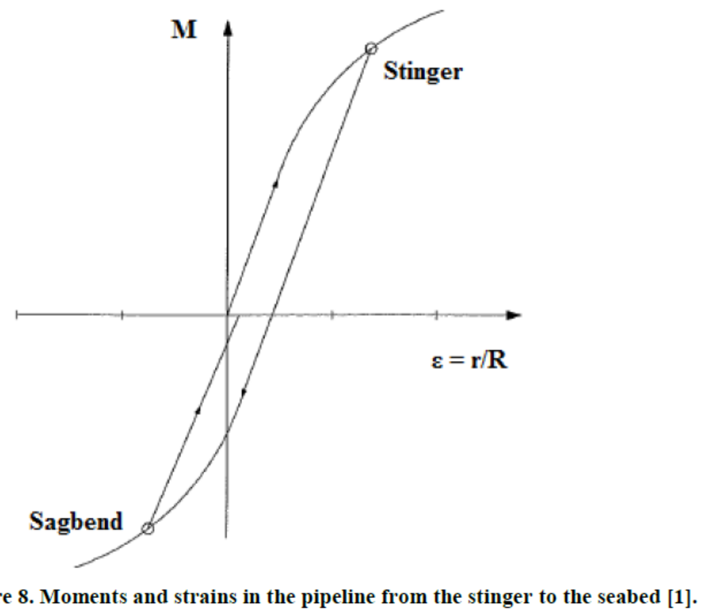

Figure 2-15: Moments and Strains in the Pipeline from the Stinger to the Seabed, Ref [34]

The figure above shows some residual curvature that is occured after the stinger location. A large moment added to the pipeline in the sagbend. The moment can help straighten the pipeline, however it also can create residual curvature in opposite direction if the value is very large.

A large ovalisation will result the reduction of pipeline structural capacity. At certain location/condition such as artificial supports, shoulders of free span and settlemet at support, the point load may accur. Furthermore, according to DNV, the ovalisation should be investigated for the point load on each section of the pipe.

Ovalisation issues can be reduced by increasing the pipeline wall thickness. Increasing the pipeline bending curvature will lead the increment of ovalisation more than proportionlaly. Some of the ovalisation will be in plastic if the curvature in plastic strain, which means that residual ovalisation will remain eventhough the stress has been removed. The maximum ovalisation for pipeline with a large wall thickness will be less than 0.5 to 1 % if the strains are less than 0.5 %; which means that the residual ovalisation is very small after stress has been removed Ref [34].

Large bending radius on the pipeline will cause ovalisation. Ovalisation is a condition when the pipeline cross section is not a perfect circle but will be flattened by some degree.

CHAPTER 3 DESIGN CRITERIA AND METHODOLOGY

3.1 Design Codes

The following standards and recommended practices should be applied for pipeline installation in deep water and ultra-deep water conditions:

- DNV-OS-F101 (2007) Submarine Pipeline Systems;
- DNV-RP-F109 (2007) On-bottom Stability Design of Submarine Pipelines.

3.2 Design Criteria

3.2.1 Loads Criteria

The purpose of categorizing the different loads is to give informations about the load effects and their uncertainties.

3.2.1.1 Functional Loads

Functional loads are loads that occur due to the physical characteristics of the pipeline system and its intended use.

According to DNV-OS-F101, Ref [13], the following phenomena are the minimum requirements that need to taken into considerations when establishing functional loads :

- Weight;
- external hydrostatic pressure;
- internal pressure;
- temperature of contents;
- pre-stressing;
- reactions from components (flanges, clamps etc.);
- permanent deformation of supporting structure;
- cover (e.g. soil, rock, mattresses, culverts);
- reaction from seabed (friction and rotational stiffness);
- permanent deformations due to subsidence of ground, both vertical and horizontal;
- permanent deformations due to frost heave;
- changed axial friction due to freezing ;
- Possible loads due to ice interference, e.g. bulb growth around buried pipelines near fixed points (in-line valves/tees, fixed plants etc.), drifting ice etc;
- loads induced by frequent pigging operations.

3.2.1.2 Environmental Loads

Environmental loads are the loads on the pipeline caused by the effects of surrounding environment and that are not otherwise specified as functional or accidental loads, such as:

- Static load, water pressure;
- Wind loads;
- Hydrodynamic loads including currents;
- Ice loads.

3.2.2 Load Combinations

The combinations of all different loads that can affect the integrity of the pipeline system can be calculated by the following equations:

$$M_{sd} = M_F \gamma_F \gamma_C + M_E \gamma_E + M_I \gamma_F \gamma_C + M_A \gamma_A \gamma_C \tag{3.1}$$

$$S_{sd} = S_F \gamma_F \gamma_C + S_E \gamma_E + S_I \gamma_F \gamma_C + S_A \gamma_A \gamma_C \tag{3.2}$$

$$\varepsilon_{sd} = \varepsilon_F \gamma_F \gamma_C + \varepsilon_E \gamma_E + \varepsilon_I \gamma_F \gamma_C + \varepsilon_A \gamma_A \gamma_C \tag{3.3}$$

Where,

M_{sd}	Design moment
M_F	Moment from functional loads
M_E	Moment from environmental loads
M_I	Moment from interfere loads
M_A	Moment from accidental loads
S_{sd}	Design effective axial force
S_F	Axial force from functional loads
S_E	Axial force from environmental loads
S_I	Axial force from interfere loads
S_A	Axial force from accidental loads
ε_{sd}	Design compressive strain
ε_F	Strain from functional loads
ε_E	Strain from environmental loads
ε_I	Strain from interfere loads

ε_A	Strain from accidental loads
γ_F	Load effect factor for functional load
γ_C	Conditional load effect factor
γ_A	Load effect factor for accidental load

The load combinations should be checked for each different design limit states as per Table 3-1. The ULS design load combinations are different due to differencies in the local buckling limit states.

Table 3-1: Load Effect Factors and Load Combinations, Ref [13]

Limit State/Load Combination	Design Load Combination		Functional Loads [1]	Environmental Load	Interference Loads	Accidental Loads
			γ_F	γ_E	γ_E	γ_A
ULS		System Check [2]	1.2	0.7		
		Load Check	1.1	1.3	1.1	
FLS			1.0	1.0	1.0	
ALS			1.0	1.0	1.0	1.0

1) If the functional load effect reduces the combined load effects, γ_F shall be taken as 1/1.1
2) This load combination shall only be checked when system effects are present, i.e. when the major part of the pipeline is exposed to the same functional load. This will typically only apply to pipeline installation.

The condition load effect factors in Table 3-2 are applied to calculate load combinations as presented in equations (3.1) to (3.3).

Table 3-2: Condition Load Effect Factors, Ref [13]

Condition Load Effect Factor, γ_C	
Condition	γ_C
Pipeline Resting on Uneven Seabed	1.07
Continuously Stiff Supported	0.82
System Pressure Test	0.93
Otherwise	1.00

3.2.3 Material Resistance Factor

According to the Load and Resistance Factor Design (LFRD) method, the material resistance factor should be taken into account for safety reasons. The material resistance factor (γ_m) is categorized as per DNV-OS-F101 requirement as shown in Table 3-3.

Table 3-3: Material Resistance Factor, Ref [13]

Material Resistance Factor, γ_m		
Limit State Category	**SLS/ULS/ALS**	**FLS**
γ_m	1.15	1.00

3.2.4 Safety Class Definition

Pipeline installation can be classified as low safety class. The reason is because there are not many human activities during pipeline installations and usually pipeline installations have low risk of human injuries and low environment impacts. But if the installation is exposed to higher risk to the personnel and environmental damage, a higher safety class shall be implemented. The safety class resistance factor (γ_{sc}) is presented in Table 3-4.

Table 3-4: Safety Class Definition, Ref [13]

Safety Class Resistance Factors. γ_{SC}			
Safety Class	**Low**	**Medium**	**High**
Pressure Containment	1.046	1.138	1.308
Other	1.04	1.14	1.26

3.2.5 Material grades

The material grades of the pipeline should refer to API standard. The following table shows the Specified Minimum Yield Strength (SMYS) and Specified Minimum Tensile Strength (SMTS) for grade X42 to X80.

Table 3-5: API Material Grades, Ref [13]

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

Note: Ksi=6.895 MPa; 1 MPa =0.145 ksi;1 ksi=1000 psi

3.2.6 Characteristic material properties

Based on DNV 2007, the following equations for characteristic material strength f_y and f_u are used in the limit state criteria:

$$f_y = (SMYS - f_{y,temp})\alpha_u \quad (3.4)$$

$$f_y = (SMYS - f_{y,temp})\alpha_u \quad (3.5)$$

Where :

$f_{y,temp}$; $f_{u,temp}$: are the de-rating value due to temperature, see Figure 3-1

α_u : Is the material strength factor, see Table 3-6

Table 3-6: API Material Strength Factor, α_u, Ref [13]

Material Strength Factor, α_u		
Factor	**Normally**	**Supplementary Requirement α_u**
α_u	0.96	1.00

Based on the chart shown in Figure 3-1, C-Mn steel shall be considered for the temperature above 50° C and material 22 Cr and 25 Cr need to be considered for temperatures above 20° C.

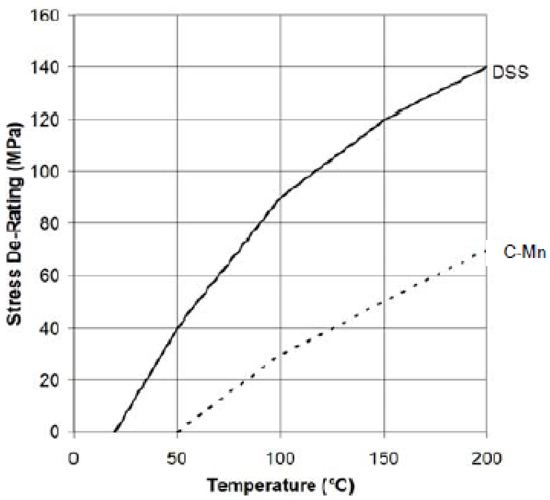

Figure 3-1 : De-rating Values for Yield Stress of C-Mn and Duplex Stainless Steel, Ref [13]

3.2.7 Maximum fabrication factor

To accommodate the different strengths for pipes in tension and compression due to the manufacturing processes, a fabrication factor is normally used for pipeline design. The value of the maximum fabrication factor presented in Table 3-7 can be used in case there are no detailed informations available regarding the manufactoring process.

Table 3-7: Maximum Fabrication Factor, Ref [13]

Maximum Farication Factor, α_{fab}			
Pipe	**Seamless**	**UO&TRB&ERW**	**UOE**
α_{fab}	0.96	0.93	0.85

3.3 Limit State

A Limit State is the condition where the structure is not able to satisfy the requirements. Limit states for pipelines can be categorized as, Ref [13]:

- Serviceability Limit State (SLS): Pipeline must be able to continue its function when subjected to routine loads;
- Ultimate Limit State (ULS): A condition that if the criterion is exceeded, it can endanger the integrity of the pipeline system;
- Accidental Limit State (ALS): the pipeline shall be able to withstand accidental or unplanned loads such as dropped object, fire, impact from fishing trawl, and so on. ALS consition also known as ULS condition due to accident (in-frequent) loads;
- Fatigue Limit State (FLS): The pipeline needs to be designed to sustain accumulated cyclic dynamic loads during the operations.

Based on DNV-OS-F101, the design load (L_{Sd}) shall not exceed the resistance factor design (R_{Rd}). It can be expressed by following equation:

$$f\left(\left(\frac{L_{sd}}{R_{RD}}\right)\right) \leq 1 \qquad (3.6)$$

3.3.1 Ovalization

The condition that is characterized by changing the pipeline cross section from its original shape (circle) into an elliptic shape is known as ovalization. During the pipeline installation process, the pipe will be exposed to bending, either in the elastic or plastic regime. If it is occured in the plastic regime, the pipeline cross section will experience permanent deformations. This condition will reduce the pipe's resistance to external pressure that can cause the collapse and pigging problem for the pipeline.

Mechanism of ovalization is shown in Figure 3-2. Figure 3-2 (a) shows the longitudinal stress phenomena due to combination of bending and external pressure. The lower part will experience tension while the upper part will experience compression. This condition will cause ovality of the pipe, see Figure 3-2 (b) for illustration.

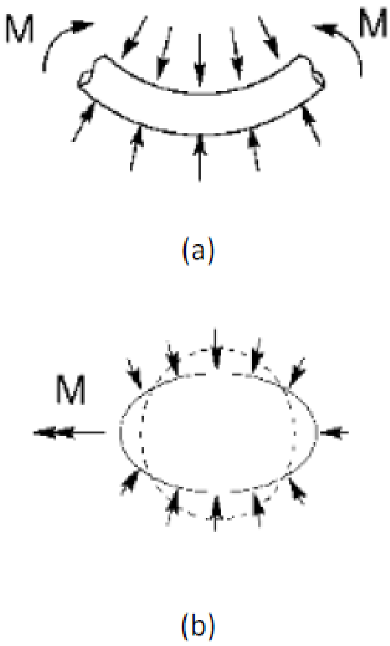

Figure 3-2 : Ovalizationduring Bending,Ref [26]

$$f_0 = \frac{D_{max} - D_{min}}{D} \tag{3.7}$$

Where:

f_0	the out of roundness of the pipe, prior to loading (Initial ovality). Not to be taken < 0.005, Ref [13]
D_{max}	Greatest measured inside or outside diameter
D_{min}	Smallest measured inside or outside diameter
D	Outer diameter of the pipe

Based on DNV-OS-F101 (2007), the out of roundness tolerance from fabrication together with flattening due to bending should not exceed 3%, except when there are some special considerations, such as if:

- A corresponding reduction in moment resistance has been included;
- Geometrical restrictions are met, such as pigging requirements;
- Additional cyclic stresses caused by the ovalization have been considered;
- Tolerances in the relevant repair system are met.

Any point along the pipeline subjected to a point load, such as at freespan shoulders, artificial supports, and support settlements must be checked for ovalization.

3.4 Stability and Wall Thickness Design Criteria

3.4.1 On BottomStability

The pipeline should not move from its installed position even under extreme loading conditions. To satisfy this requirement, the pipeline must be supported, anchored in an open trench or be buried. These conditions do not include permissible lateral or vertical movements, thermal expansion, and a limited amount of settlement after installation.

For on-bottom stability purposes, the submerged weight of the pipeline should be higher than the buoyancy loads.

According to DNV (2007), the following criteria shall be met to ensure vertical stability:

$$\gamma_w \frac{b}{w_s+b} \leq 1.0 \tag{3.8}$$

Where:

$$b = \rho_w g \pi \frac{D^2}{4} \tag{3.9}$$

γ_w Safety factor. Can be applied as 1.1 if a sufficiently low probability of negative buoyancy is not documented

w_s Pipe submerged weight per unit length

b Pipe buoyancy per unit length

D Outer diameter of the pipe including all coatings

g Gravity acceleration; 9.81m/s^2

ρ_w Mass density of water; 1025 kg/m^3 for sea water

3.4.2 Local Buckling

In deep water conditions, the pipeline may experience local buckling because there is high external hydrostatic pressure. Local buckling initially will occur in the weakest point of the pipeline and lead to pipe collapse failure. As a result, ovalization will occur and lead to buckling propagation especially in deep water conditions.

Based on DNV (2007) any locations along the pipeline should satisfy the following criteria:

$$P_e - P_{min} \leq \frac{P_c(t_1)}{\gamma_m \gamma_{SC}} \tag{3.10}$$

Where:

P_{min} Minimum internal pressure that can be sustained. Usually zero for as-laid pipeline.

P_e External pressure

γ_m Material resistance factor; see Table 3-3 of this thesis

γ_{SC} Safety class resistance factor; see Table 3-4 of this thesis

P_c Characteristic collapse pressure

t_1 Characteristic wall thickness; $t - t_{fab}$ prior to operation

$$(P_c(t) - P_{el}(t))(P_c(t)^2 - P_p(t)^2) = P_c(t)P_{el}(t)P_p(t)f_0\frac{D}{t} \quad (3.11)$$

Where :

P_{el} Elastic Collapse Pressure

$$P_{el}(t) = \frac{2E\left(\frac{t}{D}\right)^3}{1-\nu^2} \quad (3.12)$$

P_p Plastic Collapse Pressure

$$P_p(t) = f_y\alpha_{fab}\frac{2t}{D} \quad (3.13)$$

α_{fab} Fabrication factor; 0.85 for UOE pipes

f_0 Initial ovality (out-of-roundness)

t_1 Characteristic wall thickness; t-t_{fab} prior to operation. t shall be replaced with t_1 in the above formulas due to possible failure where low capacity-system effects arepresent.

t_{fab} Fabrication thickness tolerance for wall thickness; 1.0 mm

D Outer diameter of the pipe

E Young's Modulus

ν Poisson's ratio

3.4.3 **Buckle Propagation**

Buckle propagation may be caused by local buckling, a dent, denting during installation or due to corrosion of the steel wall. Propagation buckling may be eliminated if the pipeline is strong enough to resist the local buckling effects or by providing buckle arrestors. Pipelines subjected to both bending and external pressure are vulnerable to propagation buckling phenomena. According to Omrani, Gharabaghi and Abedi (2009), Ref [35], the external collapse propagation pressure is smaller compared to the external collapse pressure required to collapse locally, typically only 15-20%. To satisfy the propagation buckling requirements by increasing the wall thickness are very expensive. This is because the pipeline design to avoid propagation buckling is too conservative, therefore other solutions could become alternatives to avoid damagesby propagations. The probability of the occurence of propagating buckling in long distance can be decreased by installing buckle arrestors in the pipelines (Figure 3-3).

$$P_e < \frac{P_{pr}}{\gamma_m \gamma_{SC}} \tag{3.14}$$

Where:

γ_m	Material resistance factor; see Table 3-3
γ_{SC}	Safety class resistance factor; see Table 3-4
P_e	External pressure
P_{pr}	Propagating pressure

$$P_{pr} = 35 f_y \alpha_{fab} \left(\frac{t_2}{D}\right)^{2.5}, \frac{D}{t_2} < 45 \tag{3.15}$$

f_y	Characteristic yield stress
α_{fab}	Fabrication factor
t_2	Characteristic wall thickness; *t* for pipelines prior to installation
D	Outer diameter of the pipe

3.4.4 **Buckle Arrestor**

Bending stiffness increases by providing buckle arrestors. These buckle arrestors are placed at some intervals along the pipeline, then the pipeline damage due to collapse propagation can be reduced.

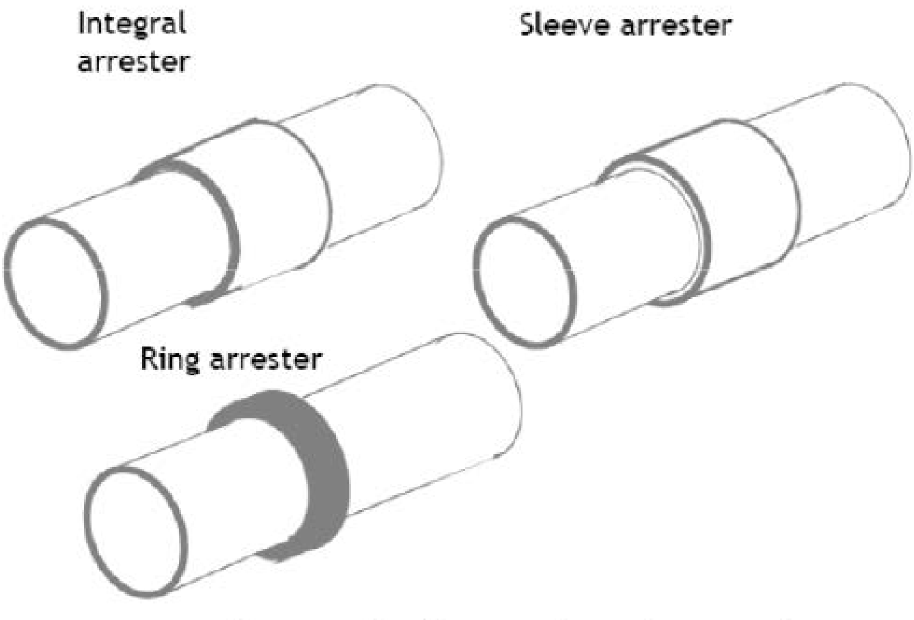

Figure 3-3 : Three Types of Buckle Arrestors,Ref [26]

According to DNV (2007), Ref [13], an integral buckle arrestor can be designed based on the following equation:

$$P_e \leq \frac{P_x}{1.1\gamma_m\gamma_{SC}} \qquad (3.16)$$

Where:

γ_m	Material resistance factor; see Table 3-3 of this thesis
γ_{SC}	Safety class resistance factor; see Table 3-4 of this thesis
P_e	External pressure
P_x	Crossover pressure

$$P_x = P_{pr} + \left(P_{pr,BA} - P_{pr}\right)\left[1 - EXP\left(-20\frac{t_2 L_{BA}}{D^2}\right)\right] \qquad (3.17)$$

Where:

$P_{pr,BA}$	Propagating buckle capacity of an infinite arrestor
P_{pr}	Propagating pressure
L_{BA}	Buckle arrestor length
t_2	Characteristic wall thickness; t for pipelines prior to operation

The capacity of the buckle arrestor depends on, Ref [13]:

- The propagation buckle resistance from the adjacent pipe;
- Propagating buckle resistance of an infinite buckle arrestor;
- The arrestor length.

3.5 Laying Design Criteria

The pipeline installation analysis should be performed based on DNV-OS-F101 (2007) for Submarine Pipeline System.

3.5.1 Simplified Laying Criteria

For preliminary design of local buckling, the simplified laying criteria can be used according to DNV-OS-F101 2007 section 13 H300. Limit states for concrete crushing, fatigue and rotation should be checked as additional requirements.

Overbend

Based on DNV-OS-F101-2007, for static loading the strain in the overbend region should not exceed the criterion I in Table 3-8. The strain should consider the effects of bending, axial loads, and local roller loads. Effects due to varying stiffness (e.g. strain concentration at field joints or buckle arrestors) do not need to be included. For static plus dynamic loading, the strain in the overbend region should not exceed the criterion II in Table 3-8. The strain should consider all effects, including varying stiffness due to field joints or buckle arrestors.

Table 3-8: Simplified Criteria for Overbend, Ref [13]

Simplified Criteria for Overbend				
Criterion	X70	X65	X60	X52
I	0.270 %	0.250 %	0.230 %	0.205 %
II	0.325 %	0.305 %	0.290 %	0.260 %

Sagbend

For combination of static and dynamic loads, the following equation shall be satisfied both in the sagbend and at the stinger tip:

$$\sigma_{eq} < 0.87 f_y \qquad (3.18)$$

Where:

$f_y \quad = yield\ stress$

$\sigma_{eq} \quad = equivalent\ stress$

Effects due to varying stiffness or residual strain from the overbend can be ignored. For installation in deeper water, where collapse is a potential problem, the sagbend should meet the requirements for buckling criteria in DNV-OS-F101 Section 5 D600. The pipelines in the sagbend region should be designed based on load controlled condition criteria.

3.5.2 Local Buckling – Combined Loading Criteria

For pipeline installation in deepwater, local buckling is one of the criteria that has high potential to damage the pipeline system during lay operation. There are two conditions that need to be considered for checking local buckling of the pipeline:

- Load Controlled condition (LC condition);
- Displacement Controlled condition (DC condition).

3.5.2.1 Load Controlled Condition

A load controlled condition is one in which the structural response is primarily governed by the imposed loads. According to DNV-OS-F101, pipes that are exposed to bending, effective axial force and internal overpressure should meet the following requiremnts :

$$\left\{\gamma_m\gamma_{sc}\frac{|M_{sd}|}{\alpha_c M_p(t_2)}+\left\{\frac{\gamma_m\gamma_{sc}S_{sd}(p_i)}{\alpha_c S_p(t_2)}\right\}^2\right\}^2+\left(\alpha_p\frac{p_i-p_2}{\alpha_c P_b(t_2)}\right)^2\leq 1 \qquad (3.19)$$

$$\left\{\gamma_m\gamma_{sc}\frac{|M_{sd}'(t_2)|}{\alpha_c}+\left\{\frac{\gamma_m\gamma_{sc}S_{sd}'(p_i,t_2)}{\alpha_c}\right\}^2\right\}^2+\left(\alpha_p\frac{p_i-p_2}{\alpha_c P_b(t_2)}\right)^2\leq 1 \qquad (3.20)$$

Applies for $\frac{D}{t_2}\leq 45,\quad P_i > P_e$

Where:

M_{sd}	is the design moment, see Eq. 4.5 DNV page 48
S_{sd}	is the design effective axial force. See Eq. 4. 7 (DNV)
p_i	is the internal pressure
p_e	is the external pressure
p_b	is the burst pressure

S_p and M_p denote the plastic capacities for a pipe defined by :

$$S_p(t)=f_y\pi(D-t)t \qquad (3.21)$$

$$M_p(t)=f_y(D-t)^2 t \qquad (3.22)$$

$$M_{sd}'=\frac{M_{sd}}{M_p}\ (normalised\ moment) \qquad (3.23)$$

$$S_{sd}{}' = \frac{S_{sd}}{S_p}\ (normalised\ effective\ force) \tag{3.24}$$

$$\alpha_c = (1-\beta) + \beta\frac{f_u}{f_y} \tag{3.25}$$

$$\alpha_p = \begin{cases} 1-\beta for \frac{p_i - p_e}{p_b} \le \frac{2}{3} \\ 1-3\beta\left(1-\frac{p_i-p_e}{p_b}\right) for \frac{p_i-p_e}{p_b} \ge \frac{2}{3} \end{cases} \tag{3.26}$$

$$\beta = 0.5 \qquad for \frac{D}{t_2} < 15$$

$$\beta = \left(\frac{60 - D/t_2}{90}\right) for\ \ 15 \le \frac{D}{t_2} \le 15 \tag{3.27}$$

$$\beta = 0 \qquad for \frac{D}{t_2} > 15$$

t_2 is the characteristic wall thickness, t (prior to operation)

p_{min} is the minimum internal pressure that can be sustained by the pipelines. For pipeline installation with the condition where the pipeline is not water filled, this value is normally taken as zero

p_c is the characteristic collapse pressure

D is the outer diameter of pipe

t is the nominal pipe wall thickness

3.5.2.2 Displacement Controlled Condition

A displacement controlled condition is one in which the structural response is primarily governed by the imposed geometric displacement.

According to DNV-OS-F101, the following equation shall be satisfied for the pipeline exposed to longitudinal compressive strain (bending moment and axial force), and external overpressure:

$$\left(\frac{\varepsilon_{sd}}{\frac{\varepsilon_c(t_2,0)}{\gamma_\varepsilon}}\right)^{0.8} + \frac{p_e - p_{min}}{\frac{p_c(t_2)}{\gamma_m \gamma_{sc}}} \le 1 \tag{3.28}$$

Where:

ε_{sd} is the designed compressive strain

ε_c is the characteristic bending strain resistance

$$\varepsilon_c(t, p_{min} - p_e) = 0.78\left(\frac{t}{D} - 0.01\right)\left(1 + 5\frac{p_{min} - p_e}{p_b(t)\frac{2}{\sqrt{3}}}\right)\alpha_h^{-1.5}\alpha_{gw} \tag{3.29}$$

D is the outer diameter of pipe

t is the nominal pipe wall thickness

α_h is the minimum strain hardening, refer to DNV-OS-F101 (2007) section 7 Table 7-5 page71

$$\alpha_h = \left(\frac{R_{t0.5}}{R_m}\right)_{max} \tag{3.30}$$

α_{gw} is the girth weld factor, refers to DNV-OS-F101 (2007) section 13 E1000.

3.6 Design Methodology

Iteration processes are required in pipeline installation to find out the optimum configuration in certain conditions. The design methodology is shown in Figure 3-4 and Figure 3-5.

Figure 3-4 presents the sequence of wall thickness design. Wall thickness should be designed to avoid :

- Bursting (pressure containment);
- Local buckling or collapse due to combination of external pressure and bending moment;
- Propagating buckling.

Once the required wall thickness has been choosen, the pipeline installation analysis can be done with sequence as presented in Figure 3-5. This sequence is repeated for different pipe diameters in various water depths.

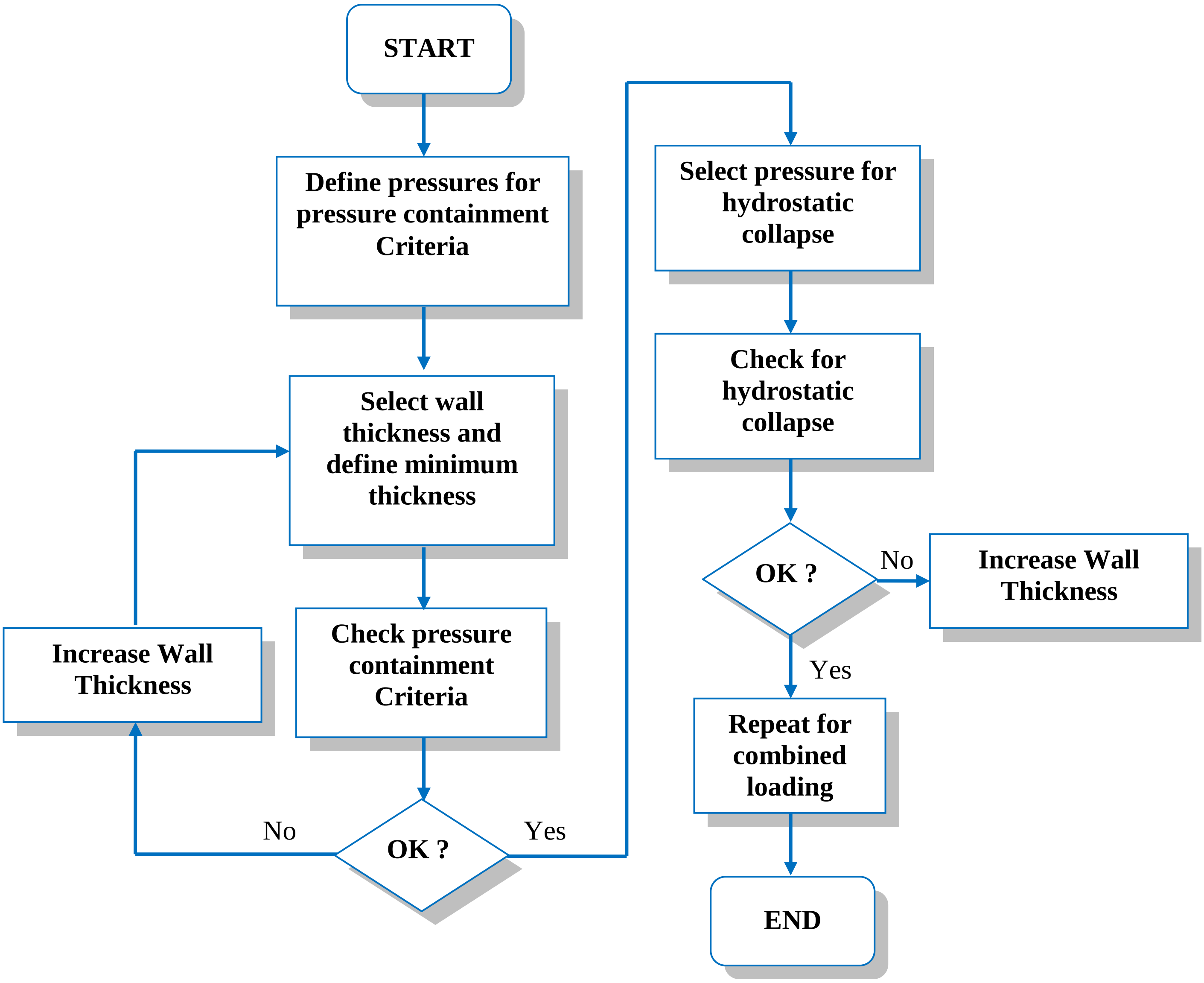

Figure 3-4 : Wall Thickness Design Flowchart, Ref [20]

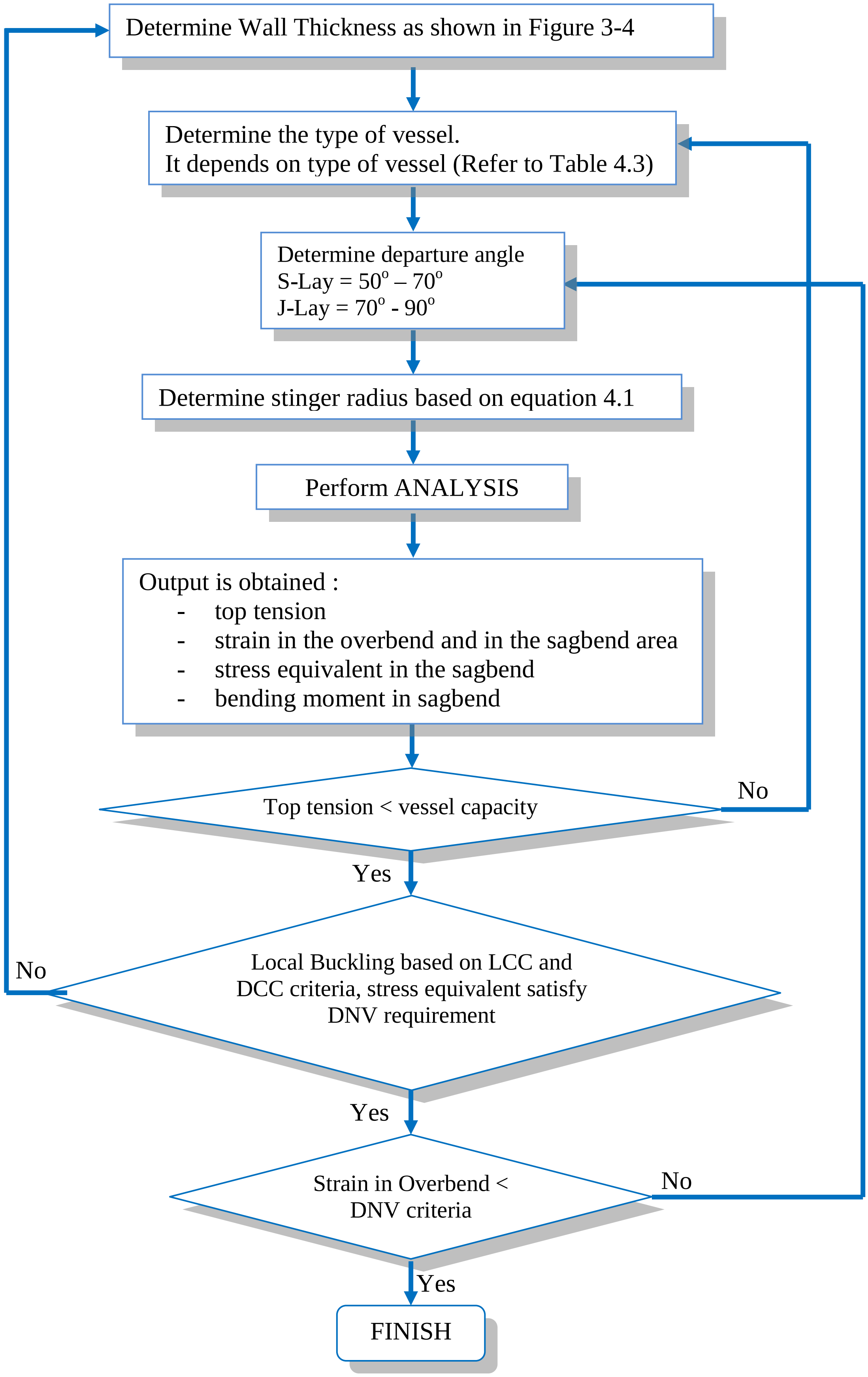

Figure 3-5 : Pipeline Installation Analysis Flowchart

CHAPTER 4 ANALYSIS STUDY

This chapter presents the inputs, assumptions and modeling part for the static analysis performed by SIMLA. The purpose of this study is to evaluate the possibility of installing different diameter pipelines in various water depths.

Lay analyses were carried out using SIMLA software to get some results:

- Pipeline layability for various pipe diameters and water depths with S-Lay and J-lay method;
- Effects of increasing the allowable overbend strain criteria (up to 0.5%);
- Effects on the installation process by increasing the steel grade to X70, X80, and X100, respectively;
- Effects of reducing the length of stinger.

4.1 Pipelay Parameter

The following parameters have significant effects on the pipe lay analysis, Ref [4] :

- Stinger radius (for S-lay);
- Roller position (for S-Lay);
- Departure angle;
- Pipelay tension;
- Pipe bending stiffness;
- Pipe weight;
- Water depth.

During pipeline installation, the above parameters will change some factors, such as :

- Top tension;
- Overbend strains (S-lay);
- Sagbend bending moments;
- Contact-force between pipe and seabed.

As explained in section 3, the following criteria can be used for preliminary design during installation analysis :

- Sagbend:

  Combination of bending moment and external pressure in the sagbend region is checked using a Load Controlled condition (LCC) criteria based on DNV (2007). Refer to section 3.5.2 of this report.

- Overbend:

  The overbend region is checked using a Displacement Controlled Condition (DCC) criteria and should satisfy the strain requirement as given in Table 3-8. For sensitivity study, a maximum allowable overbend strain criterion of 0.5% is used.

Material parameters presented in Table 4-1 are used in this study considering the following location and safety class, Ref [13]:

- Location class 1: there are not much human activities.
- Clasified as a low safety class because the pipeline installation operations have low risk of human injuries, low environmental impacts and minor economic consequences.

Table 4-1: Material Parameter

Factor	Class	Value
Material resistance factor, γ_m	SLS/ULS/ALS	1.15
Safety class resistance factor, γ_{SC}	LOW	1.04
Material strength factor, α_U	NORMAL	0.96
Maximum fabrication factor, α_{fab}	UOE	0.85
Temperature de-rating		None
Condition load effect factor, γ_C	Pipe resting on uneven seabed	1.07
Minimum Strain Hardening		0.93

4.2 Pipelay Study Input

4.2.1 Pipeline Data

The pipeline data used in this study are presented in Table 4-2.

Table 4-2: Material Properties

Characteristics	Unit	Values
Carbon Steel Pipe	Inch	14, 20, 28, and 30
Density	kg/m^3	7850
Young's Modulus	MPa	2.00×10^5
Poisson's Ratio	-	0.3
Ovality		1.5%

4.2.2 Environmental Data

4.2.2.1 Water Depth

This study considers pipeline installations in water depths of 800 m, 1300 m, 2000 m, 2500 m, 3000 m, 3500 m and 4000 m.

4.2.2.2 Seawater Properties

Seawater density is 1025 kg/m^3 and minimum temperature is assumed to be 5.0^oC.

4.2.2.3 Seabed Friction

The seabed friction is assumed to be: 0.3 in x and y direction.

4.2.3 Lay Vessel Data

Table 4-3 and Table 4-4 present the vessels' data for S-Lay and J-lay respectively.

Table 4-3: S-Lay Vessel Data

Lay Vessel	Minimum Stinger Radius (m)	Tension Capacity	Stinger Length	Ramp Height	Ramp Angle
Pieter Schelte	70	2000 t, Ref [1]	170 m	-	0^o
Solitaire	70	1050 t	140 m	10.5 m	0^o
Castorone	70	750 t	120 m	-	-
Lorelay	70	135 t	118 m	12.0 m	0^o

Allseas Company has awarded a contract to build the world's largest pipelay vessel. This vessel, *Pieter Schelte* is a dynamic positioned (DP) vessel. With a dynamic positioned system, the vessel has better ability to operate in deeper water depth compared to anchored vessel. Pieter Schelte has topside lift capacity of 48000 t, jacket lift capacity of 25000 t and pipelay tension capacity around 2000 t, Ref [1]. This tension capacity will be doubling the capacity of Allseas' Solitaire. Pieter Schelte is supposed to be ready for offshore operation in early 2014.

Table 4-4: J-Lay Vessel Data

Lay Vessel	Tension Capacity	Lay Angle
Aegir (Herema)	2000 t, Ref [17]	
Balder	1050 t	50-90
Saipem 7000	525 t	90-110
Deep Blue	770 t	58-90

Aegir is a new deepwater construction vessel (DCV) with capability to execute complex infrastructure and pipeline J-Lay installation in ultra-deep water, Ref [17].

4.2.4 Assumptions

Some assumptions are used in this study and outlined in the following list:

- Only static analyses will be carried out because the study is only a general study and performed for no specific location. In an actual project, a dynamic analysis should be performed especially in case of static analyses with critical result i.e. close to installation limits;
- The seabed is assumed to be flat, continuous and elastic. In reality the seabed may be uneven and probably it would have varied topography and different soil types and potentially rocks;
- The pipeline is assumed to be empty during installation;
- Pipeline coating is not considered during installation analysis. In actual conditions, coating thickness may be presented and the effect of this coating should be taken into consideration. The coating thickness will be different from one location to another, depending on location and water depth. The higher the thickness of the coating the bigger the pipeline weight will be. Furthermore the heavier pipelines require vessels with higher tension capability;
- For the S-Lay method, 3 types of vessel which are characterized by different stinger lengths are considered for each water depth (800-4000m). Furthermore the optimum configuration that satisfy the installation criteria will be chosen. Using the following equation, the departure angle can be estimated depending on the stinger length and stinger radius, Ref [23];

$$\xi = \frac{30}{R_{sti}} . \frac{180}{2\pi} + \frac{(L_{sti}-30)}{R_{sti}} \frac{180}{\pi} + \alpha_{ramp-angle} \qquad (4.1)$$

Where:

ξ : Departure Angle

R_{sti} : Stinger Radius

L_{sti} : Stinger Length

$\alpha_{ramp-angle}$: Stinger/Ramp angle

The stinger radius can be adjusted depending on the water depth, but as far as possible the radius is set so that the top tension is still within the capacity of existing lay vessels. The relationship between departure angle and stinger radius for each vessel are presented in Figure 4-1 and Table 4-5.

Table 4-5: Stinger Radius vs Departure Angle

Stinger Radius (R_{sti})	Departure Angle (degree)			
	Lorelay (L_{sti} =118 m)	Castorone (L_{sti} =120m)	Solitaire (L_{sti} =140 m)	Pieter Schelte (L_{sti} =170 m)
50	118.09	120.38	143.31	177.71
60	98.41	100.32	119.43	148.09
70	84.35	85.99	102.37	126.93
80	73.81	75.24	89.57	111.07
90	65.61	66.88	79.62	98.73
100	59.04	60.19	71.66	88.85
110	53.68	54.72	65.14	80.78
120	49.20	50.16	59.71	74.04
130	45.42	46.30	55.12	68.35
140	42.17	42.99	51.18	65.82
150	39.36	40.13	47.77	59.24
160	36.90	37.62	44.79	55.53
170	34.73	35.41	42.15	52.27
180	32.80	33.44	39.81	49.36

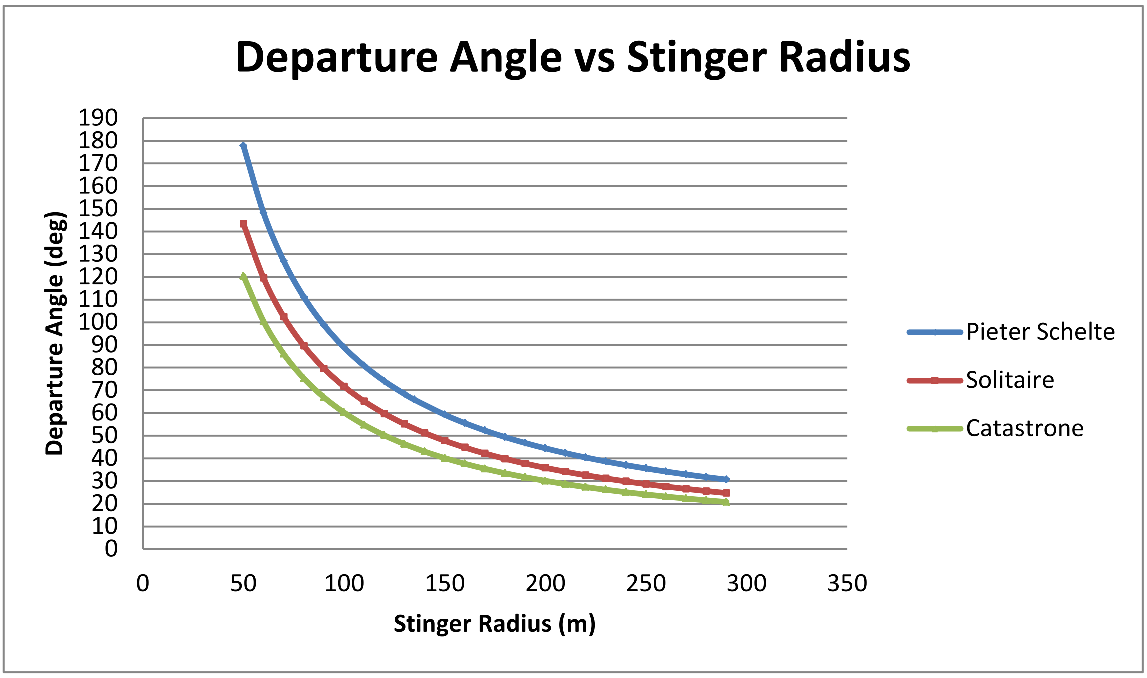

Figure 4-1 : Stinger Radius vs Departure Angle

Other parameters used in this study are given in the following list:

S-Lay

- Departure angle typically between 45^o to 70^o;
- Minimum stinger radius is 70 m;
- Maximum top tension is 2000t (Pieter Schelte);
- Minimum gap between the last roller and the pipe is 300mm (based on engineering judgment to allow dynamic effects);
- The strains in the overbend and the tension capacity of the lay vessel give the limitation for S-Lay installation.

J-Lay

- Departure angle typically between 70^o to 90^o;
- Maximum top tension is 2000t (Aegir Herema Vessel);
- Combination of bending moment and external pressure in the sagbend and the vessel's tension capacity give limitations for J-lay method.

4.3 Pipelay Modeling

Pipe lay analyses is carried out using SIMLA software. SIMLA is a finite element computer program for engineering analysis of offshore pipelines during design, installation and operations.

As results of installation analysis, an optimum pipelay configuration and required tension are found. Specifically for S-Lay, the configuration of the stinger and the departure angle are known. Strain and stress in the overbend and sagbend region should satisfy the criteria mentioned in Section 3.5.

Some of the SIMLA features are:

- Non-linear static and dynamic Finite Element Analyses;
- Global Buckling;
- Bottom Roughness;
- Pipelay;
- Trawling/Anchor Hooking;
- J-tube pull-in.

SIMLA also has some robust visualization tools such as :

- XPOST;
- SIMVIS;
- Routing and Intervention.

The important parameters of the pipelaying analyses such as strain in the overbend and sagbend, moment and axial tension along the pipe are provided by SIMLA as analyses output. The analysis is carried out so that the tension is kept within the existing vessel capacity by adjusting the stinger radius.

The global and local coordinate system in SIMLA is shown in Figure 4-2 and Figure 4-3, respectively. A right handed Cartesian coordinate system is applied, Ref [42]. In global axis, gravity is acting in the negative z-direction, where z positive is upwards and z negative is downward. Sea surface is situated at z = 0.

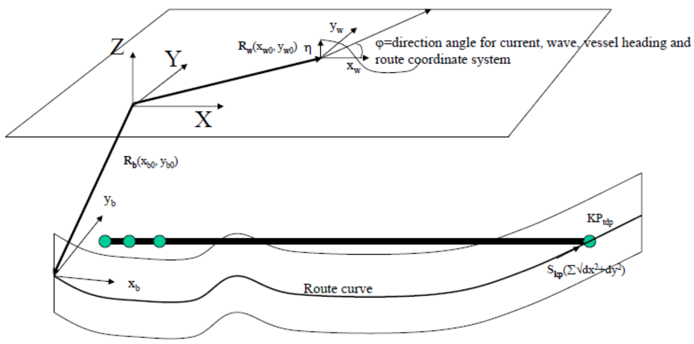

Figure 4-2 : Global Coordinate System in SIMLA, Ref [42]

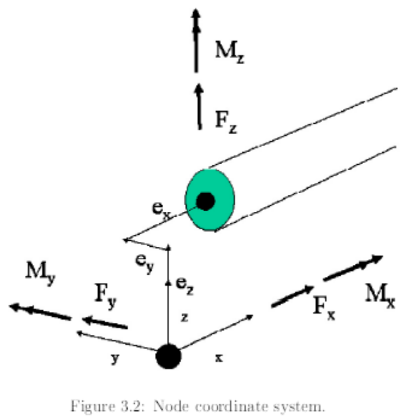

Figure 4-3 : Local Coordinate System in SIMLA, Ref [42]

There are several modules in SIMLA. These modules are used at the sequence presented in the Figure 4-4.

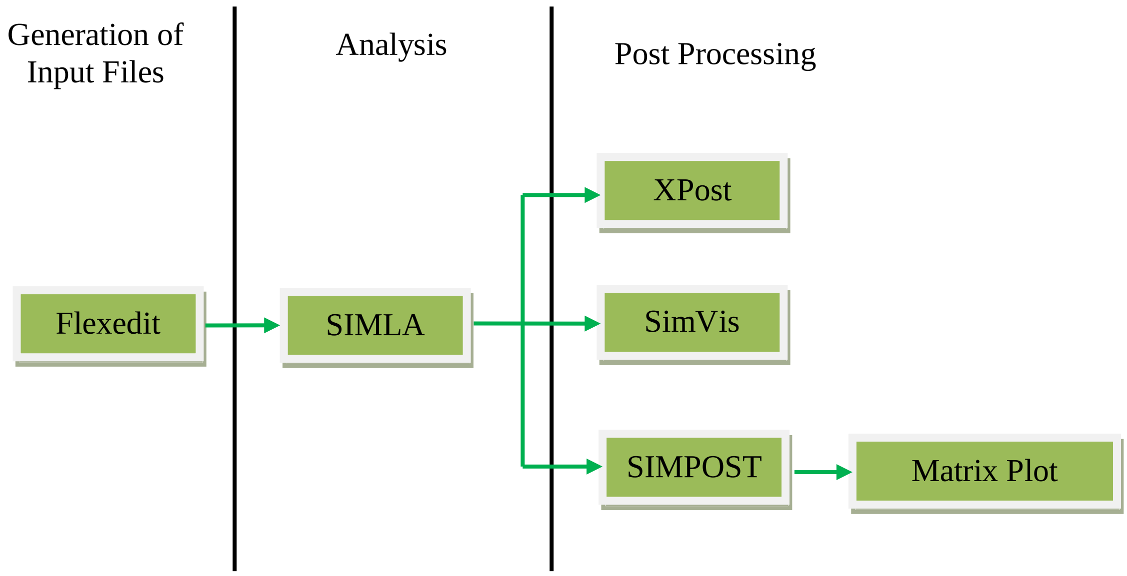

Figure 4-4 : Purpose and Communication between Modules in SIMLA, Ref [42]

1. FlexEdit

FlexEdit is text editor used to present the input data that will be used in the analysis. The flexedit view is shown in Figure 4-5 and refers to Appendix A for the detailed input.

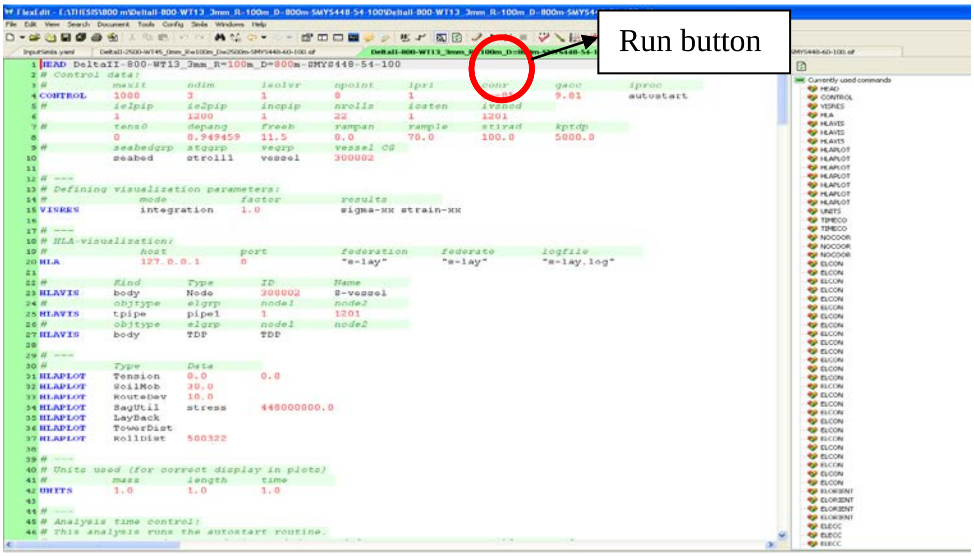

Figure 4-5 : FlexEdit View

2. SIMLA

The purpose of this module is to run the analysis of the pipeline during design, installation and operation. Running analysis in SIMLA can be done using “Python” as shown in Figure 4-6 or using “Run button” in FlexEdit as shown in the Figure 4-5.

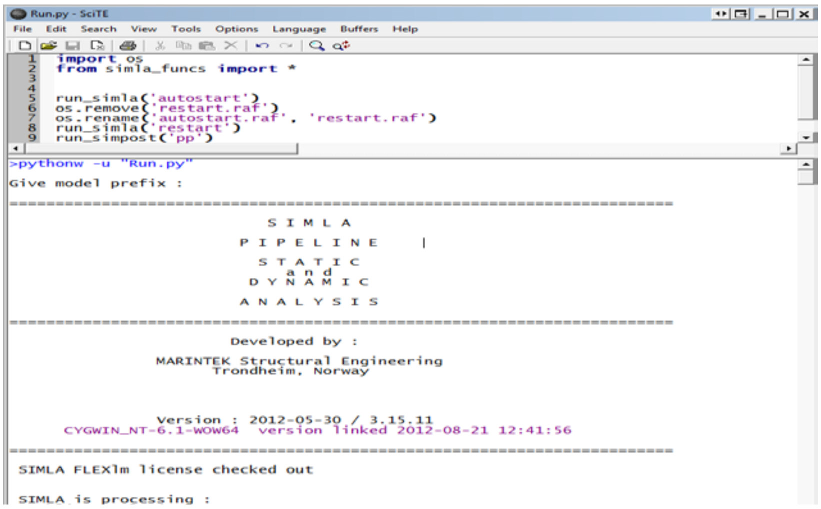

Figure 4-6 : Example of Run Operator in SIMLA using Python

3. XPOST

XPOST is 3D visualization program. The result of thenumerical model can be seen using XPOST. Figure 4-7 presents the example of lay analysis visualization.

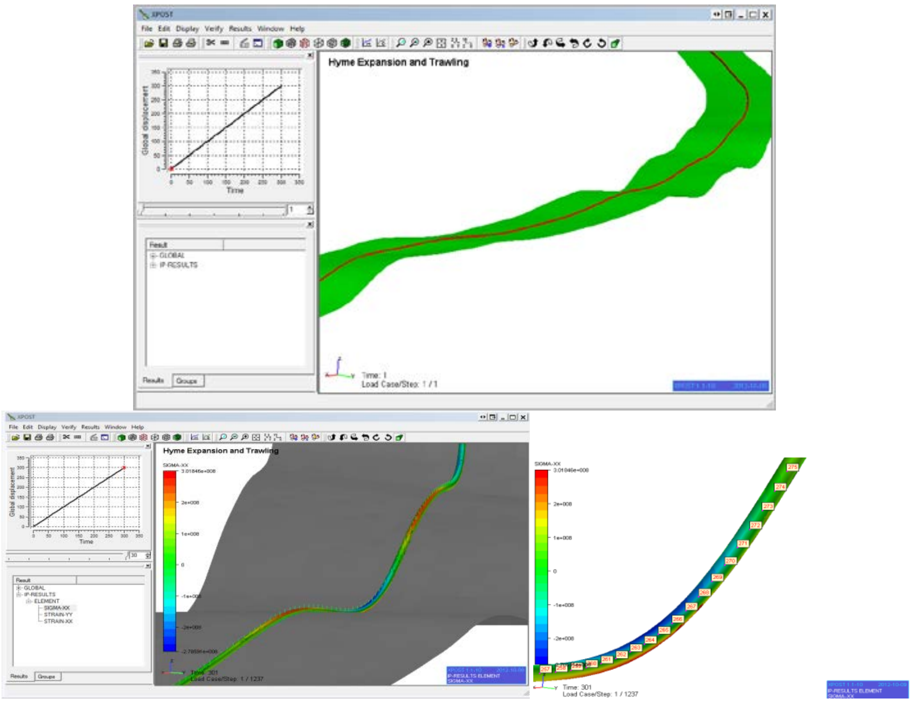

Figure 4-7 : Example of XPOST View

4. SimVis

SimVis is part of the post processing module in SIMLA. This module presents 3D visualizations of the pipe and the surrounding environment such as the seabed feature in the 3D terrain model, Figure 4-8.

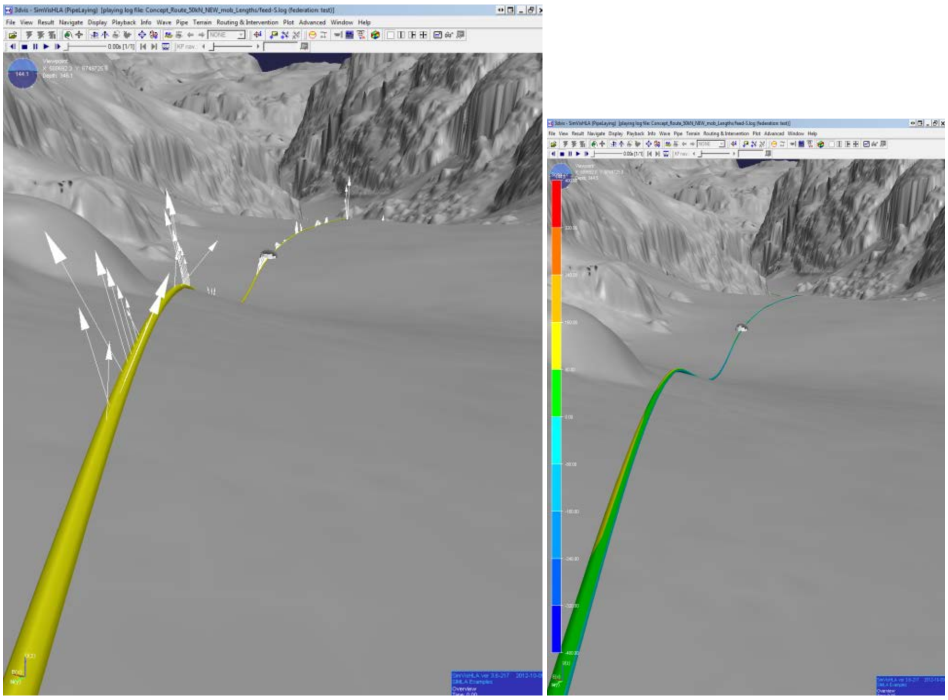

Figure 4-8 : Example of Simvis View

5. SIMPOST

Using SIMPOST module, the results generated by Simla can be extracted as detailed lists or plotted as a chart.

6. Matrix Plot

Matrix plot is one of SIMLA module that presents the plotting of the results extracted by SIMPOST. Anexample of a matrix plot view can be seen in Figure 4-9.

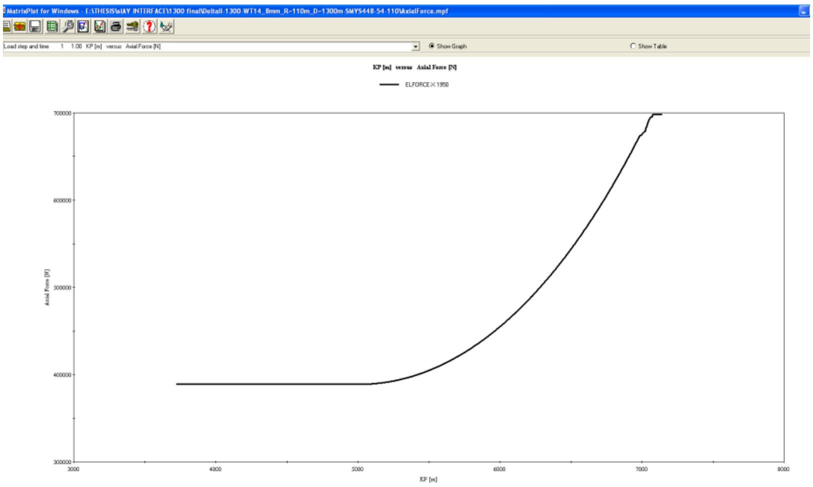

Figure 4-9 : Example of Result Visualization using Matrix Plot

4.3.1 S-Lay Model

The S-Lay model is shown in Figure 4-10.

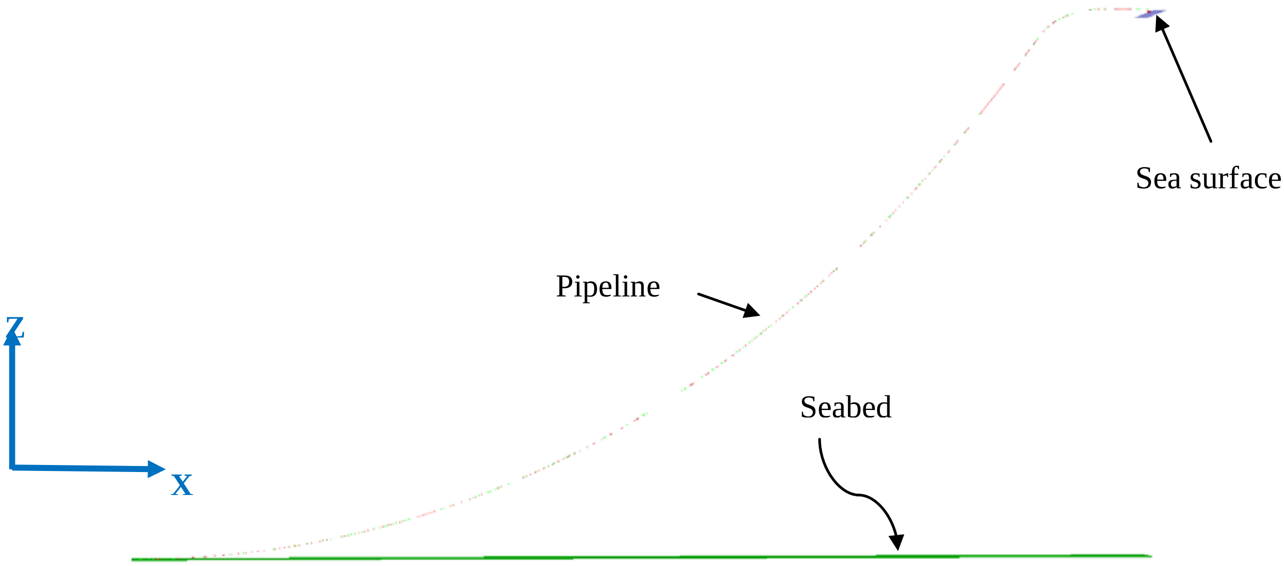

Figure 4-10 : S-Lay Model

The sea is modeled as an arbitrary set of 4 noded shell elements. Each node is fixed for translation in x, y, and z directions. While pipe is modeled as a beam element structure.

Seabed/soil is modeled as spring support. Elastoplastic material is used for x and y directions while in z direction it is modeled as hyperelastic (nonlinear) material. SIMLA also provide facilities to model the route. Here one can also define how many lines will be used in the route. Each line defines the terrain of the seabed. The following figure presents example of route corridor with eleven lines.

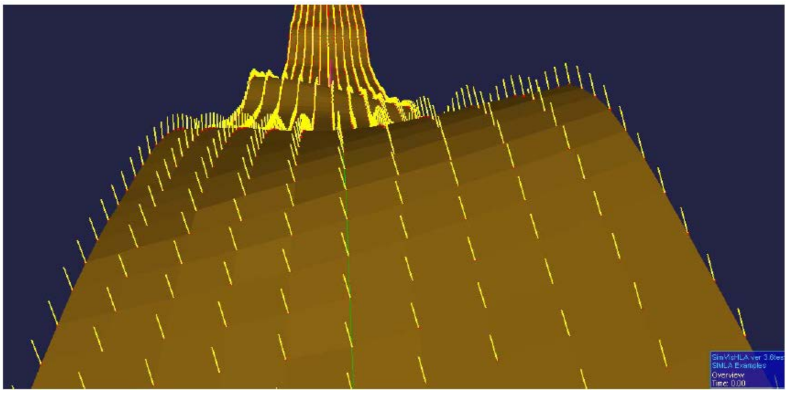

Figure 4-11 : Example of a Route

The vessel is modeled as a rigid body. Constraint for vessel is specified as prescribe displacement type. In this case no displacement for translation in x, y, and z directions and also for rotation in x, y, z directions.

The connection between the pipe upper-end and the vessel is specified by a liniar constraint equation with factor of 1 for “master and slaves”. The concept of the “Master-Slave” facility is that the slave node will deflect as its master node.

Constraints at the pipe bottom end are specified as zero prescribing the displacement type for translations in x, y, and z directions.

The stinger geometry is represented by the roller configuration. The roller is modeled as a rigid body, fixed to the vessel for translation in z direction and for rotation in x and y directions. Figure 4-12 shows the roller position in this study.

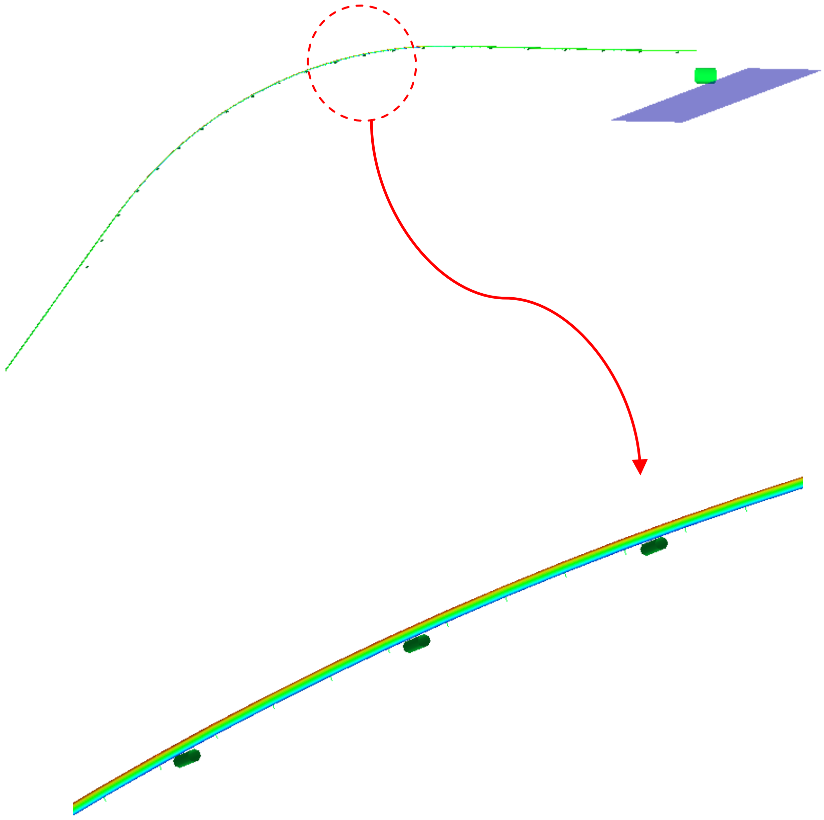

Figure 4-12 : Roller Configurations

The pipe configuration for the S-lay method in SIMLA is specified by choosing the “S type” in the SIMLA card. With this command, the geometry is automaticaly formed depending on the water depth, pipe weight and departure angle. Deck height above the water is assumed to be 15 m.

4.3.1.1 Stinger Configuration

The roller position will be generated by SIMLA based on the stinger radius, stinger length and departure angle that are specified as input. Figure 4-13 shows the example of the roller configuration for 120 m stinger length. According to Table 4-3, the Castorone vessel has 120 m stinger length. Using the same stinger length, different departure angles can be adjusted based on water depth requirement.

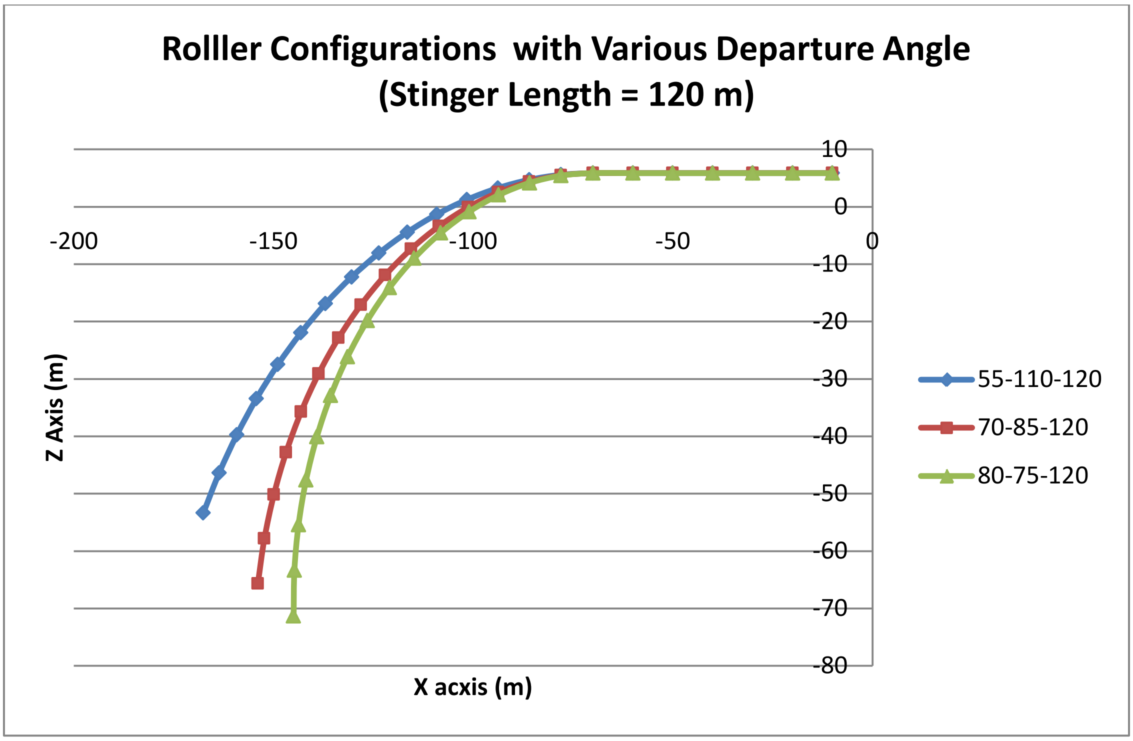

Figure 4-13 : Roller Configurations with Various Departure Angle for 120 m Stinger Length

There are three different departure angles shown in Figure 4-13, i.e. 55 degree, 70 degree and 80 degree. The stinger radiuses are 110 m, 85 m, 80 m for 55 degree, 70 degree and 80 degree departure angles respectively. The relation between the departure angles, stinger radius and stinger length can be found inequation 4.1.

The roller configuration for 70 degree departure angle is steeper than the roller configuration for a 55 degree departure angle. Roller configuration with 80 degree departure angle is steeper than for 70 degree. The bigger departure angle, the steeper the roller configuration will be. Furthermore, the steeper configuration will create bigger strain in the overbend region but the required top tension will be decreased. This relation of strain in the overbend region and stinger configuration is studied in this thesis and presented in chapter 5.4.3.

4.3.2 **J-Lay Model**

The J-Lay model is shown in Figure 4-14.

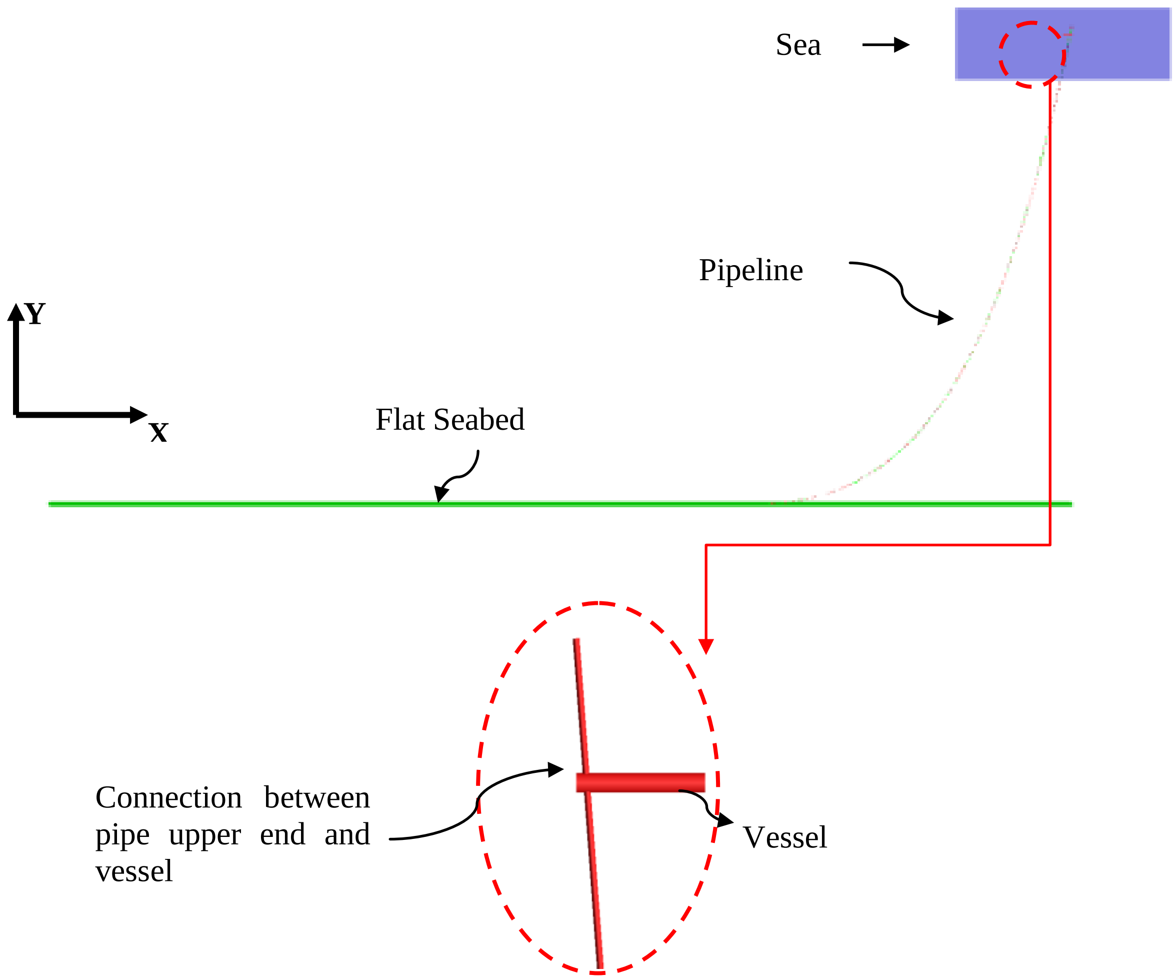

Figure 4-14 : J-Lay Model

As with the S-Lay model, the sea is modeled as an arbitrary set of 4 noded shell elements. Each node is fixed for translation in x, y, and z directions. While pipe is modeled as a beam element structure.

Seabed/soil modeled as spring support. Elastoplastic material is used for x and y directions while in the z direction the support is modeled as using hyperelastic (nonlinear) material.

The vessel is modeled as rigid body. Constraints for the vessel are specified as prescribing the displacement type. In this case no translation displacements in x, y, and z directions and also for rotation in x, y, z directions.

The connection between the pipe upper-end to the vessel is specified by a liniar constraint equation with factor of 1 for "master and slaves". The concept of the "Master-Slave" facility is that the slave node will deflect as its master node.

Constraint at pipe bottom end is specified as zero prescribe displacement type for translation in x, y, and z directions.

The pipe configuration for the J-lay method in SIMLA is specified by choosing “J type” in SIMLA card. With this command, the geometry is automaticaly formed depending on the water depth, pipe weight and departure angle. Deck height above the water is assumed to be 15m.

CHAPTER 5 RESULTS AND DISCUSSIONS

5.1 Wall Thickness Design

The wall thickness is one of the most important parameters that need to be taken into consideration during the pipeline design phases. The wall thickness will determine the pipe's capability to withstand internal and external pressure, the effect of corrosion, longitudinal stress as well as hoop stress. Furthermore, the wall thickness will influence the required tension during installation and the total cost of implementing the project.

Wall thickness should be designed to follow DNV specification to avoid, Ref [13]:

• Bursting (pressure containment);

• Local buckling (collapse);

• Propagating buckling.

High external hydrostatic pressure will cause high wall thickness requirement to avoid local buckling (collapse) and buckle propagation. However, using buckle propagation criteria to select wall thickness is not efficient and too expensive. Buckle arrestors are often provided to solve this problem.

The wall thickness requirement based on local buckling criterion (collapse) could be even bigger in deeper water. In the sagbend area, the pipe should be able to withstand local buckling due to combination of external pressure and bending moment based on Load Controlled Condition Criteria (LCC). While in the overbend area, the thickness should satisfy Displacement Controlled Criteria (DCC).

In deep and ultra deep waters the wall thicknesses are governed by external pressure and bending moment, therefore bursting (loss of pressure containment) is not considered in this thesis.

The minimum wall thicknesses for various water depths, various pipe diameters and various steel grades are shown in Table 5-1 to Table 5-3. The detailed calculation of wall thickness design based on local buckling and propagation buckling criteria are presented in APPENDIX C.

Local Buckling (System Collapse)

The minimum required wall thicknesses to satisfy local buckling criteria are presented in the following Table 5-1. The detailed concept and formula are described in chapter 3.

Table 5-1: Wall Thickness (mm) Based on Local Buckling (System Collapse)

Diameter	Steel Grade	Water Depth (m)						
		800	1300	2000	2500	3000	3500	4000
14 inch	X65	11.8	14.8	17.8	20.3	23.8	27.0	30.0
	X70	11.69	14.0	17.0	20.0	23.0	25.4	27.2
	X80	11.52	13.8	16.8	18.8	21.0	23.0	25.0
	X100	11.32	13.3	15.8	17.42	19.0	20.64	22.17
20 inch	X65	17.05	21.0	26.5	30.5	33.5	37.8	45.0
	X70	16.85	20.5	25.4	29.0	33.0	36.2	41.0
	X80	16.64	20.0	24.2	27.5	30.5	33.5	37.0
	X100	16.34	19.3	23.0	25.35	27.49	29.8	32.4
28 inch	X65	23.94	30.0	37.5	43.0	48.0	54.0	60.0
	X70	23.64	28.8	36.0	41.5	46.5	52.0	57.2
	X80	23.3	28.0	34.2	39.0	43.0	47.5	52.2
	X100	22.95	27.12	32.67	35.80	39.1	42.3	45.72
30 inch	X65	25.76	32.0	40.0	45.0	51.8	58.0	65.0
	X70	25.51	31.0	38.6	44.3	50.0	56.0	61.5
	X80	25.14	30.0	37.0	41.5	46.2	51.0	56.0
	X100	24.68	29.0	35.0	38.6	42.03	45.36	49.0

Stability

For on bottom stability purposes, the submerged weight of the pipeline should be higher than the buoyancy weight. Considering 1.1 specific gravity for design stability, the wall thicknesses are obtained as shown in Table 5-2.

Table 5-2: Wall Thickness Based on Stability Criteria

Diamter	Minimum Wall Thickness (mm)
14 inch	13.3
20 inch	19.1
28 inch	26.6
30 inch	28.5

Propagation Buckling

The minimum required wall thicknesses to satisfy propagation buckling criteria are presented in the following Table 5-3. The detailed concept and formula are described in chapter 3.

Table 5-3: Wall Thickness (mm) Based on Buckle Propagation

Diameter	Steel Grade	Water Depth (m)						
		800	1300	2000	2500	3000	3500	4000
14 inch	X65	21.0	25.3	29.9	32.6	35.0	37.1	39.1
	X70	20.4	24.6	29.0	31.7	34.0	36.1	38.0
	X80	19.4	23.4	27.6	31.7	32.3	34.3	36.1
	X100	17.8	21.5	25.3	27.6	29.6	31.4	33.1
20 inch	X65	29.6	35.7	42.3	46.1	49.5	52.6	55.4
	X70	28.8	34.7	41.1	44.8	48.1	51.1	53.9
	X80	27.3	33.0	39.0	44.8	45.7	48.5	51.1
	X100	25.1	30.2	35.7	39.0	41.8	44.4	46.8
28 inch	X65	41.0	49.6	58.8	64.2	68.9	73.3	77.2
	X70	39.9	48.2	57.1	62.3	67.0	71.2	75.0
	X80	37.9	45.8	54.2	62.3	63.5	67.5	71.2
	X100	34.7	41.9	49.6	54.1	58.2	61.8	65.1
30 inch	X65	43.9	53.1	62.9	68.7	73.8	78.4	82.7
	X70	42.7	51.6	61.1	66.7	71.7	76.2	80.3
	X80	40.5	49.0	58.0	66.7	68.0	72.3	76.2
	X100	37.1	44.8	53.1	57.9	62.3	66.2	69.7

The required wall thicknesses based on propagation buckling are very high compared to the required thicknesses based on local buckling criteria. Therefore it will not be considered in this study. In industry practice buckle arrestors are most often used to avoid buckle propagation.

5.1.1 Wall Thickness Summary

Considering the design parameters as explained above, the wall thicknesses that will be used in the analysis are summarized in the following Table 5-4.

Table 5-4: Wall Thickness Summary (mm)

Diameter	Steel Grade	Water Depth (m)						
		800	1300	2000	2500	3000	3500	4000
14 inch	X65	13.3	14.8	17.8	20.3	23.8	27.0	30.0
	X70	13.3	14.0	17.0	20.0	23.0	25.4	27.2
	X80	13.3	13.8	16.8	18.8	21.0	23.0	25.0
	X100	13.3	13.3	15.8	17.42	19.0	20.64	22.17
20 inch	X65	19.1	21.0	26.5	30.5	33.5	37.8	45.0
	X70	19.1	20.5	25.4	29.0	33.0	36.2	41.0
	X80	19.1	20.0	24.2	27.5	30.5	33.5	37.0
	X100	19.1	19.3	23.0	25.35	27.49	29.8	32.4
28 inch	X65	26.6	30.0	37.5	43.0	48.0	54.0	60.0
	X70	26.6	28.8	36.0	41.5	46.5	52.0	57.2
	X80	26.6	28.0	34.2	39.0	43.0	47.5	52.2
	X100	26.6	27.12	32.67	35.80	39.1	42.3	45.72
30 inch	X65	28.5	32.0	40.0	45.0	51.8	58.0	65.0
	X70	28.5	31.0	38.6	44.3	50.0	56.0	61.5
	X80	28.5	30.0	37.0	41.5	46.2	51.0	56.0
	X100	28.5	29.0	35.0	38.6	42.03	45.36	49.0

The graphical information of wall thickness requirement for 14 inch pipe diameter X65 based on various criteria is shown in Figure 5-1.

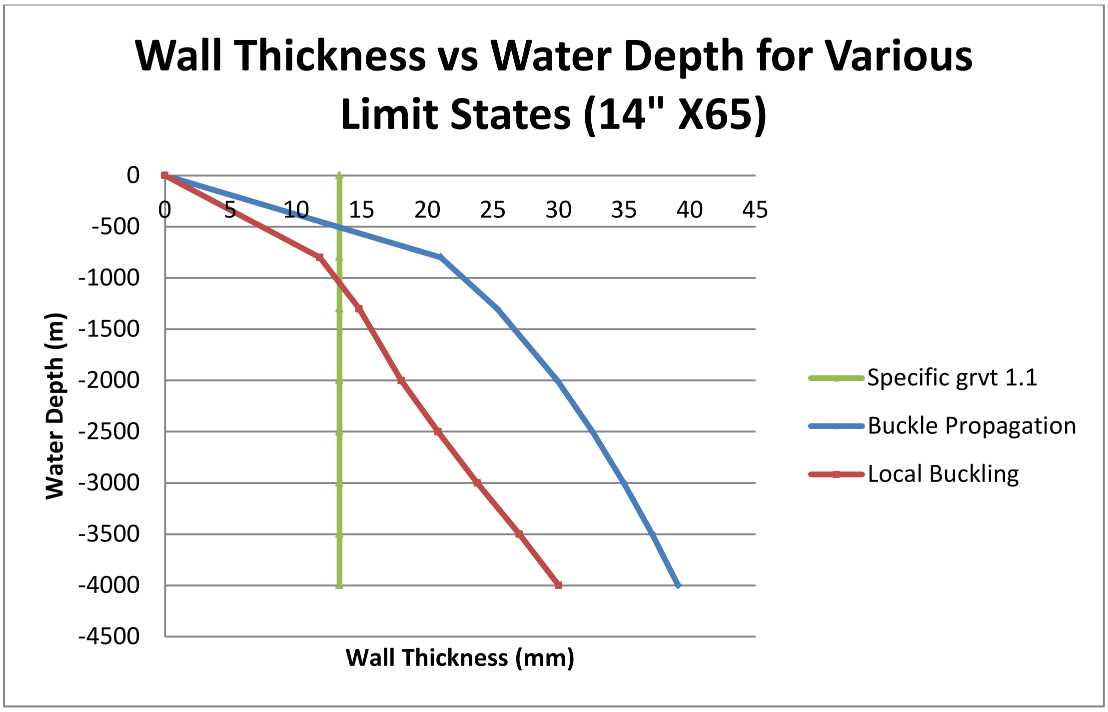

Figure 5-1 : Wall Thickness for Various for Various Limit States (X65)

5.1.2 Effect of Changing the Steel Grades

The effect of changing steel grades on the requirement of wall thickness has been shown in the previous section. This section presents the percent decrease in the required wall thickness for different steel grades.

Due to increasing the material grade from X65 to X100, in 800 meter water depth, the required wall thickness is decreased by:

- 0.48 mm or 4.1% for a 14 inch pipeline;
- 0.71 mm or 4.16% for a 20 inch pipeline;
- 0.99 mm or 4.14% for a 28 inch pipeline;
- 1.08 mm or 4.19 % for a 30 inch pipeline.

In 1300 meter water depth the required wall thickness is decreased by:

- 1.5 mm or 10.14% for a 14 inch pipeline;
- 1.7 mm or 8.1% for a 20 inch pipeline;
- 2.88 mm or 9.6% for a 28 inch pipeline;
- 3.0 mm or 9.38% for a 30 inch pipeline.

In 2000 meter water depth the required wall thickness is decreased by:

- 2 mm or 11.24% for a 14 inch pipeline;
- 3.5 mm or 13.21% for a 20 inch pipeline;
- 4.83 mm or 12.88% for a 28 inch pipeline;
- 5 mm or 12.5% for a 30 inch pipeline.

In 2500 meter water depth the required wall thickness is decreased by:

- 2.88 mm or 14.19% for a 14 inch pipeline;
- 5.15 mm or 16.89% for a 20 inch pipeline;
- 7.2 mm or 16.75% for a 28 inch pipeline;
- 6.4 mm or 14.22% for a 30 inch pipeline.

In 3000 meter water depth the required wall thickness is decreased by:

- 4.8 mm or 20.17% for a 14 inch pipeline;
- 6.01 mm or 17.94% for a 20 inch pipeline;
- 8.9 mm or 18.54% for a 28 inch pipeline;
- 9.77 mm or 18.86% for a 30 inch pipeline.

In 3500 meter water depth the required wall thickness is decreased by:

- 6.36 mm or 23.56% for a 14 inch pipeline;
- 8.0 mm or 21.16% for a 20 inch pipeline;
- 11.7 mm or 21.67% for a 28 inch pipeline;
- 12.64 mm or 21.79% for a 30 inch pipeline.

In 4000 meter water depth the required wall thickness is decreased by:

- 7.83 mm or 26.1% for a 14 inch pipeline;
- 12.6 mm or 28% for a 20 inch pipeline;
- 14.28 mm or 23.8% for a 28 inch pipeline;
- 16 mm or 24.62% for a 30 inch pipeline.

The results mentioned above shows that the effect of increasing the grade of steel is higher in 1300 m water depth compared to 800 m water depth. This effect is higher as increasing the water depth.

The graphical information about required wall thicknesses for various diameters in different water depths are presented in Figure 5-2 to Figure 5-5.

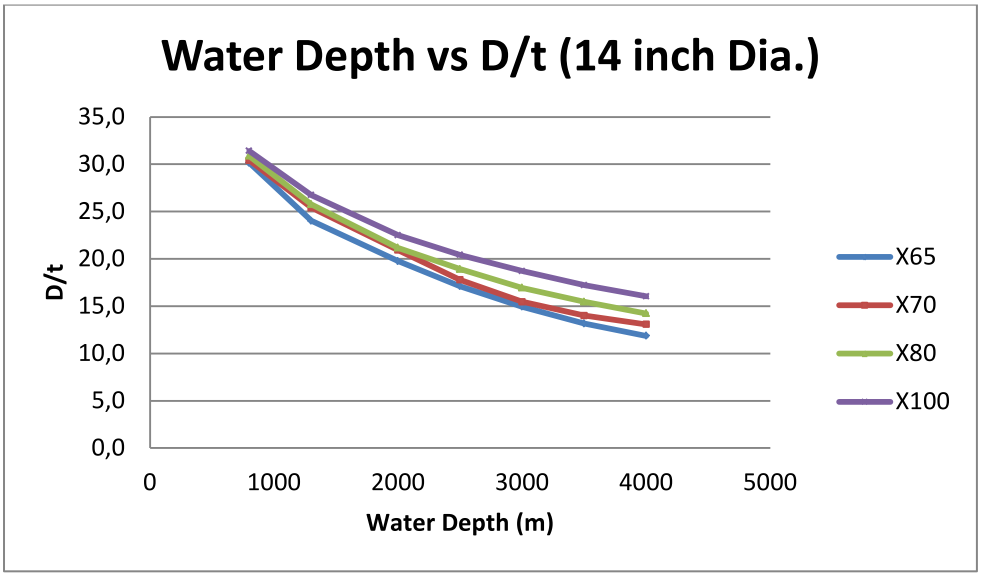

Figure 5-2 : D/t as Function of Steel Grades (14 Inch Diameter)

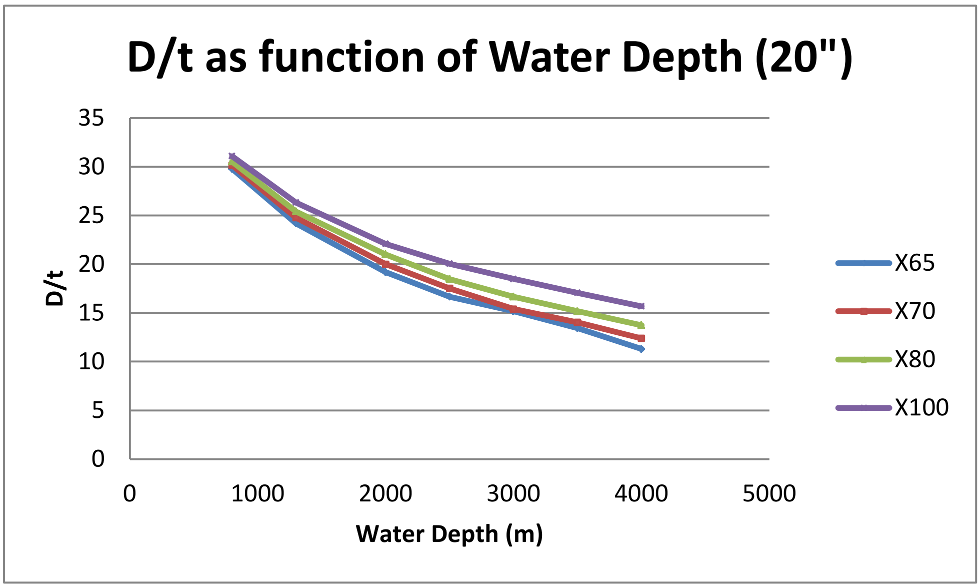

Figure 5-3 : D/t as Function of Steel Grades (20 Inch Diameter)

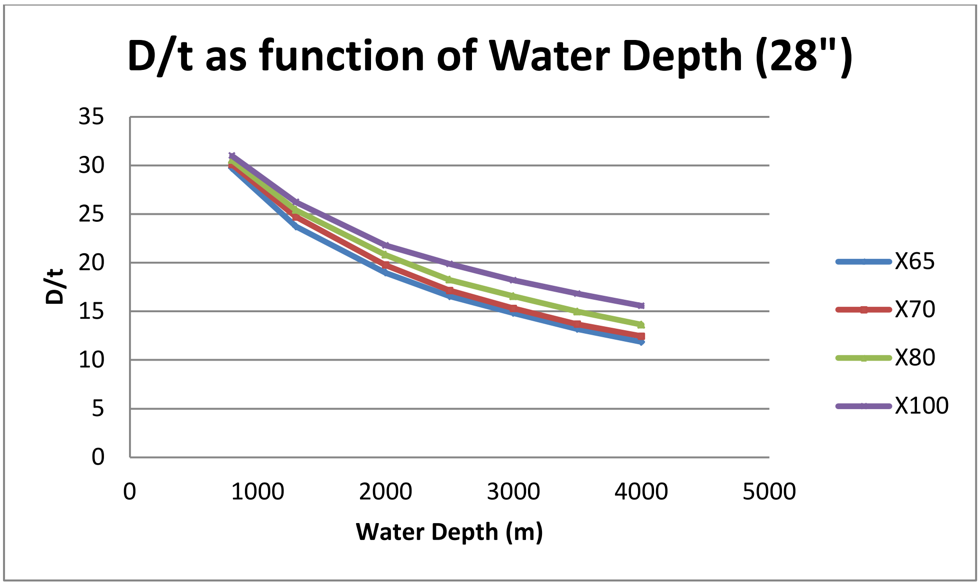

Figure 5-4 : D/t as Function of Steel Grades (28 Inch Diameter)

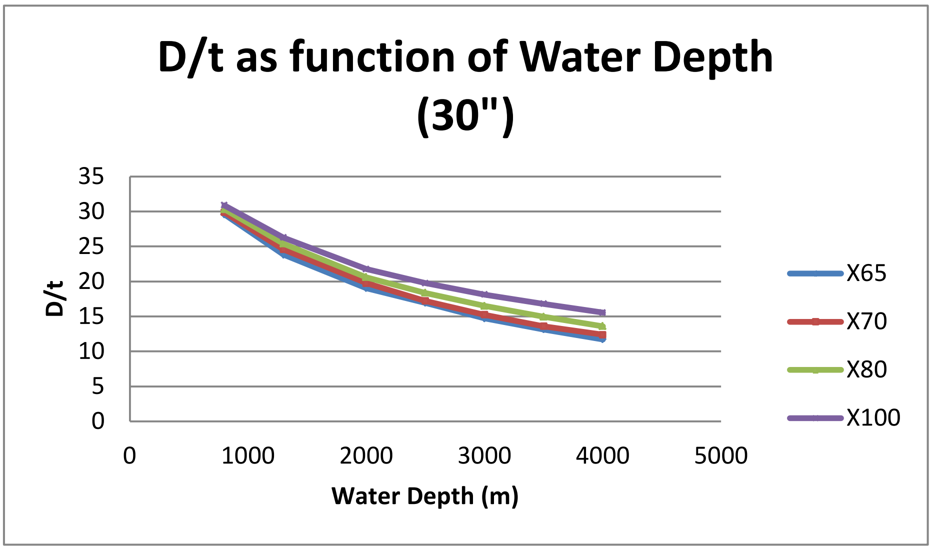

Figure 5-5 D/t as Function of Steel Grades (30 Inch Diameter)

5.1.3 Effects of Changing in Pipe Ovality

Pipe ovality also influences the wall thickness requierements. According to requirements of DNV OS F101 2007, bending and out of fabrication tolerances should not lead to flattening of more than 3%, except for special cases. In this thesis an ovality of 1.5% is used for all diameters and for all water depths.

Combination of hydrostatic external pressure and bending moment during installation tends to cause high pipe ovalities. The wall thickness should be strong enough to withstand the collapse or local buckling in deep and ultra deep water conditions. The required external pressure to buckle the pipe, known as collapse pressure (equation 3-11) will depend on the ratio of diameter to the thickness (D/t). Lower D/t ratio will allow higher external pressure before collapse, Ref [26].

One of the objectives of this study is to carry out wall thickness design due to changes of pipe ovality from 0.5 % up to 3 %, which are the minimum and maximum values recommended by DNV OS F101 2007. The minimum wall thickness required for various pipe diameters and various water depths are provided in Table 5-5 to Table 5-8 and Figure 5-6 to Figure 5-9.

The results show that the wall thickness is decreased from 12 % up to 16 % due to the effect of reducing the ovality from 3% to 0.5%.

Table 5-5: 14 Inch X65 Wall Thickness (mm) vs Ovality

Water Depth (m)	Ovality (%)					
	0.5	1	1.5	2	2.5	3
800	10.80	11.10	11.75	12.09	12.42	12.73
1300	13.43	13.84	14.53	14.94	15.34	15.73
2000	17.12	17.66	18.41	18.93	19.44	19.92
2500	19.76	20.40	21.19	21.79	22.36	22.91
3000	22.39	23.14	23.96	24.64	25.28	25.90
3500	25.02	25.87	26.74	27.49	28.21	28.90
4000	27.66	28.61	29.51	30.34	31.13	31.89

For 14 inch pipe diameter, as the ovality decreases from 3% to 0.5% the required wall thickness is decreased by:

- 1.93 mm or 15.19 % in 800 m water depth
- 2.29 mm or 14.58 % in 1300 m water depth
- 2.28 mm or 14.04 % in 2000 m water depth
- 3.16 mm or 13.77 % in 2500 m water depth
- 3.51 mm or 13.57 % in 3000 m water depth
- 3.87 mm or 13.40 % in 3500 m water depth
- 4.23 mm or 13.27 % in 4000 m water depth

Table 5-6: 20 Inch X65 Wall Thickness (mm) vs Ovality

Water Depth (m)	Ovality (%)					
	0.5	1	1.5	2	2.5	3
800	15.84	16.37	16.87	17.35	17.82	18.28
1300	19.56	20.22	20.79	21.44	22.01	22.56
2000	24.78	25.62	26.29	27.16	27.87	28.56
2500	28.50	29.48	30.21	31.24	32.06	32.85
3000	32.22	33.34	34.14	35.33	36.25	37.13
3500	35.95	37.20	38.07	39.41	40.44	41.42
4000	39.67	41.05	41.99	43.50	44.62	45.70

For 20 inch pipe diameter, as the ovality decreases from 3% to 0.5% the required wall thickness is decreased by:

- 2.44 mm or 13.35 % in 800 m water depth
- 3.00 mm or 13.30 % in 1300 m water depth

- 3.79 mm or 13.26 % in 2000 m water depth
- 4.35 mm or 13.23 % in 2500 m water depth
- 4.91 mm or 13.22 % in 3000 m water depth
- 5.47 mm or 13.20 % in 3500 m water depth
- 6.03 mm or 13.19 % in 4000 m water depth

Table 5-7: 28 Inch X65 Wall Thickness (mm) vs Ovality

Water Depth (m)	Ovality (%)					
	0.5	1	1.5	2	2.5	3
800	22.17	22.91	23.61	24.29	24.95	25.59
1300	27.39	28.31	29.18	30.01	30.81	31.59
2000	34.68	35.87	36.97	38.02	39.02	39.99
2500	39.90	41.27	42.54	43.74	44.88	45.98
3000	45.11	46.68	48.11	49.46	50.75	51.98
3500	50.33	52.08	53.67	55.18	56.61	57.98
4000	55.54	57.48	59.24	60.90	62.47	63.98

For 28 inch pipe diameter, as the ovality decreases from 3% to 0.5% the required wall thickness is decreased by:

- 3.42 mm or 13.35 % in 800 m water depth
- 4.20 mm or 13.30 % in 1300 m water depth
- 5.30 mm or 13.26 % in 2000 m water depth
- 6.09 mm or 13.24 % in 2500 m water depth
- 6.87 mm or 13.22 % in 3000 m water depth
- 7.66 mm or 13.20 % in 3500 m water depth
- 8.44 mm or 13.19 % in 4000 m water depth

Table 5-8: 30 Inch X65 Wall Thickness (mm) vs Ovality

Water Depth (m)	Ovality (%)					
	0.5	1	1.5	2	2.5	3
800	24.22	25.02	25.80	26.53	27.24	27.93
1300	29.84	30.83	31.78	32.67	33.53	34.36
2000	37.71	38.97	40.15	41.27	42.34	43.37
2500	43.33	44.78	46.13	47.41	48.63	49.81
3000	48.95	50.59	52.11	53.55	54.92	56.24
3500	54.57	56.39	58.09	59.69	61.21	62.68
4000	60.19	62.20	64.07	65.83	67.51	69.11

For 30 inch pipe diameter, as the ovality decreases from 3% to 0.5% the required wall thickness is decreased by:

- 3.71 mm or 13.27 % in 800 m water depth
- 4.52 mm or 13.15 % in 1300 m water depth
- 5.66 mm or 13.05 % in 2000 m water depth
- 6.47 mm or 12.99 % in 2500 m water depth
- 7.29 mm or 12.95 % in 3000 m water depth

- 8.10 mm or 12.93 % in 3500 m water depth
- 8.92 mm or 12.90 % in 4000 m water depth

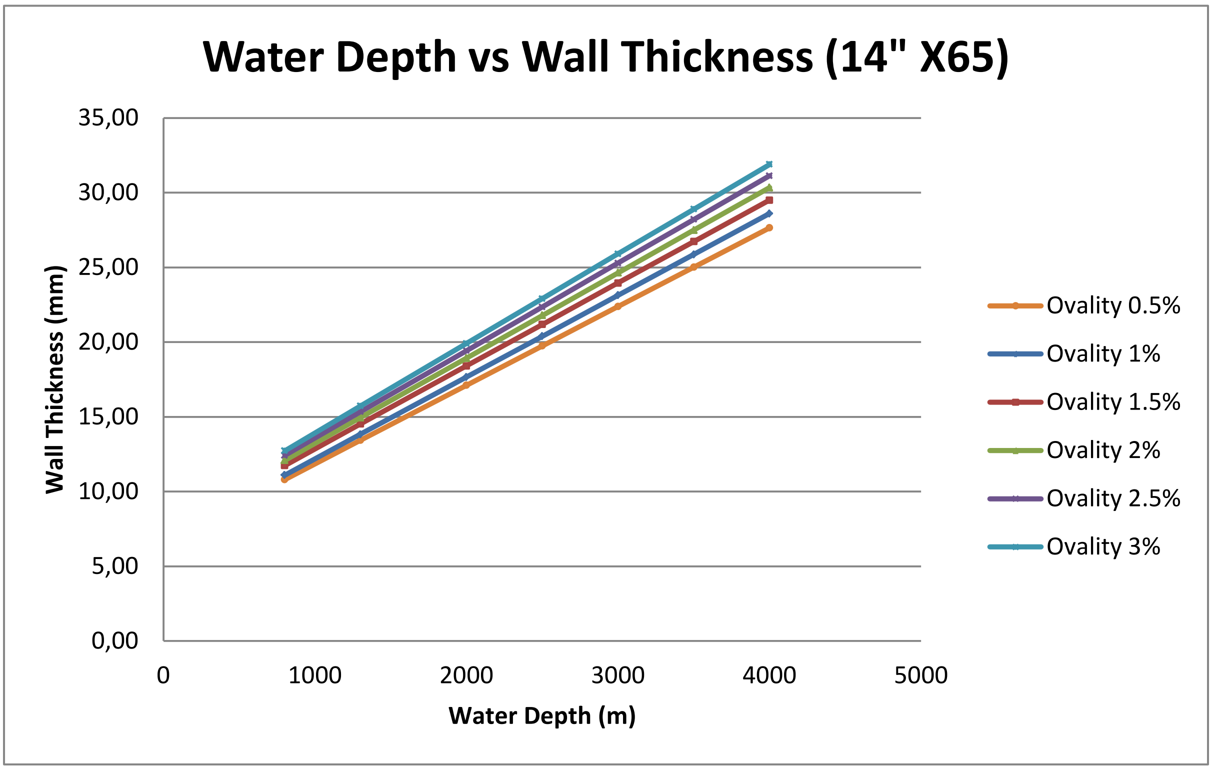

Figure 5-6 : 14 Inch X65 Wall Thickness (mm) vs Ovality

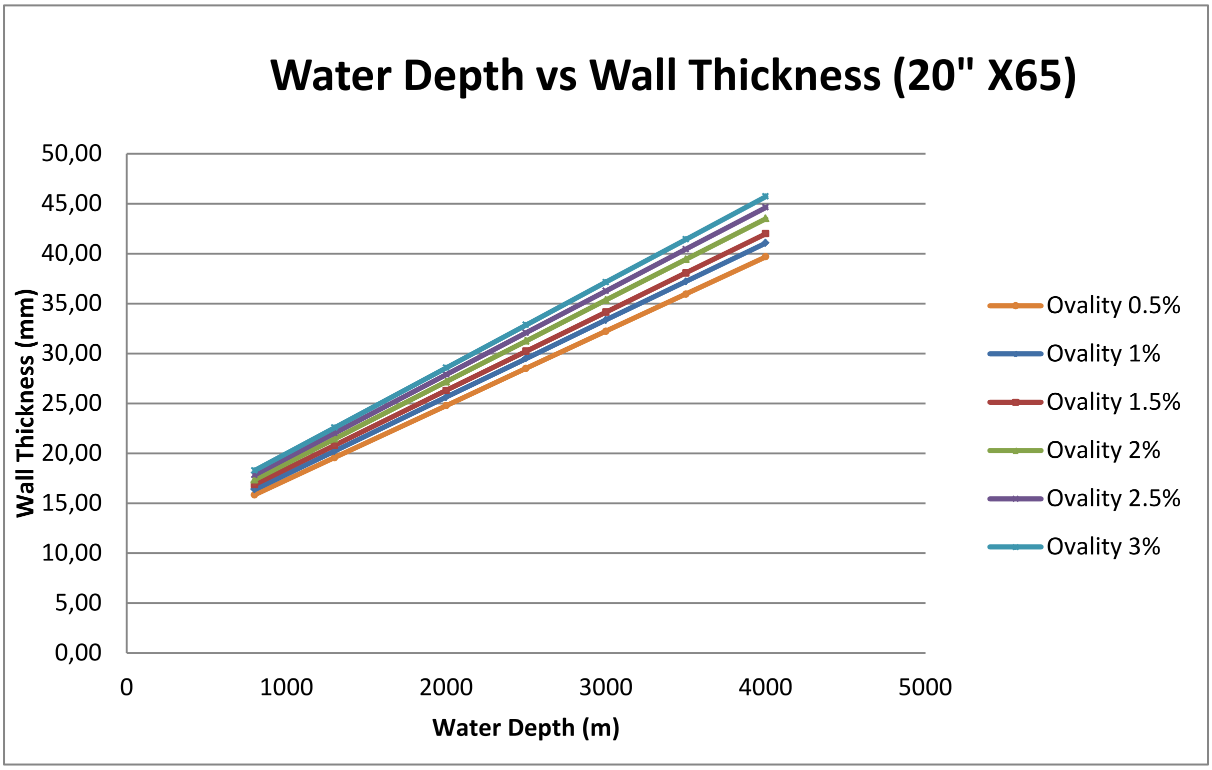

Figure 5-7 : 20 Inch X65 Wall Thickness (mm) vs Ovality

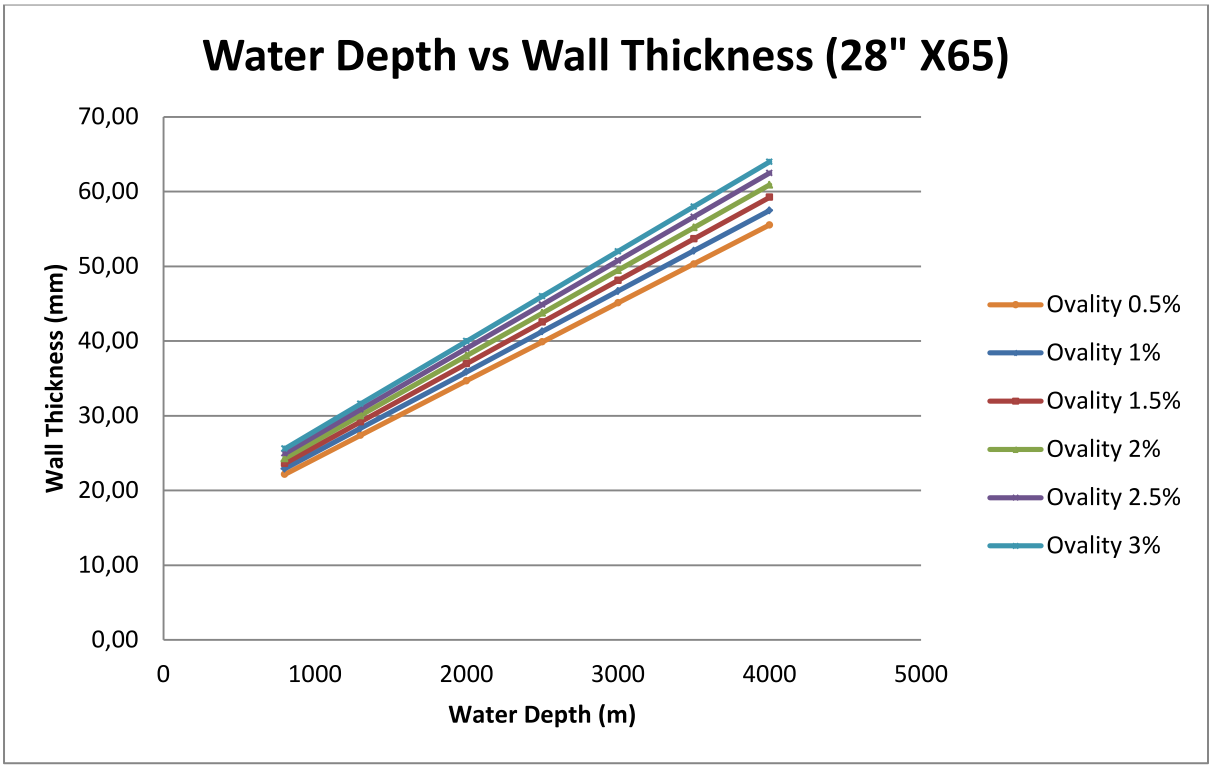

Figure 5-8 : 28 Inch X65 Wall Thickness (mm) vs Ovality

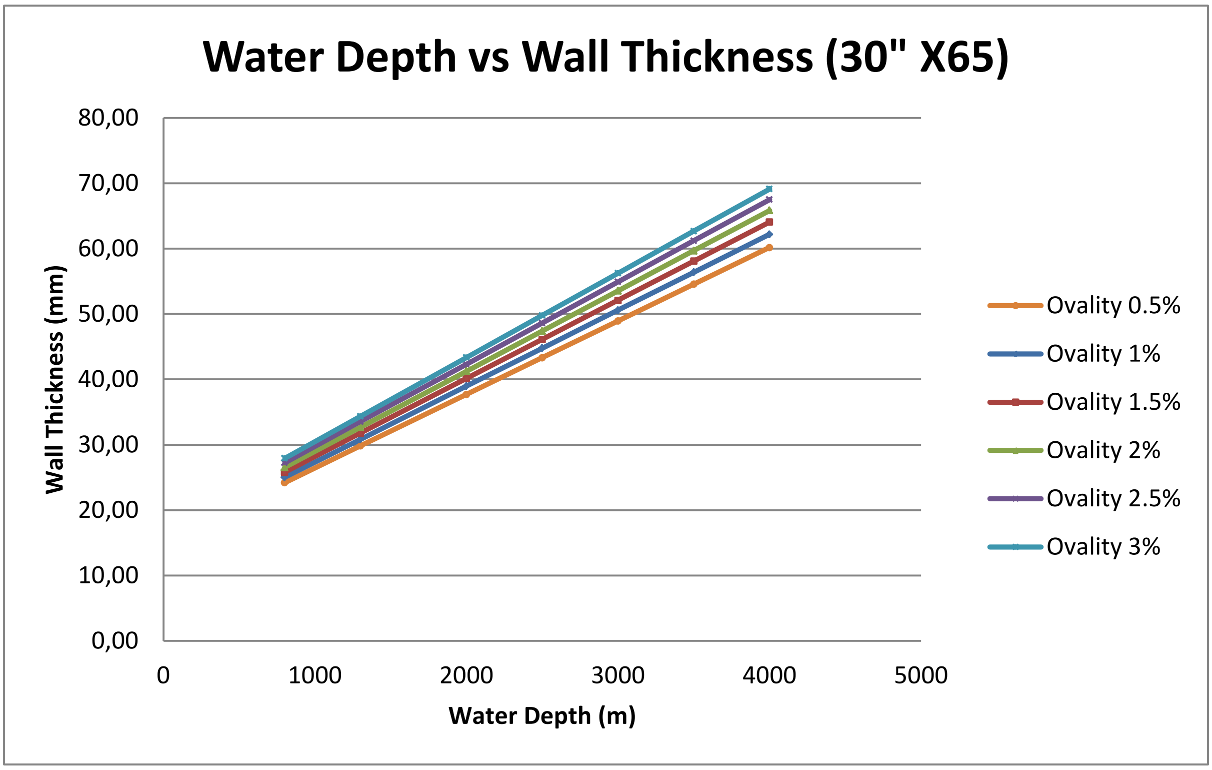

Figure 5-9 : 30 Inch X65 Wall Thickness (mm) vs Ovality

5.1.4 Discussion of Wall Thickness Parameter Study

The conclusions of the wall thickness parameter study are discussed below:

- Using higher steel grades will decrease the required wall thickness. This effect is getting higher as installation go to the deeper water. This is because the total pipe length extending from the vessel to the seabed is increased in deeper waters; therefore the submerged weight due to reduction of the thickness is decreased proportionally.

- The reduction of wall thickness requirement due to increasing of steel grades is not depending significantly on the pipe diameter. The percentage of wall thickness reductions for 14 inch, 20 inch, 28 inch and 30 inch are close for the same water depth.

- The wall thickness is decreased by around 12 % and up to 16 % due to the effect of reducing the ovality from 3% to 0.5%. Therefore, ovality has significant influences on the wall thickness requirement.

- The effect of reducing the ovality from 3% to 0.5% is higher for bigger pipe diameter.

- The percentage of reduction is slightly smaller in deeper water for the same pipe diameter..

5.2 Required Top Tension

5.2.1 S-Lay Method

The analysis of pipelaying is carried out using the computer program SIMLA. As results the layability of the pipeline will be obtained. The results for X65 steel grade is summarized in the following Figure 5-10. The detailed results are presented in APPENDIX C.

The increasing of required top tension is linear up to 1300 m water depth. The reason is because the specific gravity requirement set the minimum value with small variations in wall thickness at water depth less than 1300 m. The wall thickness is increasing rapidly at water depth more than 1300 m to meet local buckling requirement. The impact is heavier pipes that needs vessel with bigger lay tension capacity. Beyond 2000 m the required top tension increase even steeper since the wall thickness increase rapidly due to higher external pressure in deep water condition.

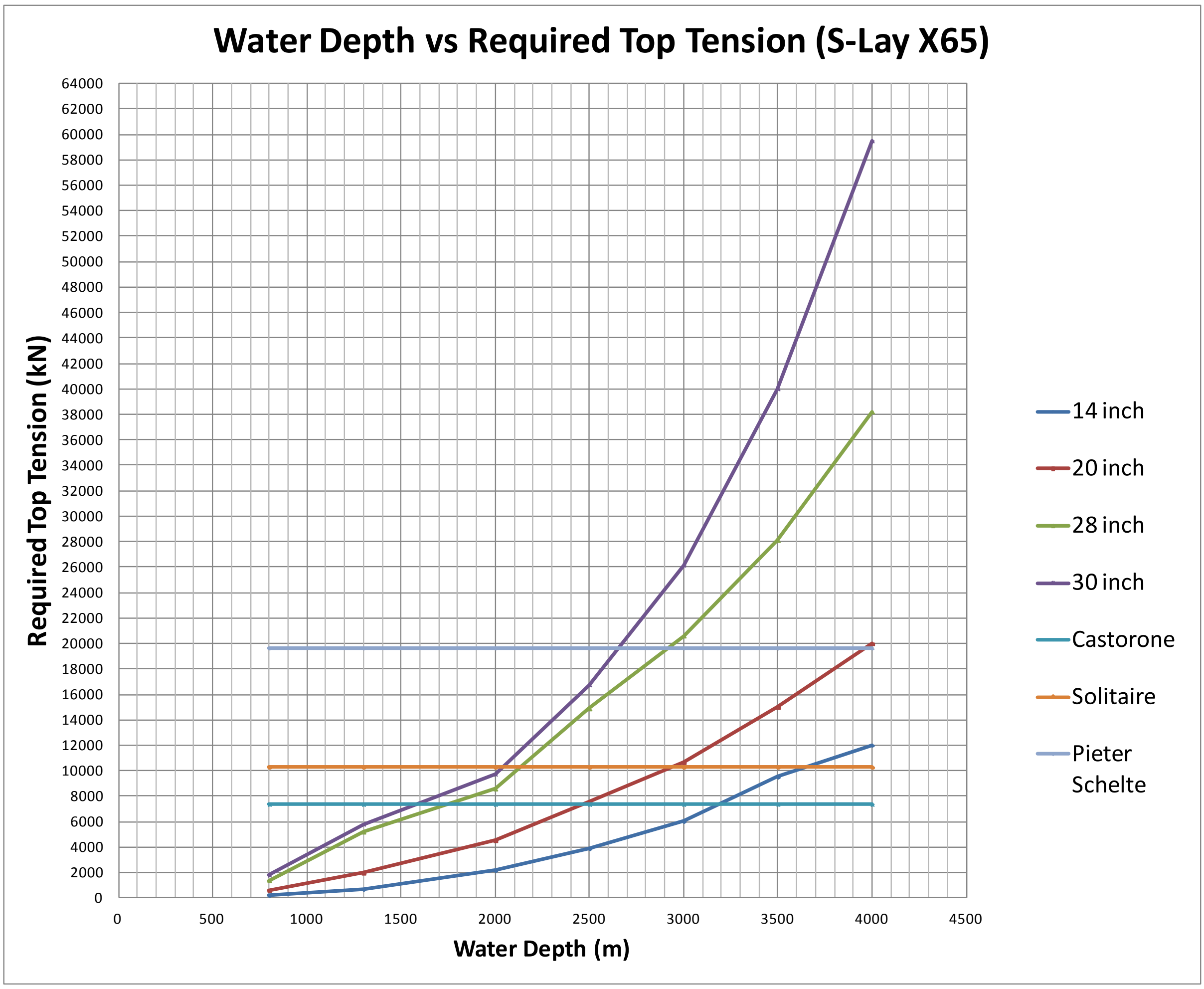

Figure 5-10 : Required Top Tension as Function of Water Depth for S-Lay X65

Based on information from Figure 5-10 the following conclusions are obtained:

- The required top tensions for 14 inch pipe diameter are within the tension capacity of the existing lay vessel for all water depths. Castorone can be used for installation at water depth less than 3200m, while for 3200 m to 3700 m water depth, Solitaire can be used as a solution.
- The required top tension for 20 inch pipe diameter is higher compared to the requirement for 14 inch diameter. However it is still within the capacity of the most powerful upcoming S-Lay vessel, Pieter Schelte.
- For 28 inch pipe diameter, the required top tensions increase even steeper. Pieter Schelte can only possibly be used for installations in water depth less than 2900 m.
- And for 30 inch pipe diameter, Pieter Schelte can only possibly be used for installations in water depth less than 2650 m.

5.2.2 J-Lay Method

As with the S-Lay method, analysis by J-Lay is also carried out in this study, and the summary of the results are given in the Figure 5-11.

The increasing of required top tension is linear up to 1300 m water depth. The reason is because the specific gravity requirement set the minimum value with small variations in wall thickness at water depth less than 1300 m. The wall thickness is increasing rapidly at water depth more than 1300 m to meet local buckling requirement. The impact is heavier pipes that needs vessel with bigger lay tension capacity. Beyond 2000 m the required top tension increase even steeper since the wall thickness increase rapidly due to higher external pressure in deep water condition.

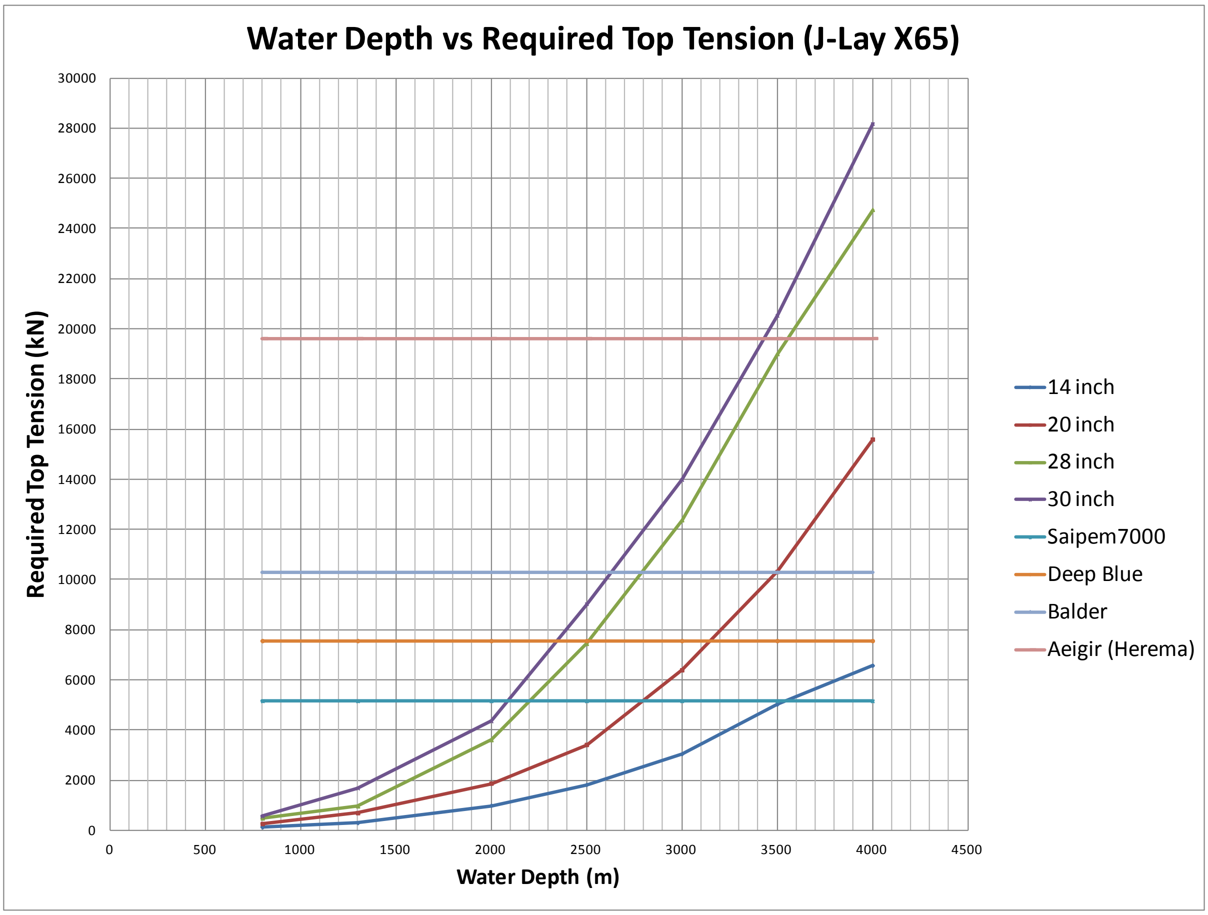

Figure 5-11 : Required Top Tension as Function of Water Depth for J-Lay X65

Based on information from Figure 5-11, the following conclusions are obtained:

- The required top tensions for 14 inch pipe diameter are within the tension capacity of existing lay vessel for all water depths. Saipem 7000 is possible to be used for installation at water depth less than 3550 m. For water depth more than 3550 m Deep Blue can be used as a solution
- The required top tension for 20 inch pipe diameter is higher compared to requirement for 14 inch diameter. However it is still within the capacity of the most powerful upcoming J-Lay vessels, Aegir (Herema).
- For 28 inch pipe diameter, the required top tension increases even steeper. Aegir (Herema) can only possibly be used for installation in water depth less than 3550m.
- And for 30 inch pipe diameter, Aegir (Herema) can only possibly be used for installation in water depth less than 3400 m.

5.3 Comparisons of S-Lay and J-Lay

5.3.1 14 inch Pipe Diameter

Figure 5-12 shows the comparison result of installation using S-Lay and J-Lay method for 14 inch pipe diameter.

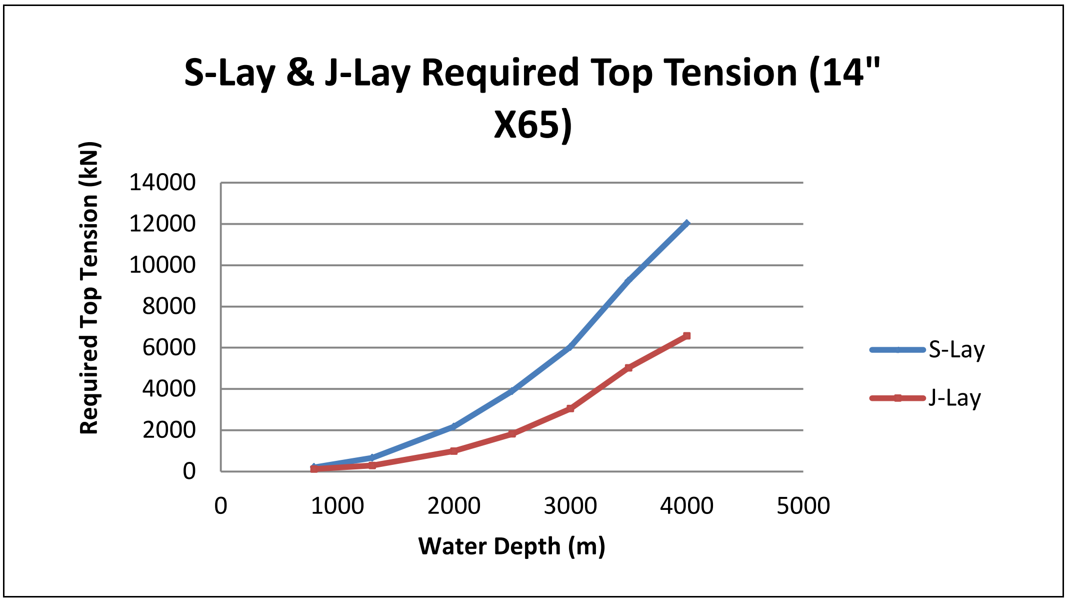

Figure 5-12 : S-Lay and J-Lay Required Top Tension as Function of Water Depth (14”X65)

Based on information provided in Table 5-9 and Table 5-10, all the utilization factors are less than one; this means that the LCC (Load Control Condition) and the DCC (Displacement Control Condition) criteria are satisfied at all water depths for both S-lay and J-lay methods. DCC is a criterion that needs to be satisfied for the pipeline exposed .to longitudinal strain and external pressure. DCC criterion is used to check the overbend region. While LCC is a criterion that needs to be satisfied for the pipeline exposed .to bending, axial force and internal overpressure. LCC criterion is used to check the sagbend region.

Table 5-9: 14” Pipe S-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Overbend (%)	DCC Check	LCC Check
800	55	"110/120"	13.30	26.74	205.6	0.172	0.75	0.40
1300	55	"110/120"	14.80	24.03	692	0.198	0.92	0.65
2000	55	"110/120"	17.80	19.98	2171.42	0.235	0.99	0.78
2500	55	"110/120"	20.30	17.52	3890.18	0.268	0.99	0.83
3000	55	"110/120"	23.80	14.94	6029.89	0.303	0.96	0.85
3500	55	"130/140"	27.00	13.17	9515.38	0.31	0.96	0.99
4000	55	"130/140"	30.00	11.85	12025.1	0.38	0.97	0.91

Note:

1) Strain criteria is set as 0.25%
2) The detailed LCC and DCC calculations are presented in Appendix C

The concusions of S-lay installation analysis for 14 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessels at all water depths. Refer to Table 4-3 for the information about S-lay vessel capacity;
- Strain in overbend region is within the criteria of 0.25% for X65 at 800 m, 1300 m, and 2000 m water depth. Starting from 2500 m water depth, the strain criteria has been exceeded;
- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less than one at all water depths;
- The pipe can be possibly installed with 55˚ departure angles for all water depth;
- The distance between the last stinger roller and the pipe is set to be 300 mm for all cases.

Table 5-10: 14" Pipe J-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilization	LCC Check
800	86	13.30	26.74	122.41	0.096	210.00	389.76	0.54	0.40
1300	86	14.80	24.03	294	0.0850	170.00	389.76	0.44	0.66
2000	86	17.50	20.32	988.78	0.0700	140.00	389.76	0.36	0.78
2500	86	20.30	17.52	1819.7	0.0530	106.00	389.76	0.27	0.81
3000	86	22.80	15.60	3045.32	0.0720	144.00	389.76	0.37	0.76
3500	78	25.40	14.00	5021.16	0.0950	190.00	389.76	0.49	0.88
4000	78	28.60	12.43	6567.64	0.1160	232.00	389.76	0.60	0.87

The concusions of J-lay installation analysis for 14 inch diameter are:

- The required top tensions were found to be within the tension capacities of existing vessels at all water depths. Refer to Table 4-4 for the information about J-lay vessel capacity;
- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less than one at all water depths;
- Stress equivalent in sagbend are inside the allowable stress at all water depths;
- Departure angles are between 75˚- 90˚.

5.3.2 20 inch Pipe Diameter

Figure 5-13 shows the comparison of the result of installation using S-Lay and J-Lay method for 20 inch pipe, see also Table 5-11 and Table 5-12.

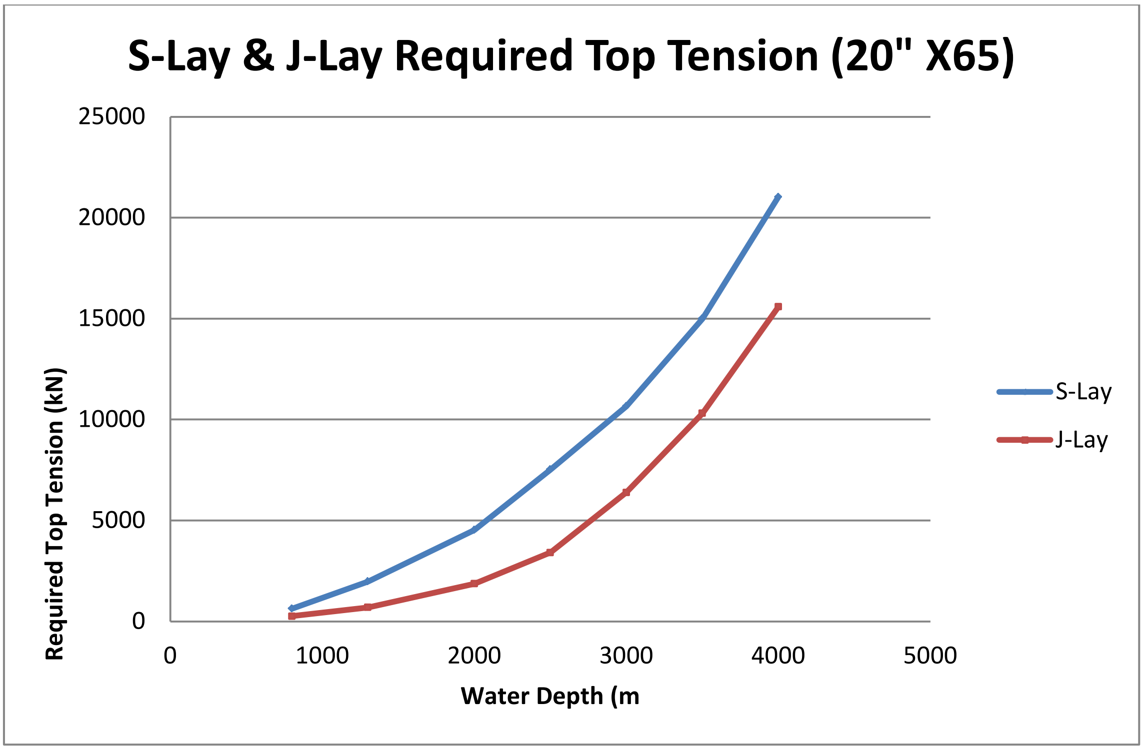

Figure 5-13 : S-Lay and J-Lay Required Top Tension as Function of Water Depth (20"X65)

Table 5-11: 20" Pipe S-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Overbend	DCC Check	LCC Check
800	45	"134/120"	19.10	26.60	630	0.189	0.74	0.39
1300	45	"134/120"	21.00	24.19	1975.97	0.224	0.95	0.39
2000	58	"103/120"	26.50	19.17	4527.65	0.303	0.95	0.90
2500	60	"100/120"	30.50	16.66	7523.41	0.347	0.95	0.74
3000	60	"100/140"	33.50	15.16	10664.1	0.368	0.99	0.70
3500	65	"110/140"	37.80	13.44	13825.7	0.357	0.98	0.83
4000	65	"136/170"	45.00	11.29	21031	0.402	0.90	0.80

The concusions of S-lay installation analysis for 20 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessel up to 2900 m water depth. However it is possible to perform pipeline installation up to 3900 m using the most powerfull upcoming S-Lay vessel (Pieter Schelte);
- Strain in overbend region is within the criteria of 0.25% for X65 only at 800 m and 1300 m water depth. Starting from 2000 m water depth, the strain criteria has been exceeded;
- Combinations of bending moment and external pressure in sagbend area (LCC Check) are less that one at all water depths;
- Departure angles are between 45°- 70°.

Table 5-12: 20" Pipe J-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilizatio n	LCC Check
800	86	19.10	18.62	258.86	0.125	250.0	389.76	0.64	0.39
1300	86	21.00	16.93	692.281	0.105	210.0	389.76	0.54	0.68
2000	86	24.40	14.57	1871	0.070	140.0	389.76	0.36	0.90
2500	86	28.00	12.70	3411.73	0.060	120.0	389.76	0.31	0.90
3000	86	34.50	10.31	6390.02	0.072	144.0	389.76	0.37	0.82
3500	78	37.80	9.41	10309.3	0.096	192.0	389.76	0.49	0.79
4000	75	45.00	7.90	11115.3	0.107	214.0	389.76	0.55	0.68

The concusions of J-lay installation analysis for 20 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessels up to 3500 m water depths. However ; it is possible to perform pipeline installation up to 4000 m using the most powerfull upcoming J-Lay vessel (Aegir-Herema);
- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less that one at all water depths;
- Stress equivalents in sagbend are inside the allowable stress at all water depths;
- Departure angles are between 75°- 90°.

5.3.3 28 inch Pipe Diameter

Figure 5-14 shows the comparison result of installation using S-Lay and J-Lay method for 28 inch pipe diameter, see also Table 5-13 and Table 5-14.

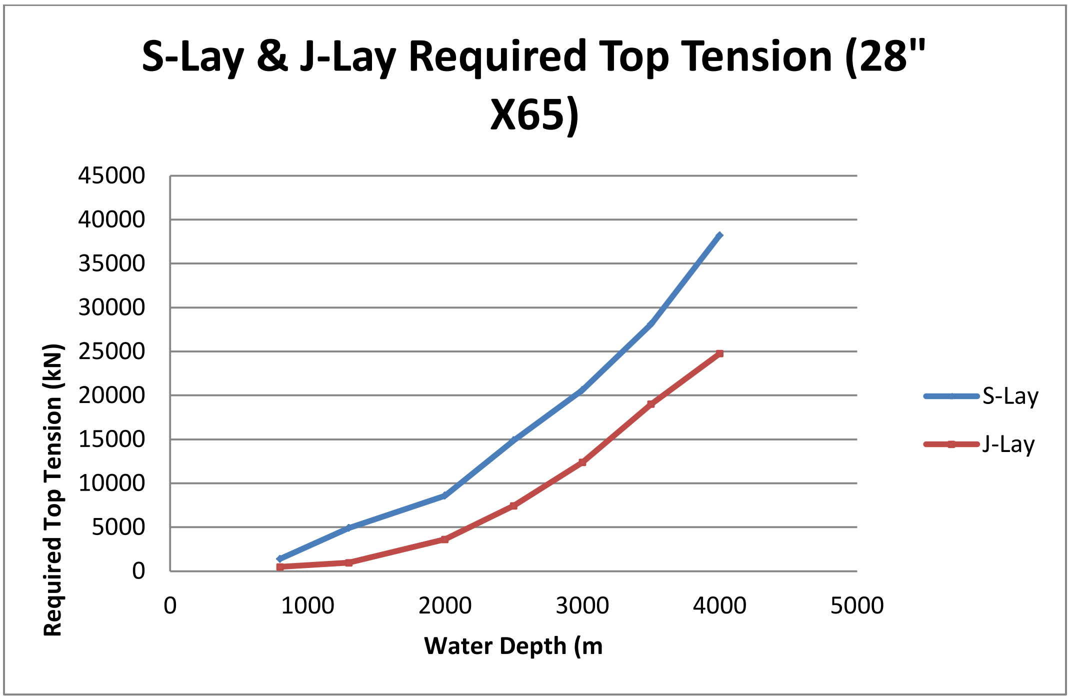

Figure 5-14 : S-Lay and J-Lay Required Top Tension as Function of Water Depth (28"X65)

Table 5-13: 28" Pipe S-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Overbend (%)	DCC Check	LCC Check
800	41	"150/120"	26.60	26.74	1389	0.238	0.78	0.40
1300	38	"160/120"	30.00	23.71	5923.96	0.241	0.92	0.62
2000	60	"100/120"	37.50	18.97	8582.77	0.38	0.96	0.91
2500	60	"100/120"	43.00	16.54	14880.7	0.41	0.96	0.79
3000	55	"160/170"	48.00	14.82	20604.4	0.38	0.97	0.76
3500	65	"135/170"	54.00	13.17	28113.2	0.416	0.98	0.80
4000	65	"135/170"	60.00	11.85	38211.7	0.44	0.98	0.94

The concusions of S-lay installation analysis for 28 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessels up to 2000 m water depth. Pieter Schelte, as the most powerfull upcoming S-Lay vessel can only possibly be used up to 2800 m water depth;
- Strain in overbend region is within the criteria of 0.25% for X65 at 800 m and 1300 m water depth. Starting from 2000 m water depth, this strain criterion has been exceeded;
- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less that one at all water depths;
- Departure angles are between 38°- 70°;
- The distance between the last stinger roller and the pipe is set to be 300 mm for all cases.

Table 5-14: 28" Pipe J-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilization	LCC Check
800	86	26.60	13.37	481.901	0.153	306.00	389.76	0.79	0.40
1300	86	27.70	12.84	963.834	0.125	250.00	389.76	0.64	0.87
2000	86	34.00	10.46	3606.14	0.107	214.00	389.76	0.55	0.92
2500	86	41.00	8.67	7442.67	0.094	188.00	389.76	0.48	0.79
3000	86	48.00	7.41	12374.5	0.101	202.00	389.76	0.52	0.75
3500	80	54.00	6.59	20053.1	0.159	318.00	389.76	0.82	0.75
4000	75	60.00	5.93	30298.1	0.180	360.00	389.76	0.92	0.78

The concusions of J-lay installation analysis for 28 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessels up to 2500 m water depths. Aegir (Herema) as the most powerfull upcoming J-Lay vessel can only possibly be used up to approximately 3400 m water depth;
- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less that one at all water depths;
- Stress equivalents in the sagbend are inside the allowable stress at all water depths;

- Departure angles are between 80˚- 90˚.

5.3.4 30 inch Pipe Diameter

Figure **5-15** shows the comparison result of installation using S-Lay and J-Lay method for 30 inch pipe diameter, see also Table 5-15 and Table 5-16.

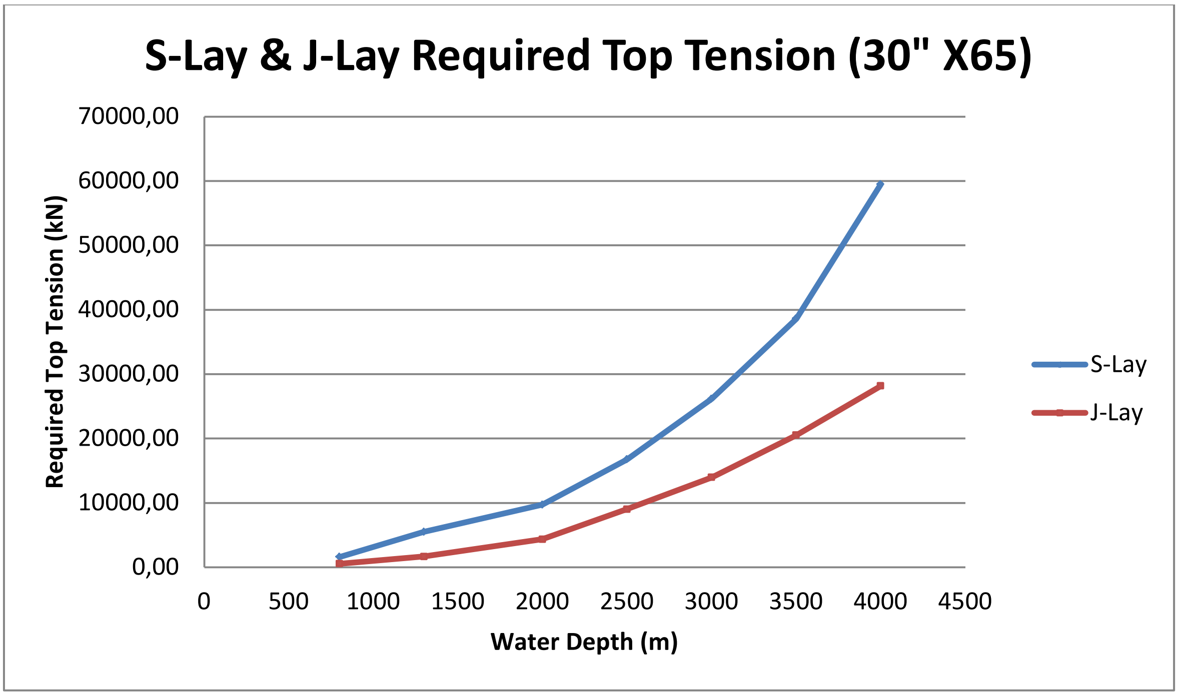

Figure 5-15 : S-Lay and J-Lay Required Top Tension as Function of Water Depth (30"X65)

Table 5-15: 30" Pipe S-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Overbend	DCC Check	LCC Check
800	41	"150/120"	28.50	24.95	1593.26	0.26	0.79	0.39
1300	38	"160/120"	32.00	22.23	6652.45	0.27	0.94	0.64
2000	60	"120/140"	40.00	17.78	9726.61	0.37	0.96	0.86
2500	59	"150/170"	45.00	15.80	16753.30	0.36	0.99	0.74
3000	59	"150/170"	51.00	13.95	26153.50	0.39	0.99	0.77
3500	59	"150/170"	58.00	12.26	38594.90	0.43	0.98	0.78
4000	59	"150/170"	65.00	10.94	59479.60	0.46	0.97	0.92

The concusions of S-lay installation analysis for 30 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessels up to 2000 m water depth. Pieter Schelte can only possibly be used up to 2500 m water depth;
- Strains in overbend region exceeds the criteria of 0.25% for X65 at all water depth;

- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less that one at all water depths;
- Departure angles are between 38˚- 70˚
- The distance between the last stinger roller and the pipe is set to be 300 mm for all cases.

Table 5-16: 30” Pipe J-Lay Result (X65)

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	D/t	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilization	LCC Check
800	86	28.50	12.48	551.76	0.160	320.00	389.76	0.82	0.41
1300	86	29.00	12.26	815.35	0.119	238.00	389.76	0.61	0.97
2000	86	37.00	9.61	4349.47	0.117	234.00	389.76	0.60	0.87
2500	86	45.00	7.90	9024.61	0.103	206.00	389.76	0.53	0.74
3000	86	51.00	6.97	13978.60	0.114	228.00	389.76	0.58	0.76
3500	86	58.00	6.13	20521.80	0.167	334.00	389.76	0.86	0.75
4000	86	65.00	5.47	28171.00	0.180	360.00	389.76	0.92	0.76

The concusions of J-lay installation analysis for 30 inch diameter are:

- Required top tensions were found to be within the tension capacities of existing vessels up to 2500 m water depth. Aegir Herema can only possibly be used up to 3400 m water depth;
- Combinations of bending moment and external pressure in sagbend area (LCC Check) were less that one at all water depths;
- Stress equivalents in sagbend are inside the allowable stress at all water depths;
- Departure angles are between 80˚- 90˚

5.3.5 Summary of Layability of the Pipeline

Table 5-17 presents the summary of layability of the pipeline for S-Lay and J-Lay methods. The previous section presents the summary result for X65 steel grade. Refer to Appendix C for the results of X70 and X80 material grades.

Table 5-17: Summary of Layability of the Pipeline (X65 Steel Grade)

Pipe Diameter	S-Lay		J-Lay
	Limited by Lay Vessel Tension Capacity	Limited by Strain in the Overbend	Limited by Lay Vessel Tension Capacity
14 inch	4000 m	2000 m	4000 m
20 inch	2900 m 1) 3900 m 2)	1300 m	3500 m 3) 4000 m 4)
28 inch	2000 m 1) 2900 m 2)	1300 m	2500 m 3) 3550 m 4)
30 inch	2000 m 1) 2650 m 2)	Exceed the criteria for all water depth	2500 m 3) 3400 m 4)

Note:
1) Using existing S-Lay vessel
2) Using Pieter Schelte (upcoming S-Lay vessel)
3) Using existing J-Lay vessel
4) Using Aegir Herema (Upcomming J-Lay vessel)

Table 5-18: Summary of Layability of the Pipeline (X70 Steel Grade)

Pipe Diameter	S-Lay		J-Lay
	Limited by Lay Vessel Tension Capacity	Limited by Strain in the Overbend	Limited by Lay Vessel Tension Capacity
14 inch	4000 m	2540 m	4000 m
20 inch	2950 m 1) 4000 m 2)	1730 m	2950 m 3) 4000 m 4)
28 inch	2210 m 1) 2900 m 2)	1450 m	3000 m 3) 3700 m 4)
30 inch	2109 m 1) 2720 m 2)	1390 m	2800 m 3) 3600 m 4)

Note:
1) Using existing S-Lay vessel
2) Using Pieter Schelte (upcoming S-Lay vessel)
3) Using existing J-Lay vessel
4) Using Aegir Herema (Upcomming J-Lay vessel)

Table 5-19: Summary of Layability of the Pipeline (X80 Steel Grade)

Pipe Diameter	S-Lay		J-Lay
	Limited by Lay Vessel Tension Capacity	Limited by Strain in the Overbend	Limited by Lay Vessel Tension Capacity
14 inch	4000 m	3100 m	4000 m
20 inch	3160.8 m [1)] 4000 m [2)]	1880 m	3800 [3)] 4000 [4)]
28 inch	2350 m [1)] 3140 m [2)]	1460 m	3210 [3)] 4000 [4)]
30 inch	2950 m [1)] 2700 m [2)]	1407 m	2600 [3)] 3600 [4)]

Note:
1) Using existing S-Lay vessel
2) Using Pieter Schelte (upcoming S-Lay vessel)
3) Using existing J-Lay vessel
4) Using Aegir Herema (Upcomming J-Lay vessel)

5.3.6 Discussions on Results

The conclusions of pipeline installation anlyses are discussed below:

- Using X65 steel grades, the required top tensions for S-Lay method are within the capability of existing lay vessel for 14 inch diameter pipes. However for 20 inch diameter, Pieter Schelte is only possible to be used in water depth less than 3900 m, and in less than 2800 m and 2500 m for 28 inch and 30 inch diameter respectively.
- The strain in the overbend region often exceeds the criteria for X65 and X70 especially in deep water conditions. In deepwater more than 3000 m, the strain is beyond the criteria for all pipe diameters. If this occures in the plastic regime, the pipeline cross section will experience permanent deformations. This condition will reduce the pipe's resistance to external pressure that can cause collapse and pigging problems for the pipeline.
- For 14 and 20 inch pipe diameter, the J-Lay method using X65 steel grade can be performed for pipeline installation up to 4000 m water depth. Aegir (Herema) can only possibly be used for installation in water depth less than 3550 m for 28 inch diameter and in less than 3400 m for 30 inch diameter. Increasing up to 30% of the Aegir lay tension capacity is required in order to carry out installation up to 4000m.
- In the J-Lay method, the requirement to satisfy the strain criteria in the overbend region can be eliminated. However, since the bending moment in the sagbend area is quite higher compared to the S-Lay method; it is necessary to provide sufficient tension to avoid excessive bending that may cause the pipelines to buckle. Excessive bending, local buckling and collapse could happen if the tension at the top is lost due to sudden movements of the ship or any others reasons.

- The J-Lay method is better to be used for installation in deep water compared to S-Lay. For example the J-lay method can install 28 inch pipe diameter up to 3550 m water depth. The tension capacity of the existing vessels is the only factor that limits the layability by the J-Lay method. On the contrary, the S-Lay method is not only limited to the vessel tension capacity but also limited to strain criteria in the overbend area.
- The required top tension for the J-Lay method is lower than for the S-Lay method. However S-Lay has higher production rate compared to J-Lay, causing the S-Lay method to be more efficient to install long pipelines.

5.4 Sensitivity Analysis

5.4.1 Effect of Increasing Material Grades for S-Lay Method

5.4.1.1 X70 Material Grade

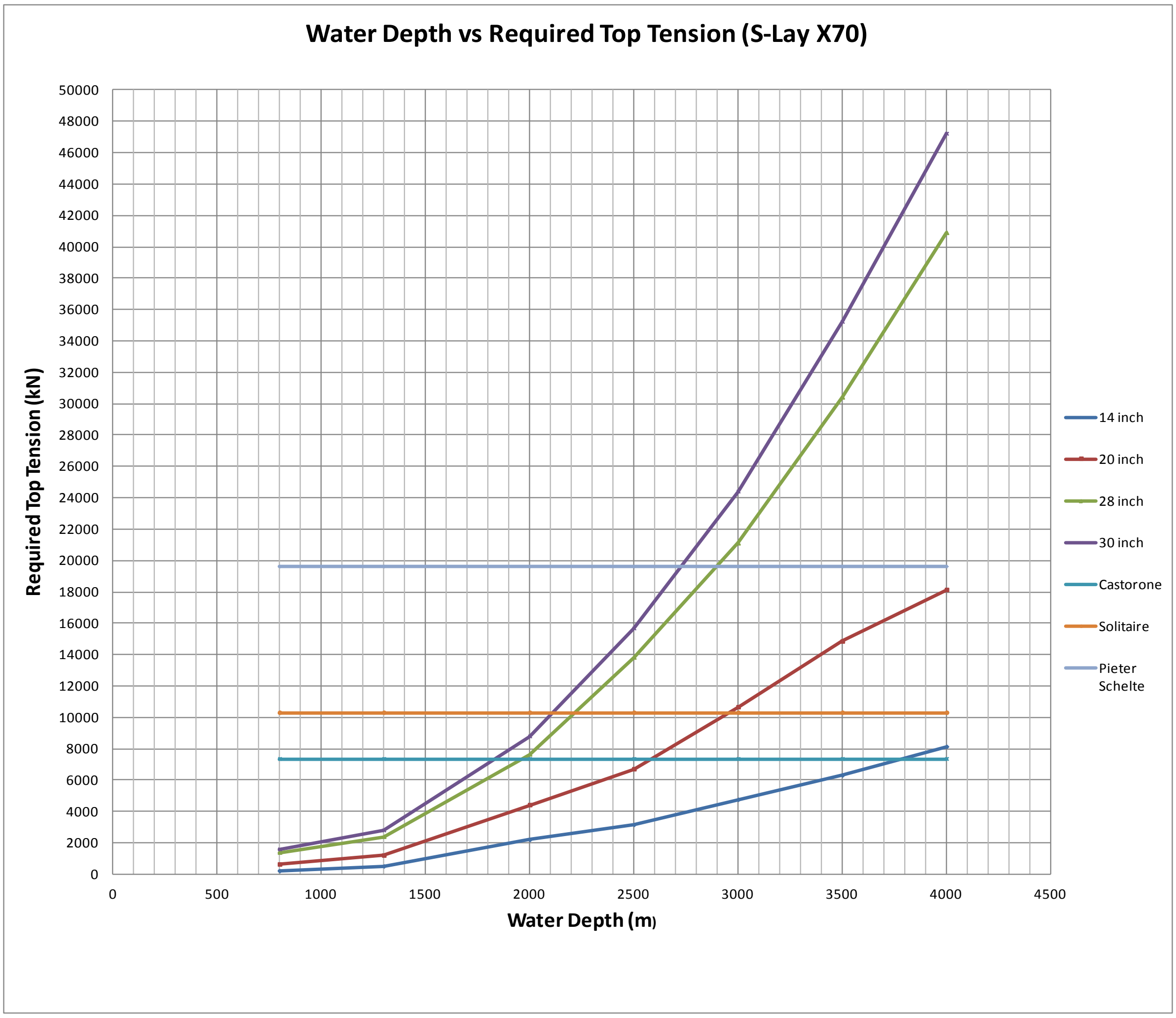

Figure 5-16 : Required Top Tension as Function of Water Depth for S-Lay X70

The result of using X70 steel grade for S-Lay method is shown Figure 5-16, and based on the information in this figure the following conclusions are obtained:

- The required top tensions for 14 inch pipe diameter are within the tension capacity of existing lay vessel for all water depths. Since the required top tension for 14 inch diameter is less than 750 ton, Castorone can be used to install pipeline at water depth less than 3850 m. For water depth more than 3850 m Solitaire can be used as a solution.
- The required top tension for 20 inch pipe diameter is higher compared to requirement for 14 inch diameter. However it is still inside the capacity of Pieter Schelte.
- For 28 inch pipe diameter, the required top tensions increase even steeper. Pieter Schelte can only possibly be used for installations in water depth less than 2900 m.
- And for 30 inch pipe diameter, Pieter Schelte is only possible to be used for installations in water depth less than 2700 m.

5.4.1.2 X80 Material Grade

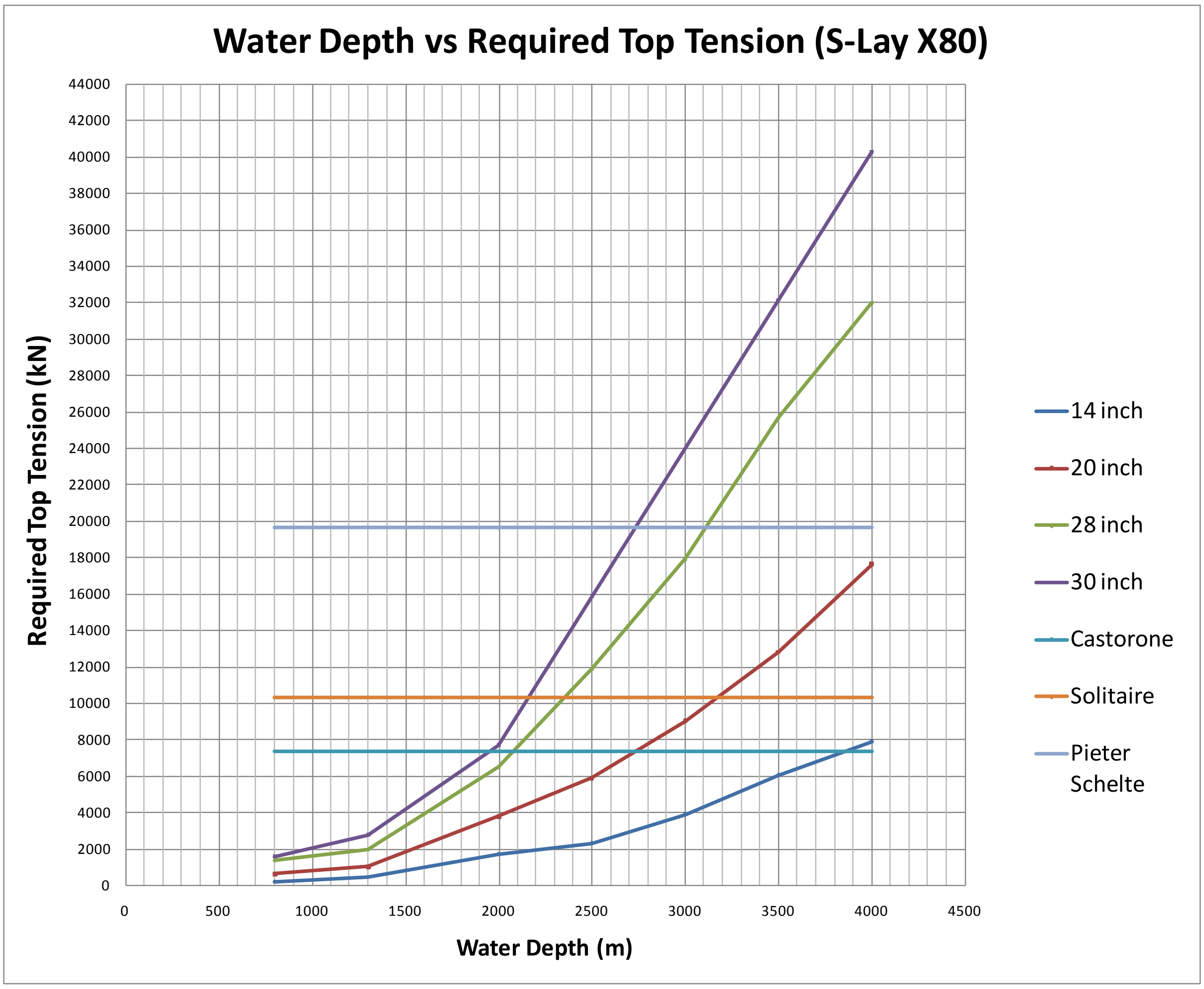

Figure 5-17 : Required Top Tension as Function of Water Depth for S-Lay X80

Even though higher steel grade hasn't been used in industry practice because of the difficulties in welding operations, the study is carried out to find the informations about the required top tension at various water depths. Installation analysis using X80 material grade gave the conclusions as discussed below:

- The required top tensions for 14 inch pipe diameter are within the tension capacity of existing lay vessel for all water depths.

- The required top tension for 20 inch pipe diameter is higher compared to requirement for 14 inch. However, it is still within the capacity of Pieter Schelte.
- For 28 inch pipe diameter, the required top tension increases even steeper. Pieter Schelte can only possibly be used for installations in water depth less than 3100 m.
- And for 30 inch pipe diameter, Pieter Schelte is only possible to be used for installations in water depth less than 2750 m.

5.4.2 Effect of Increasing Material Grades for J-Lay Method

5.4.2.1 X70 Material Grade

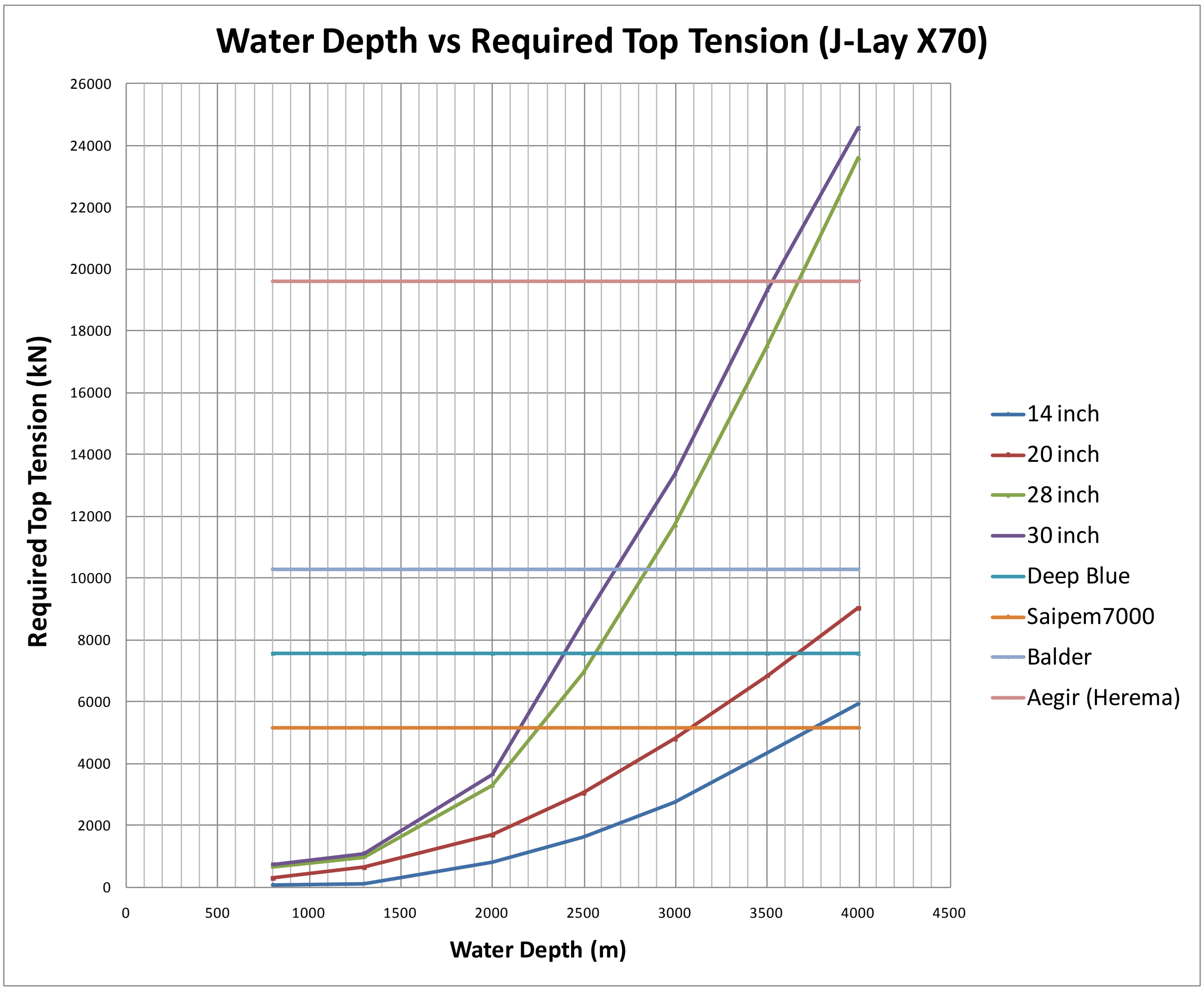

Figure 5-18 : Required Top Tension as Function of Water Depth for J-Lay X70

Based on information from Figure 5-18, the following conclusions are obtained:

- The required top tensions for 14 inch pipe diameter are within the tension capacity of existing lay vessel for all water depths. Saipem 7000 is possible to be used for installation at water depth less than 3750 m. For water depth more than 3750 m Deep Blue can be used as a solution.
- The required top tension for 20 inch pipe diameter is higher compared to requirement for 14 inch diameter. However it is still within the capacity of the existing lay vessels.

- For 28 inch pipe diameter, the required top tension increase even steeper. Aegir (Herema) can only possibly be used for installations in water depths less than 3700 m.
- And for 30 inch pipe diameter, Aegir (Herema) can only possibly be used for installations in water depths less than 3500 m.

5.4.2.2 X80 Material Grade

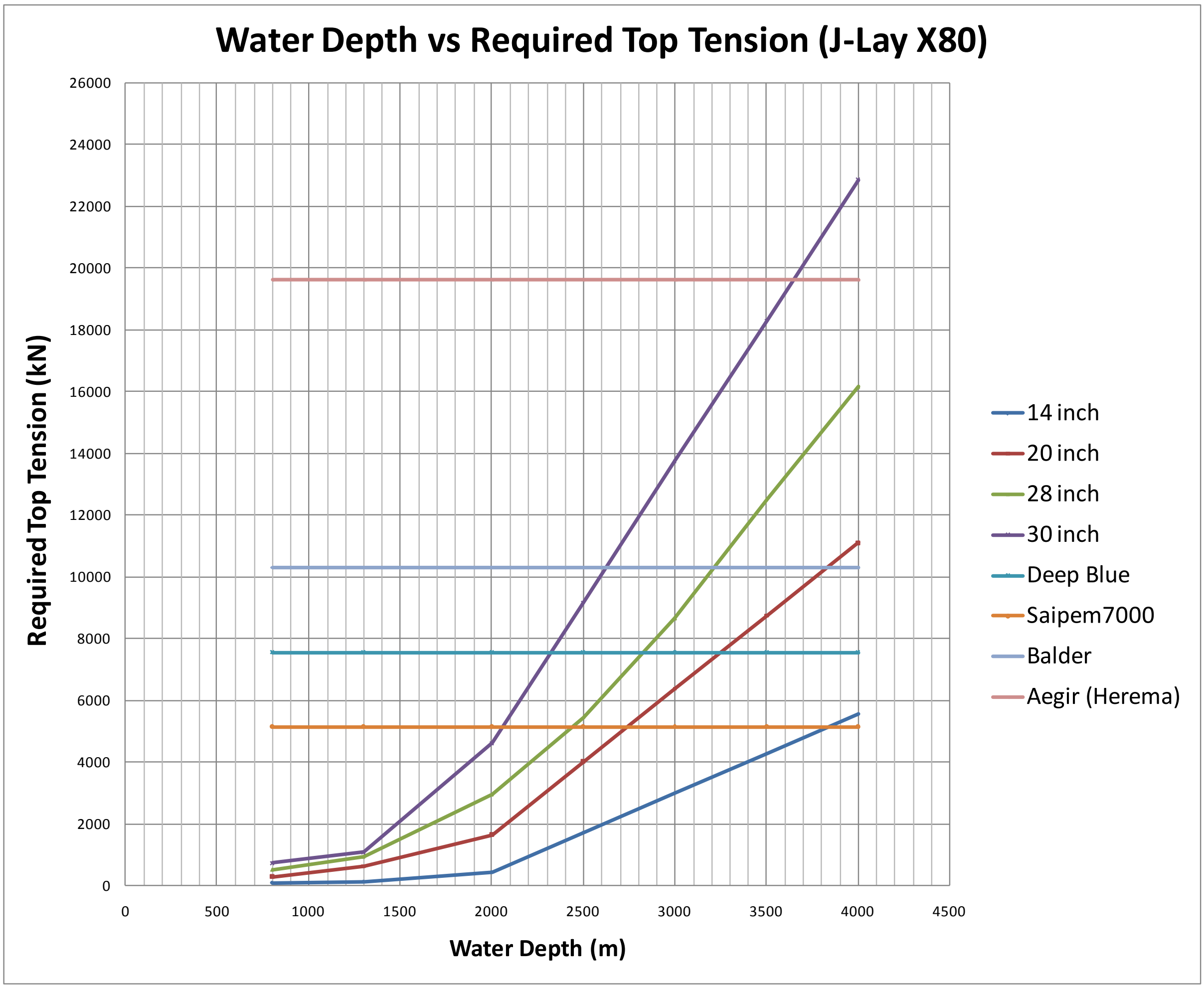

Figure 5-19 : Required Top Tension as Function of Water Depth for J-Lay X80

Even though higher steel grade hasn't been used in industry practice because of the difficulties in welding operations, the study is carried out to find out the informations about required top tension at various water depths. From installation analysis using X80 material grade, the following conclusions are obtained:

- The required top tensions for 14 inch pipe diameter are within the tension capacity of existing lay vessel for all water depths. Saipem 7000 can only possibly be used for installations at water depth less than 3850 m. For water depth more than 3850 m Deep Blue can be used as a solution.
- The required top tension for 20 inch pipe diameter is higher compared to requirement for 14 inch diameter. For 28 inch pipe diameter, the required top tension increase even steeper. However it is still within the capacity of Aegir (Herema).

- For 30 inch pipe diameter, Aegir (Herema) can only possibly be used for installation in water depth less than 3650 m.

5.4.3 Effects of Increasing Allowable Strain in Overbend Region

Increasing the allowable strain in the overbend region from 0.25% (X65) to 0.5% may cause the installation to be possible to be performed in deeper water. In this thesis the effect of this parameter on the required top tension, stinger radius, and departure angle will be studied. More research needs to be done to support the idea to increase the allowable strain and to allow permanent deformations after installation.

5.4.3.1 14 Inch Pipeline Result

Table 5-20 presents results of the S-lay analysis for 14 inch pipe diameter with 0.25% and 0.5% allowable strain in the overbend region.

Table 5-20: Effect of Increasing Allowable Strain In Overbend (14" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800 1)	205.6	0.172	0.03	-38.70	383.20	0.75	55	"110/120"
800 2)	**135.64**	**0.21**	**0.12**	**-113.00**	**383.20**	**0.76**	**71**	**"85/120"**
1300 1)	692.0	0.198	0.01	27.50	421.00	0.92	55	"110/120"
1300 2)	**442.97**	**0.23**	**0.07**	**-79.00**	**421.00**	**0.94**	**71**	**"85/120"**
2000 1)	2171.42	0.235	0.04	-20.89	486.45	0.99	55	"110/120"
2000 2)	**1375.92**	**0.26**	**0.09**	**-60.00**	**486.45**	**0.999**	**71**	**"85/120"**
2500 1)	3890.18	0.268	0.06	-25.09	550.92	0.99	55	"110/120"
2500 2)	**1988.74**	**0.30**	**0.10**	**-126.00**	**550.92**	**1.00**	**80**	**"75/120"**
3000 1)	6029.89	0.303	0.07	-17.56	605.65	0.96	55	"110/120"
3000 2)	**3076.39**	**0.32**	**0.10**	**-120.00**	**605.65**	**0.98**	**80**	**"75/120"**
3500 1)	9515.38	0.31	0.08	-15.82	659.83	0.96	55	"130/140"
3500 2)	**5887.17**	**0.33**	**0.10**	**-100.00**	**659.83**	**0.99**	**72**	**"100/140"**
4000 1)	**12985.0**	0.38	0.09	-20.89	722.80	0.97	**55**	**"130/140"**
4000 2)	**8872.30**	**0.41**	**0.10**	**-20.89**	**722.80**	**1.00**	65	"110/140"

Note:
1: Allowable strain in overbend region is 0.25%, Ref [13]
2: Allowable strain in overbend is increased up to 0.5%

The effects of increasing the allowable strain in the overbend region from 0.25% to 0.5% are:

- Decreasing the required top tension
- Increasing the strain in the sagbend area
- Increasing the bending moment in the sagbend area

- Increasing the departure angle
- Decreasing the stinger radius

The stinger radius is reduced by:

- 25 m or 22.7% at 800m water depth
- 25 m or 22.7% at 1300m water depth
- 25 m or 22.7% at 2000m water depth
- 35 m or 31.8% at 2500m water depth
- 35 m or 31.8% at 3000m water depth
- 30 m or 23.1% at 3500m water depth
- 20 m or 15.4% at 4000m water depth

The required top tension is reduced by:

- 74.77kN or 35.53% at 800m water depth
- 255.55 kN or 36.58% at 1300m water depth
- 816.19 kN or 37.23% at 2000m water depth
- 1901.4 kN or 48.88% at 2500m water depth
- 2953.5 kN or 48.98% at 3000m water depth
- 3257.73 kN or 38.13% at 3500m water depth
- 3152.8 kN or 26.22% at 4000m water depth

In depths up to 2000 m, the overbend strains are inside the allowable criteria (0.25% for X65). Sagbend bending moments for all water depths are less than the allowable bending moments.

Increasing the allowable overbend strain up to 0.5% is not necessary suggested in water depth less than 2000 m. The reasons are because there are other criteria that need to be satisfied, such as allowable bending moment and the layability of the pipe with certain departure angle. S-lay method can be performed up to maximum 80 degrees departure angle depending on water depth and pipe diameter.

5.4.3.2 20 Inch Pipeline Result

Table 5-21 presents the results of the S-lay analysis for 20 inch pipe diameter with 0.25% and 0.5% allowable strain in the overbend region.

Table 5-21: Effect of Increasing Allowable Strain In Overbend (20" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800 1)	630.0	0.189	0.05	-173.00	1122.42	0.74	45	"134/120"
800 2)	**241.20**	**0.33**	**0.19**	**-590.00**	**1122.42**	**0.75**	**80**	**"75/120"**
1300 1)	1975.97	0.224	0.08	-172.21	1220.15	0.95	45	"134/120"
1300 2)	**746.62**	**0.32**	**0.10**	**-560.00**	**1220.15**	**0.99**	**80**	**"75/120"**
2000 1)	4527.65	0.303	0.09	-156.00	1389.16	0.95	58	"103/120"
2000 2)	**2867,36**	**0.34**	**0.10**	**-440.00**	**1389.16**	**0.99**	**80**	**"75/120"**
2500 1)	7523.41	0.347	0.10	-87.00	1560.12	0.95	60	"100/120"
2500 2)	**4552.42**	**0.38**	**0.11**	**-450.00**	**1560.12**	**0.99**	**80**	**"75/120"**
3000 1)	10664.1	0.368	0.09	-88.21	1784.37	0.99	60	"100/140"
3000 2)	**7105.42**	**0.42**	**0.10**	**-480.00**	**1784.37**	**1.00**	**80**	**"75/120"**
3500 1)	13825.70	0.357	0.10	-81.70	1985.81	0.98	65	"110/140"
3500 2)	**10798.70**	**0.42**	**0.11**	**-270.00**	**1985.81**	**0.99**	**80**	**"75/170"**
4000 1)	21031	0.40	0.12	-110.31	2263.80	0.90	65	"136/170"
4000 2)	**19450.90**	**0.46**	**0.14**	**-119.00**	**2263.80**	**0.99**	**68**	**"130/170"**

Note:
1: Allowable strain in overbend region is 0.25%, Ref [13]
2: Allowable strain in overbend is increased up to 0.5%

As one of the effects of increasing allowable strain from 0.25% to 0.5%, the stinger radius is decreased by:

- 75 m or 50 % at 800m water depth
- 85 m or 53.13 % at 1300m water depth
- 23 m or 23 % at 2000m water depth
- 23 m or 23 % at 2500m water depth
- 50 m or 31.25% at 3000m water depth
- 17 m or 12.59% at 3500m water depth
- 5 m or 3.70 % at 4000m water depth

And the required top tension will be reduced by:

- 202.07 kN or 45.59 % at 800m water depth
- 418.95 kN or 35.94 % at 1300m water depth
- 1217.60 kN or 36.67 % at 2000m water depth
- 2429.57 kN or 39.49 % at 2500m water depth

- 3224.86 kN or 33.37 % at 3000m water depth
- 3027.0 kN or 21.89 % at 3500m water depth
- 12185 kN or 38.51 % at 4000m water depth

Using steel grade X65, the overbend strains are inside the allowable criteria only in water depths less than 1300 m. However bending moments in the sagbend region are less than the allowable bending moments for all water depths.

5.4.3.3 28 Inch Pipeline Result

Table 5-22 presents the results of the S-lay analysis for 28 inch pipe diameter with 0.25% and 0.5% allowable strain in the overbend region.

Table 5-22: Effect of Increasing Allowable Strain In Overbend (28" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800 1)	1389.00	0.238	0.04	-292.00	3065.63	0.78	41	"150/120"
800 2)	**443.76**	**0.45**	**0.20**	**-2860.00**	**3065.63**	**0.79**	**80**	**"75/120"**
1300 1)	5923.96	0.241	0.07	-291.30	3177.46	0.92	38	"160/120"
1300 2)	**2228.59**	**0.47**	**0.08**	**-2240.00**	**3177.46**	**0.95**	**80**	**"75/120"**
2000 1)	8582.77	0.38	0.08	-144.32	3796.60	0.96	60	"100/120"
2000 2)	**5429.46**	**0.47**	**0.10**	**-1650.00**	**3796.60**	**0.99**	**78**	**"77/120"**
2500 1)	14880.7	0.41	0.09	-44.50	4443.15	0.96	60	"100/120"
2500 2)	**9440.32**	**0.47**	**0.10**	**-1520.00**	**4443.15**	**0.99**	**78**	**"77/120"**
3000 1)	20604.40	0.38	0.097	-416.00	5047.96	0.97	55	"160/170"
3000 2)	**13429.30**	**0.41**	**0.10**	**-2110.00**	**5047.96**	**0.99**	**80**	**"110/170"**
3500 1)	28113.20	0.416	0.11	-504.00	5534.53	0.98	65	"135/170"
3500 2)	**21939.00**	**0.42**	**0.12**	**-1071.00**	**5534.53**	**0.99**	**75**	**"118/170"**
4000 1)	38211.70	0.44	0.14	-505.00	5992.91	0.98	65	"135/170"
4000 2)	**35271.50**	**0.45**	**0.15**	**-584.00**	**5992.91**	**0.99**	**68**	**"130/170"**

Note:
1: Allowable strain in overbend region is 0.25%, Ref [13]
2: Allowable strain in overbend is increased up to 0.5%

As one of the effects of increasing allowable strain from 0.25% to 0.5%, the stinger radius is decreased by:

- 75 m or 50 % at 800m water depth
- 85 m or 53.13 % at 1300m water depth
- 23 m or 23 % at 2000m water depth

- 23 m or 23 % at 2500m water depth
- 50 m or 31.25% at 3000m water depth
- 17 m or 12.59% at 3500m water depth
- 5 m or 3.70 % at 4000m water depth

And the required top tension will be reduced by:

- 945.24 kN or 68.05 % at 800m water depth
- 1619.08 kN or 62.38 % at 1300m water depth
- 2352.03 kN or 36.74 % at 2000m water depth
- 4884.14 kN or 36.56 % at 2500m water depth
- 7175.10 kN or 34.82 % at 3000m water depth
- 6174.20 kN or 21.96 % at 3500m water depth
- 2940.20 kN or 7.69 % at 4000m water depth

Using steel grade X65, the overbend strains are inside the allowable criteria only in water depths less than 1300 m. However bending moments in the sagbend region are less than the allowable bending moments for all water depths.

5.4.3.4 30 Inch Pipeline Result

Table 5-23 presents the results of the S-lay analysis for 30 inch pipe diameter with 0.25% and 0.5% allowable strain in the overbend region.

Table 5-23: Effect of Increasing Allowable Strain In Overbend (30" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800[1)]	1593.26	0.26	0.05	-38.50	3770.59	0.79	41	"150/120"
800[2)]	**525.74**	**0.462**	**0.166**	**-3290**	**3770.59**	**0.80**	**78**	**"77/120"**
1300[1)]	6652.45	0.27	0.08	-192.60	3770.59	0.94	38	"160/120"
1300[2)]	**1727.64**	**0.491**	**0.085**	**-3000**	**3770.59**	**0.97**	**82**	**"73/120"**
2000[1)]	9726.61	0.37	0.09	-590.00	4732.10	0.96	60	"120/140"
2000[2)]	**6153.05**	**0.5**	**0.095**	**-2195**	**4732.10**	**0.99**	**78**	**"77/120"**
2500[1)]	16753.30	0.36	0.09	-560.00	5574.24	0.99	59	"150/170"
2500[2)]	**9891.26**	**0.404**	**0.098**	**-2700**	**5574.24**	**0.99**	**80**	**"110/170"**
3000[1)]	26153.50	0.39	0.11	-613.00	6167.60	0.99	59	"150/170"
3000[2)]	**15416.7**	**0.43**	**0.13**	**-2600**	**6167.60**	**1.00**	**80**	**"110/170"**
3500[1)]	38594.90	0.43	0.13	-667.00	6820.13	0.98	59	"150/170"
3500[2)]	**25871.3**	**0.434**	**0.15**	**-1294**	**6820.13**	**0.99**	**80**	**"110/170"**

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
4000[1)]	59479.60	0.46	0.15	-634.00	7431.58	0.97	59	"150/170"
4000[2)]	**41189.8**	**0.476**	**0.17**	**-772**	**7431.58**	**0.99**	**68**	**"130/170"**

Note:
1: Allowable strain in overbend region is 0.25%, Ref [13]
2: Allowable strain in overbend is increased up to 0.5%

As one of the effects of increasing allowable strain from 0.25% to 0.5%, the stinger radius is decreased by:

- 73 m or 48.67 % at 800m water depth
- 87 m or 54.38 % at 1300m water depth
- 43 m or 35.83 % at 2000m water depth
- 40 m or 26.67% at 2500m water depth
- 40 m or 26.67% at 3000m water depth
- 40 m or 26.67% at 3500m water depth
- 20 m or 13.33% at 4000m water depth

And the required top tension will be reduced by:

- 1067.52 □kN or 67.00% at 800m water depth
- 2204.93 kN or 74.03% at 1300m water depth
- 2838.79 kN or 36.74% at 2000m water depth
- 6862.04 kN or 40.96% at 2500m water depth
- 10736.80 kN or 41.05% at 3000m water depth
- 12723.60 kN or 32.97% at 3500m water depth
- 18289.80 kN or 30.75% at 4000m water depth

Using steel grade X65, the overbend strains are inside the allowable criteria only in water depths less than 1300 m. However bending moments in the sagbend region are less than the allowable bending moments for all water depths.

5.4.3.5 Evaluations of Results

The effects of increasing allowable strain in the overbend region up to 5% are discussed below.

Stinger radius

One of the factors that can change the strain in the overbend region is stinger configuration. The stinger configuration is controlled by stinger radius and departure angle. Increasing of the strain in the overbend region can be achieved by reducing the stinger radius.

Top tension

Top tension is the important factor that needs to be considered for laying the pipe with S-Lay method. The availability of lay vessel with sufficient tension capacity often limits the pipe layability especially in deep and ultra deep waters. With lower top tension, we not only can increase the pipe layability but also reduce the required cost. Lower required top tension can be achieved by allowing higher strain in overbend region. To reduce the tension, stinger configuration can be set by reducing stinger radius and increasing the departure angle. The steeper departure angle the lower top tension will be, and the configuration will closer to the J shape. This is the reasons why the required top tension for the J-Lay method is less than for the S-Lay method.

Sagbend bending moment

Bending moment in sagbend area is affected by the position of the touch down point relative to the vessel. The closer touch down point to the vessel the bigger sagbend bending moment will be. One of the factors that control the touch down point position is top tension. Lower top tension as result of the increase in allowable overbend strain will cause the touch down location closer to the vessel. Another factor that can increase the sagbend bending moment is stinger radius. To increase strain in the overbend region, lower stinger radius is required. Lower stinger radius will create higher departure angle, furthermore higher departure angle will reduce the required tension.

Departure angle

Departure angle is inverserly proportional to the stinger radius. Stinger radius is reduced with increasing the allowable strain in the overbend. On the contrary, departure angle will increase with increasing the allowable overbend strain.

5.4.4 Effect of Reducing the Stinger Length with Same Departure Angle

In this section, another sensitivity study's result is presented. This study is to identify the effect of reducing the stinger length to the strain limit in the overbend area and the effect to the required top tension. In section 5.3, the results using stinger lengths associated with existing S-Lay vessels are presented. These existing vessels are Castorone with 120 m stinger length, Solitaire with 140 m stinger length and the future S-Lay vessel, Pieter Schelte with 170 m stinger length.

Using the existing stinger lengths, the strain in the overbend region satisfies the requirement for some water depths. For example for 14 inch diameter, the pipe with X65 grade can be installed in up to 2000 m water depth, while for 20 inch, 28 inch and 30 inch, pipelines can only possibly be installed up to 1300m water depth.

In this section thepossibility of stinger length reduction will be investigated to reach the maximum permissible strain in the overbend region. In this case the maximum permissible strain in the overbend region is 0.25% for X65. The results for this study are presented in Table 5-24, Table 5-25, and Table 5-26 for 14 inch, 20 inch, and 28 inch pipe diameters respectively. 30 inch pipe diameter is not included in this sensitivity study since the strain in the overbend using existing stinger length has already reached the maximum permissible strain.

Table 5-24: Effect of Reducing the Stinger Length (14" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800[1)]	205.60	0.172	-38.7	383.20	0.75	55	"110/120"
800[2)]	**208.32**	**0.243**	**-41.00**	**383.20**	**0.78**	**55**	**"73/85"**
1300[1)]	692.00	0.198	27.50	421.00	0.92	55	"110/120"
1300[2)]	**695.50**	**0.230**	**-28.00**	**421.00**	**0.98**	**55**	**"88.5/100"**
2000[1)]	2171.42	0.235	-20.89	486.45	0.99	55	"110/120"
2000[2)]	**2176.45**	**0.246**	**-22.00**	**486.45**	**0.99**	**55**	**"104/115"**

Note:
1: The results using stinger length associated with existing S-Lay vessel
2: The results after reducing the stinger length

The following conclusions can be drawn based on result presented in Table 5-24:

- For 14 inch pipe diameter, the reduction of stinger length can only possibly be done in up to 2000 m water depth. The reason is because the straincriteria in the overbend region have been exceeded for water depths more than 2000 m;
- The stinger length can possibly be reduced up to 35 m, 20 m and 5 m in 800 m, 1300 m and 2000m water depth respectively. This reduction is significant for 800 m and 1300 m water depth since the strain in the overbend region with the initial stinger length is quite far from the maximum permissible strain criteria. In 2000 m water depth, the reduction is small because the strain in the overbend region is very close to the allowable criteria.

Table 5-25: Effect of Reducing the Stinger Length (20" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800[1)]	630.00	0.189	-173.00	1122.42	0.74	45	"134/120"
800[2)]	**634.03**	**0.252**	**-200.00**	**1122.42**	**0.76**	**45**	**"102/95"**
1300[1)]	1975.97	0.224	-172.21	1220.15	0.95	45	"134/120"
1300[2)]	**1982.55**	**0.244**	**-64.00**	**1220.15**	**0.98**	**45**	**"114/100"**

Note:
1: The results using stinger length associated with existing S-Lay vessel
2: The results after reducing the stinger length

The following conclusions can be drawn based on results presented in Table 5-25 :

- For the 20 inch pipe diameter, the reduction of stinger length can only possibly be done in up to 1300 m water depth. This is because the strain criteria in the overbend region for water depth more than 1300 m have been exceeded;
- The stinger length can possibly be reducedup to 24 meter in 800 m water depth and up to 20 m in 1300 m water depth. This reduction is significant since the strain in the overbend region with the initial stinger length is quite far from allowable criteria.

Table 5-26: Effect of Reducing the Stinger Length (28" Pipe Diameter)

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Sagbend Bending Moment (kNm)	Allowable Bending Moment (kNm)	DCC Check	Departure Angle	Stinger Radius/Length
800[1)]	1389.00	0.238	-292.00	3065.63	0.78	41	"150/120"
800[2)]	**1393.12**	**0.256**	**-290.00**	**3065.63**	**0.80**	**41**	**"140/115"**
1300[1)]	5923.96	0.241	-291.30	3177.46	0.81	38	"160/120"
1300[2)]	**5935.0**	**0.259**	**-152.00**	**3177.46**	**0.86**	**38**	**"151/115"**

Note:
1: The results using stinger length associated with existing S-Lay vessel
2: The results after reducing the stinger length

The conclusion can be drawn based on result presented in Table 5-26:

- For the 28 inch pipe diameter, the reduction of stinger length can only possibly be done in up to 1300 m water depth;
- Both for 800 m and 1300 m water depth, the strain in the overbend region is very close to the allowable criteria. Therefore the stinger length can only possibly be reduced by less than 5 meter;
- Another impact due to the reduction of the stinger length is the required top tension and the stinger radius. The required top tension is increased when decreasing the stinger length while the stinger radius is decreased when decreasing the stinger length.

5.4.4.1 Discussion of Results

Reducing the stinger length that is followed by reducing the stinger radius will lead to increasing the strain in the overbend region. Sufficient length of the stinger is required to avoid excessive bending that may cause the pipelines to buckle. The following figure shows the effect to the stinger configurationof reducing the stinger length.

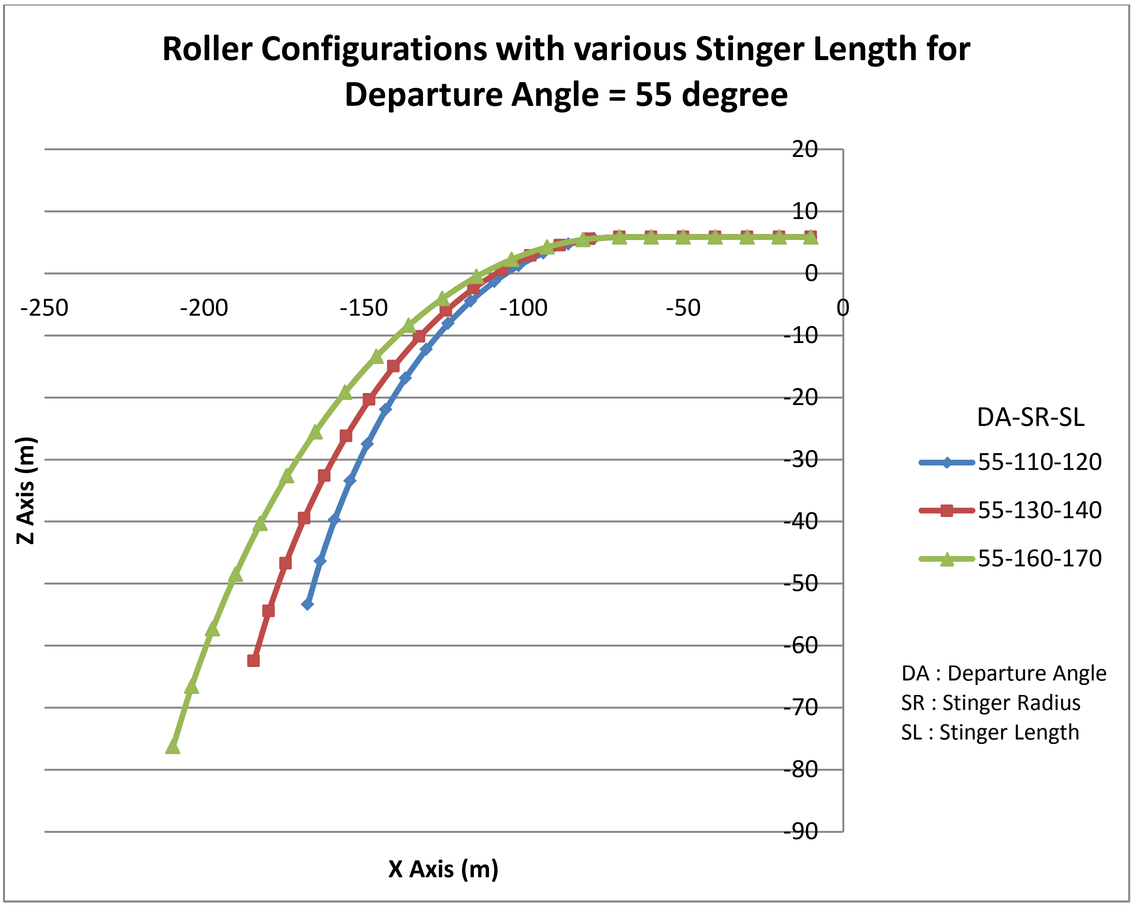

Figure 5-20 : Roller Configurations with Various Stinger Lengths for 55 degree Departure Angle

Considering the same departure angle, the roller configuration is steeper for shorter stinger length. This is indicated in Figure 6-1. The roller configuration for the 120 m stinger length is steeper than the configuration with the 140 m stinger length, and so on. Figure 6-1 proves thata shorter stinger length will cause the steeper configuration and the steeper configuration will lead to increasing the strain in the overbend region.

5.4.5 Effect of Reducing the Stinger Length with Same Stinger Radius

In the previous section, the effect of reducing the stinger length with same departure angle has been performed. Since the stinger configuration is controlled by both departure angle and stinger radius, it is also interesting to study the effect of reducing stinger length with same stinger radius. Refer to equation (4.1) for relation of stinger length, departure angle, and stinger radius.

With the same stinger radius, reducing the length of stinger will followed by decreasing departure angle. Considering equation (4.1), the relation of stinger radius and departure angle is presented in Table 4-5. Let's consider 110 m stinger radius for three types of S-Lay vessel, i.e. Castorone with 120 m stinger length, Solitaire with 140 m stinger length and Pieter Schelte with 170 m stinger length. Based on information from Table 4-5, departure angle for each type of vessel is summarized in the following table.

Table 5-27: Stinger Radius vs Departure Angle

Stinger Radius (R_{sti})	Departure Angle (degree)		
	Castorone (L_{sti} =120m)	Solitaire (L_{sti} =140 m)	Pieter Schelte (L_{sti} =170 m)
110	54.72	65.14	80.78

This study is carried out only for pipeline installation of 14 inch pipe diameter in 2000 m water depth. The result is shown in Table 5-28 and Figure 5-21.

Table 5-28: Stinger Radius vs Departure Angle

Water Depth (m)	Top Tension (kN)	Strain in Overbend (%)	Stinger Radius	Departure Angle	Stinger Length
2000	2171.42	0,235	110	54.72	120
2000	1603.58	0.232	110	65.14	140
2000	1103.91	0.221	110	80.78	170

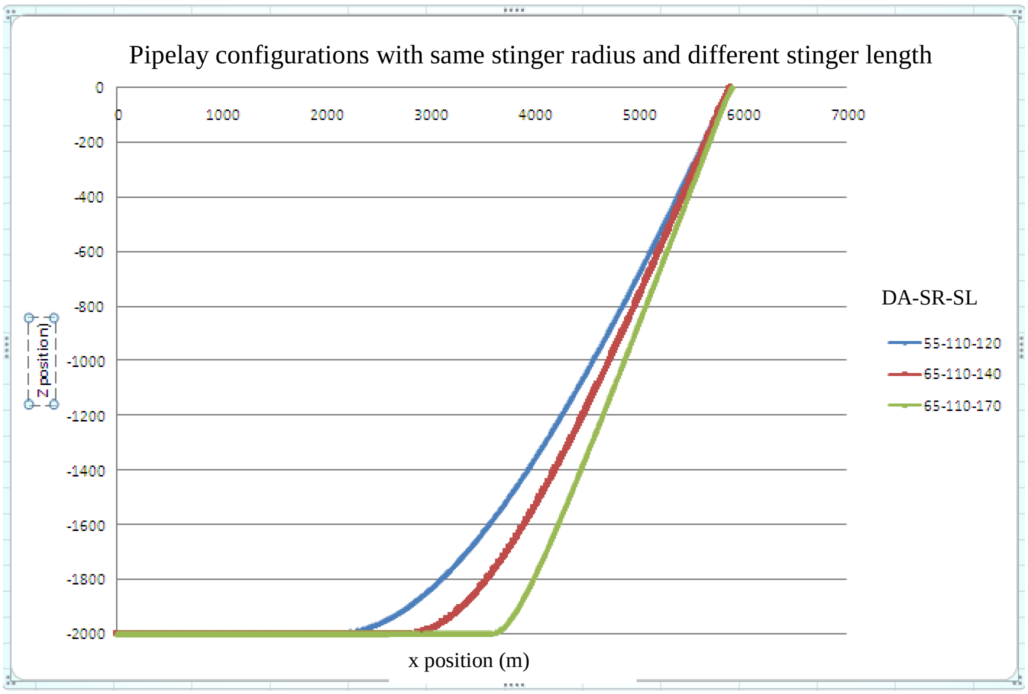

Figure 5-21 : Pipelay Configurations with Different Stinger Length

The required top tension using 140 m stinger length is bigger than using 170 m stinger length. The required top tension is increased as reducing the stinger length. With longer stinger length, the lower required top tension can be achieved.

This study is validated by comparing the result with the following figure which is taken from NOU1974:40, Ref [34].

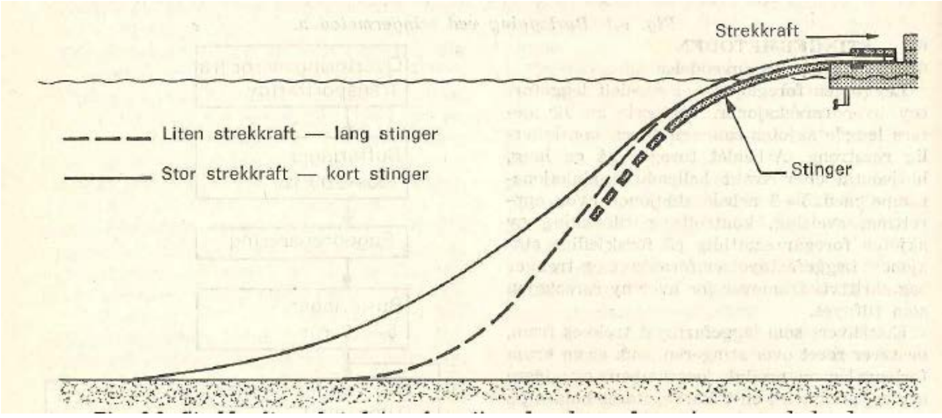

Figure 5-22 : Pipelay Configurations with Different Stinger Length, Ref [34]

5.5 Comparison Results from Simla vs OFFPIPE vs Orcaflex

The installation analysis results from SIMLA are compared to corresponding results obtained from ORCAFLEX and OFFPIPE. Thic comparison results presented in this section areonly for 2000 m water depth and are shown in the following Table 5-29.

Table 5-29: Comparison Results for the S-Lay Method

14"	
Software	**Required Top Tension (kN)**
SIMLA	2171.42
OFFPIPE	2098.03
ORCAFLEX	2190,00
Manual Calculation	2162,65
20"	
SIMLA	4527.65
OFFPIPE	4527.65
ORCAFLEX	4390.0
Manual Calculation	4629.0
28"	
SIMLA	8582.77
OFFPIPE	8588.46
ORCAFLEX	8890.0
Manual Calculation	8771.0

Table 5-30: Comparison Results fot the J-Lay Method

14"	
Software	**Required Top Tension (kN)**
SIMLA	988,78
OFFPIPE	949,00
ORCAFLEX	970,00
Manual Calculation	951,28
20"	
SIMLA	1871.0
OFFPIPE	1871.3
ORCAFLEX	1800.00
Manual Calculation	1840.0
28"	
SIMLA	3606.14
OFFPIPE	3605.0
ORCAFLEX	3550,00
Manual Calculation	3552

Table 5-29 and Table 5-30 show good match between SIMLA and RIFLEX/OFFPIPE for static analysis and linear elastic material. Results obtained from SIMLA and OFFPIPE are slightly larger compared to ORCAFLEX results. For the detailes of the manual calculations, please refer to Appendix C.

CHAPTER 6 CONCLUSIONS AND FURTHER STUDIES

6.1 Conclusions

The following conclusions can be drawn from the present study about pipeline installation:

- Design and installation in deeper water conditions give more challenges compared to shallower water. One of these challenges is high external pressure that can affect propagation buckling. Besides that, the installation capacity in the deeper water is also limited by to the vessel tension capacity and excessive strain in the overbend region may cause the pipelines to buckle for S-Lay method. For the J-Lay, buckling due to excessive bending in the sagbend region can be the critical challenges in deeper water conditions.
- Using higher steel grades will decrease the required wall thickness. This effect is getting higher as installation go to the deeper water. It can be seen that by changing the grade from X65 to X100, the thickness is decreased about 4% for 800 m water depth while for 4000 m water depth the decrease can be around 26%. The reason is because the total pipe length extending from the vessel to the seabed is increased in deeper waters; therefore the submerged weight due to reduction of the thickness is decreased proportionally.
- The wall thickness is decreased by around 12 % up to 16 % due to the effect of reducing the required ovality from 3% to 0.5%. This effect is higher for bigger pipe diameter. Decreasing the wall thickness requirement has advantages such as reducing that required top tension that can increase the layability of the pipe. However, by decreasing the allowable pipeline ovality from 3.0% to 0.5% will give another challenge related to external pressure in deep water. The high external pressure in deeper water will always cause further ovalization and will decrease the collapse resistance of the pipeline.
- The required top tension for the J-Lay method is lower than for the S-Lay method. The difference in required top tension is higher with increasing water depths and pipeline diameters. However the S-Lay method has a higher production rate compared to J-Lay, causing the S-Lay method to be more efficient to install long pipelines.
- Using X650 steel grade, 14 inch pipelines are able to be installed in up to 4000 m water depths. For 20 inch diameter, pipeline can be installed up to 3500 m using existing J-Lay vessel and up to 4000 m using upcoming J-Lay vesse. For the 28 inch and 30 inch pipe diameter, Aeigir Herema, the most powerful upcoming J-Lay vessel is only possible to be used for installation in up to 3400 m.
- For the S-Lay method, due to exceeding the strain criteria in the overbend region or its combination with exceeding the tension capacity of the existing vessel, pipelines are only installable in limited water depth. For example for 14 inch diameter, the pipe with X65 grade can be installed in up to 2000 m water depth, while for 20 inch, 28 inch pipelines are only possible to be installed in up to 1500 m.

- Using higher steel grade could increase the possibility of pipeline installation in deeper water both for S-Lay and J-Lay method. The reason is because the required wall thickness is decreased as increasing the steel grades. Beside that, the maximum permissible strain in the overbend region is increased as increasing the steel grade. Based on DNV-OS-F101 (2007) the maximum permissible strain for X65 is 0.25% and this allowable strain is increased for X70 up to 0.27%.
- The strain in the overbend region depends on the stinger configuration. The stinger configuration is controlled by the stinger radius and departure angle. Increasing the strain in the overbend region can be achieved by reducing the stinger radius. Furthermore, the departure angle will increase with increasing the allowable overbend strain. Therefore a steeper lay is achieved by increasing the departure angle and this will reduce the requirement for top tension from the vessels. As a function of reduction in required top tension, the bending moments in the sagbend region will increase.
- Another advantage of allowing the strain in the overbend region up to 0.5 % is increasing the opportunity to install pipelines with S-Lay method in deeper water. The reason is because the required top tension decreases when increasing the strain in the overbend region.
- The stinger radius is decreased by 15% to 30% when increasing the allowable strain in the overbend region from 0.25% (X65) up to 0.5%. The stinger radius reductions are bigger for bigger diameters. The required top tensions are reduced by about 26%-50% and this reduction is higher for the bigger pipe diameters.
- Reduction of stinger length can only possibly be done in up to water depths of 2000 m for the 14 inch pipe diameter and in up to 1300 m water depth for 20 inch and 28 inch pipe diameter. Using 30 inch pipe diameter, a reduction of stinger length is not possible since the strain in the overbend area has reached the maximum permissible value. The stinger reduction is significant, i.e. from 20 m to 35 m for 14 inch and 20 inch pipe diameter. On the contrary for 28 inch pipe diameter, the reductions can not be more than 5 m.
- The required top tension is increased as reducing the stinger length. And the strain is also increased as reducing the stinger length. Sufficient length of the stinger is required to avoid excessive bending that may cause the pipelines to buckle.
- The analysis results obtained from SIMLA, OFFPIPE and ORCAFLEC for static analysis are same with very negligible deviations.

6.2 Further Studies

In order to get better understanding about pipeline installation, it is recommended that further research be undertaken in the following points:

- To represent actual condition, pipeline installation analysis might be carried out for uneven seabed conditions with different topography, different soils types toidentify all the challenges and solutions for installations in these conditions.
- In this thesis, the pipe is assumed to be empty during installation. Further studies should be made to investigate the effect of water filling.

- Dynamic analysis should be carried out since in the actual condition dynamic motions due to waves and vessel motions can not be avoided. Dynamic analysis is important to increase the confidence of layability and for conservative reasons. In addition dynamic analysis become important issue to be considered since this will limit the weather when pipelines can be installed.
- If pipeline insulation and coating are required, this should be considered in the analysis as these weights will give a contribution to the total weight of the pipeline that needs to be laid.
- This thesis investigates the effect of increasing the allowable strain in the overbend area, and as a result the required top tension is reduced. With lower top tension, we not only can increase the pipe layability but also reduce the required cost. Considering this advantage, further studies need to be performed to learn more about plastic strain in the overbend region.
- The effect of pipe rotation during installation would also be investigated infurther studies

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APPENDICES

APPENDIX A : INPUT FILES

This study carried out 112 cases pipe installation for each method, i.e. S-Lay and J-Lay methods. However this appendix only covers one example of the input file. It will be typical for different water depths, diameters, steel grades, and pipe ovalities.

The example is for the 14 inch outer diameter pipeline at 800 m water depth installed by S-lay method.

A.1 Model Input File

```
HEAD DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110
# Control data:
#          maxit      ndim       isolvr     npoint     ipri       conr       gacc       iproc
CONTROL    500        3          1          8          1          1e-05      9.81       autostart
#          ie1pip     ie2pip     incpip     nrolls     icaten     ivsnod
           1          1200       1          22         1          1201
#          tens0      depang     freeb      rampan     rample     stirad     kptdp
           0          0.959931   11.5       0.0        70.0       110.0      5000.0
#          seabedgrp  stggrp     vegrp      vessel CG
           seabed     stroll1    vessel     300002

# ---
# Defining visualization parameters:
#              mode           factor         results
VISRES         integration    1.0            sigma-xx strain-xx sigma-yy strain-yy

# ---
# HLA-visualization:
#              host           port           federation     federate       logfile
HLA            127.0.0.1      0              "s-lay"        "s-lay"        "s-lay.log"

#          Kind       Type       ID         Name
HLAVIS     body       Node       300002     S-vessel
#          objtype    elgrp      node1      node2
HLAVIS     tpipe      pipe1      1          1201
#          objtype    elgrp      node1      node2
HLAVIS     body       TDP        TDP

# ---
#          Type       Data
HLAPLOT    Tension    0.0        0.0
HLAPLOT    SoilMob    30.0
HLAPLOT    RouteDev   10.0
HLAPLOT    SagUtil    stress     448000000.0
HLAPLOT    LayBack
HLAPLOT    TowerDist
HLAPLOT    RollDist   500322

# ---
# Units used (for correct display in plots)
#          mass       length     time
UNITS      1.0        1.0        1.0

# ---
# Analysis time control:
# This analysis runs the autostart routine.
#        t        dt       dtvi     dtdy     dt0      type          hla control
TIMECO   1.0      1.0      1.0      1.0      1.0      STATIC        NOHLA

TIMECO   91.0     1.0      10.0     10.0     10.0     STATIC-SIMLA  HLA

# Building up model:
# Node input:
#              Pipe nodes     no             x              y              z
NOCOOR         coordinates    1              0.000          0.000          11.500
                              1201           2400.000       0.000          11.500

#              Sea nodes      no             x              y              z
NOCOOR         coordinates    200101         150.0          80.0           0.0
                              200102         0.0            80.0           0.0
                              200103         0.0            100.0          0.0
                              200104         150.0          100.0          0.0

#              Vessel         no             x              y              z
NOCOOR         coordinates    300001         2400.0         0.0            5.0
                              300002         2405.0         0.0            5.0

# Element connectivity input:

# Pipe:
```

```
#           elgr          elty          matname       elid          nod1          nod2
ELCON       pipe1         pipe31        pipemat       1             1             2
#      n         j         k
REPEAT 1200      1         1

# The Stinger Section:
#      group     elty      material  no        node
ELCON  stroll1   cont124   roller    500301    300002
ELCON  stroll2   cont124   roller    500302    300002
ELCON  stroll3   cont124   roller    500303    300002
ELCON  stroll4   cont124   roller    500304    300002
ELCON  stroll5   cont124   roller    500305    300002
ELCON  stroll6   cont124   roller    500306    300002
ELCON  stroll7   cont124   roller    500307    300002
ELCON  stroll8   cont124   roller    500308    300002
ELCON  stroll9   cont124   roller    500309    300002
ELCON  stroll10  cont124   roller    500310    300002
ELCON  stroll11  cont124   roller    500311    300002
ELCON  stroll12  cont124   roller    500312    300002
ELCON  stroll13  cont124   roller    500313    300002
ELCON  stroll14  cont124   roller    500314    300002
ELCON  stroll15  cont124   roller    500315    300002
ELCON  stroll16  cont124   roller    500316    300002
ELCON  stroll17  cont124   roller    500317    300002
ELCON  stroll18  cont124   roller    500318    300002
ELCON  stroll19  cont124   roller    500319    300002
ELCON  stroll20  cont124   roller    500320    300002
ELCON  stroll21  cont124   roller    500321    300002
ELCON  stroll22  cont124   roller    500322    300002
# Lay-vessel:
#           elgr          elty          matname       ID            n1            n2
ELCON      vessel        pipe31        vesbeam       300001        300001        300002

# Sea bed:
#           elgr          elty          matname       elid          nod1
ELCON       seabed        cont125       route1        400001        1
#      n         j         k
REPEAT 1201      1         1

# Sea surface:
#             elgr           elty           matname         elid           nod1           nod2
nod3          nod4
ELCON          mwlsea          sea150         sea1            500001         200101         200102
200103        200104

# ---
# Orientation input:

#             Pipe          elno          x             y             z
ELORIENT      COORDINATES   1             0.0           1.0           11.5
                            1200          2400.0        1.0           11.5

#             Vessel        elno          x             y             z
ELORIENT      COORDINATES   300001        2400.0        1.0           0.0

#             Seabed        ELID          TX            TY            TZ
ELORIENT      EULERANGLE    400001        0.0           0.0           0.0
#      n         j         k
REPEAT 1201      1         0         0         0

# ---
#             Rollers       ELID          TX            TY            TZ
ELORIENT      EULERANGLE    500301        0.0           0.0           0.0
#      n         j         k
REPEAT 22        1         0         0         0

# ---
# Stinger geometry, the positions of the stinger elements are defined with eccentricies to the second
node of the vessel.:
# Roller Definiteions:
#       type      el no     end       x_ecc     y_ecc     z_ecc     phi       dx1       dy1       dz1       dx2
dy2     dz2
ELECC   stinger   500301    1       -10.0       0       5.864     0       0     -1     0      0     1     0
ELECC   stinger   500302    1       -20.0       0       5.864     0       0     -1     0      0     1     0
```

```
ELECC    stinger    500303   1     -30.0     0      5.864     0      0    -1    0     0    1    0
ELECC    stinger    500304   1     -40.0     0      5.864     0      0    -1    0     0    1    0
ELECC    stinger    500305   1     -50.0     0      5.864     0      0    -1    0     0    1    0
ELECC    stinger    500306   1     -60.0     0      5.864     0      0    -1    0     0    1    0
ELECC    stinger    500307   1     -70.0     0      5.864     0      0    -1    0     0    1    0
ELECC    stinger    500308   1     -77.993     0      5.573     0      0    -1    0     0    1    0
ELECC    stinger    500309   1     -85.944     0      4.702     0      0    -1    0     0    1    0
ELECC    stinger    500310   1     -93.81     0      3.256     0      0    -1    0     0    1    0
ELECC    stinger    500311   1     -101.551     0      1.242     0      0    -1    0     0    1    0
ELECC    stinger    500312   1     -109.124     0      -1.329     0      0    -1    0     0    1    0
ELECC    stinger    500313   1     -116.491     0      -4.444     0      0    -1    0     0    1    0
ELECC    stinger    500314   1     -123.612     0      -8.085     0      0    -1    0     0    1    0
ELECC    stinger    500315   1     -130.45     0      -12.235     0      0    -1    0     0    1    0
ELECC    stinger    500316   1     -136.968     0      -16.87     0      0    -1    0     0    1    0
ELECC     stinger     500317     1      -143.132      0        -21.967      0       0     -1     0      0     1
0
ELECC     stinger     500318     1      -148.909      0        -27.498      0       0     -1     0      0     1
0
ELECC     stinger     500319     1      -154.269      0        -33.435      0       0     -1     0      0     1
0
ELECC     stinger     500320     1      -159.184      0        -39.745      0       0     -1     0      0     1
0
ELECC     stinger     500321     1      -163.627      0        -46.395      0       0     -1     0      0     1
0
ELECC     stinger     500322     1      -167.575      0        -53.351      0       0     -1     0      0     1
0
# Element property input:
#          name        type       rad        th          CDr         CDt         CMr         CMt         wd
ws         ODp         ODw        rks
ELPROP      pipe1        pipe       0.1645      0.0133      1.0          0.1          2.0          0.2
114.495    10.677      0.3556     0.3556     0.5
ELPROP      vessel       pipe      2.0          0.1          1.0          0.1          2.0          0.2
0.001      0.001       2.0        2.0        0.5

# ---
#          name        type       rolldiam
ELPROP     stroll1     roller     0.400
ELPROP     stroll2     roller     0.400
ELPROP     stroll3     roller     0.400
ELPROP     stroll4     roller     0.400
ELPROP     stroll5     roller     0.400
ELPROP     stroll6     roller     0.400
ELPROP     stroll7     roller     0.400
ELPROP     stroll8     roller     0.400
ELPROP     stroll9     roller     0.400
ELPROP     stroll10    roller     0.400
ELPROP     stroll11    roller     0.400
ELPROP     stroll12    roller     0.400
ELPROP     stroll13    roller     0.400
ELPROP     stroll14    roller     0.400
ELPROP     stroll15    roller     0.400
ELPROP     stroll16    roller     0.400
ELPROP     stroll17    roller     0.400
ELPROP     stroll18    roller     0.400
ELPROP     stroll19    roller     0.400
ELPROP     stroll20    roller     0.400
ELPROP     stroll21    roller     0.400
ELPROP     stroll22    roller     0.400
# Defining the contact properties:
# Cosurfpr data (contact surface properties):
#           coname      cofile                                          nlines      KPstart     xstart
ystart     fi          soilID
COSURFPR    route1      "seabed_L=10000m_W=90m_d=800m.txt"             3            0.0          0.0
0.0        0.0         100    100    100

# Soil descriptions:
#          mlineid     kp1        kp2        mname
COSUPR     100         -1000.0    10000.0    Seabed1

# Contact interfaces:
#            grpname     mastername  slavename   isl          isn          tstx         tsty         tstz
maxit      igap
CONTINT     seabed      pipe1       route1      1           1201        10000.0     0.0          0.0          8
1
```

```
CONTINT    mwlsea     mwlsea     pipe1
#:
CONTINT    stroll1    stroll1    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll2    stroll2    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll3    stroll3    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll4    stroll4    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll5    stroll5    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll6    stroll6    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll7    stroll7    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll8    stroll8    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll9    stroll9    pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll10   stroll10   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll11   stroll11   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll12   stroll12   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll13   stroll13   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll14   stroll14   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll15   stroll15   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll16   stroll16   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll17   stroll17   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll18   stroll18   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll19   stroll19   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll20   stroll20   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll21   stroll21   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
CONTINT    stroll22   stroll22   pipe1      1001       1201       10000.0    10000.0    0.0        40
1
# Current Load:
#          no         glo/loc    depth      curr       phi
CURLOAD    100        LOCAL      0.0        0.0        2.47
                                 -1800.000  0.0        2.47
# Sea load:
#          seagrp     x1         y1         x2         y2         curload    thist
SEALO      mwlsea     -7500.0    -7500.0    100000.0   10000      100        400

# External Pressure and Gravity loads
#          phi        ghi
PELOAD     100        100
# Load history data
#          Buoyancy
#          NO         Ti         FACi
THIST      100        0.0        1.0
                      91.0       1.0

#          PDISP SIMLA
#          NO         Ti         FACi
THIST      200        0.0        0.0
                      91.0       0.0

#          Sea Load
#          NO         Ti         FACi
THIST      400        0.0        0.0
                      91.0       0.0

# Stinger end:
```

```
BONCON     GLOBAL     300001     3
BONCON     GLOBAL     300001     4
BONCON     GLOBAL     300001     5
# Vessel COG:
CONSTR   PDISP    GLOBAL   300002   1        0.0      200
CONSTR   PDISP    GLOBAL   300002   2        0.0      200
CONSTR   PDISP    GLOBAL   300002   3        0.0      200
CONSTR   PDISP    GLOBAL   300002   4        0.0      200
CONSTR   PDISP    GLOBAL   300002   5        0.0      200
CONSTR   PDISP    GLOBAL   300002   6        0.0      200

# Pipe Constraints:
# Pipe Upper-End:
BONCON     GLOBAL     1201       3
CONSTR   CONEQ    GLOBAL   1201     1        0        300001   1        1
CONSTR   CONEQ    GLOBAL   1201     2        0        300001   2        1
CONSTR   CONEQ    GLOBAL   1201     6        0        300001   6        1

# Pipe Seabed-End:
CONSTR   PDISP    GLOBAL   1        1        0.0      200
CONSTR   PDISP    GLOBAL   1        2        0.0      200
CONSTR   PDISP    GLOBAL   1        3        0.0      200

# Sea Surface:
BONCON     GLOBAL     200101     1
REPEAT     4          1
BONCON     GLOBAL     200101     2
REPEAT     4          1
BONCON     GLOBAL     200101     3
REPEAT     4          1
#        VesselID npipe    ID_pipe  ID_sbd
SIMLA    300002   1        pipe1    seabed
#        file     nodes    Sigmax   util     type     nelpst   rolldist tol
"supp-lay-static.txt" 5        448000000.0 1.0     S        2        0.300    0.01     stroll22

JOINTPR_APPLY route1   pipe1
JOINTPR_DEFINE route1   GENERAL
# kp1      kp2        rad        th         CDr        Cdt        CMr        CMt        wd         ws
ODp        ODw        rks        ea         eiy        eiz        git        label
-10000      1000000    0.1645     0.0133     1.0        0.1        2.0        0.2        114.495
10.677     0.3556     0.3556     0.5        2.961e+09  4.343e+07  4.343e+07  3.341e+07  "FBE/PP"
# Material data

#          name       type       poiss      talfa      tecond     heatc      beta       ea                eiy
eiz            git            em             gm
# Pipe:
MATERIAL pipemat   linear    0.3       1.17e-05  50        800       0         2.961e+09       4.343e+07
4.343e+07      3.341e+07      2.07e+11       7.962e+10
# Vessel:
MATERIAL vesbeam   linear    0.3       1.17e-05  50        800       0         3.317e+11       1.235e+11
1.235e+11      9.503e+10      2.1e+11        7.962e+10
# Soil Materials:
MATERIAL        sea1     sea      1026

MATERIAL        Seabed1 contact 1       1       soilx1  soily1  soilz1
MATERIAL        soilx1  epcurve 1
0.0            0.0
0.1            0.5
1.0            0.5

MATERIAL        soily1  epcurve 1
0.0            0.0
0.1            0.9
1.0            0.9

MATERIAL        soilz1  hycurve
-1000.0        -500000000.0
-1.0           -500000.0
1.0            500000.0
1000.0         500000000.0

MATERIAL        roller  contact 0.3     0.3     rollx1  rolly1  rollz1
MATERIAL        rollx1  hycurve
-10000.0       -2e+12
```

```
10000.0        2e+12

MATERIAL        rolly1  hycurve
-10000.0       -2e+12
10000.0        2e+12

MATERIAL        rollz1  hycurve
-10000.0       -2e+12
10000.0        2e+12
```

A.2 Run File

```
import yaml,sys
import os,shutil,math
from simla_funcs import *
#
from IKM_PlottingTool import *
#
import numpy as np

def plotting_tool(casename):
	# IKM Plotting Tool
	g = startFileLogging('logfile.out')

	# Time steps to read
	STEPS = [91] # time (s)

	# Read in result files
	StrainXX_intp3 = readSteps('Strain_intp3.mpf', STEPS, 'time', g)
	StrainXX_intp7 = readSteps('Strain_intp7.mpf', STEPS, 'time', g)
	#axDisp = readSteps('Nodisp-y.mpf', STEPS, 'time', g)
	#latDisp = readSteps('Nodisp-x.mpf', STEPS, 'time', g)

	axF = readSteps('AxialForce.mpf', STEPS, 'time', g)
	MomY = readSteps('ymoment.mpf', STEPS, 'time', g)
	MomZ = readSteps('zmoment.mpf', STEPS, 'time', g)
	resMom = resY(MomZ, MomY,'moment',g)

	# Plotting
	#IKMPlot([StrainXX_intp1,axDisp,latDisp],'autolimits','strain_and_displacement.png',g)
	IKMPlot([axF,resMom,StrainXX_intp3,StrainXX_intp7],'autolimits',casename+'.png',g)
	return()

def calc_dep_ang():
    L_crve_stgr = data['Stinger']['L']+data['Stinger']['RL']
    ECOR_stgr = data['ModelLength']*wd - L_crve_stgr - 10.0
    fda = open('departurenangles.txt', 'w')
    fda.write("%-11s%-11s\n"% ("T (s)","depang (deg)"))
    for i in range(0,9):
        ECOR,Y,c = read_mpf('ECORvsY.mpf',i)
        ECOR,Z,c = read_mpf('ECORvsZ.mpf',i)
        ECOR = np.array(ECOR)
        n2 = np.where(ECOR >= ECOR_stgr)[0][0]
        n1 = n2 - 10
        (x1, y1) = (Y[n1], Z[n1])
        (x2, y2) = (Y[n2], Z[n2])
        depang = np.arctan((y2-y1)/(x2-x1))*180.0/np.pi
        fda.write("%-11.3f%-11.3f\n"% (1.0+10.0*i,depang))

    fda.close()
    return()

#overwrite = True

with open("InputSimla.yaml") as fo: data = yaml.load(fo)

for wd in data['WD']:
    for pipe in data["PipeCases"]:
```

```
    for smys in data['SG']:
        for depang in data['DepAng']:
            for stgr in data['StgrR']:
                pipename = pipe['Pipe']
                casename = "%s-%d-%s-%s-%d-%d"%(data['ProjectName'],wd,pipename,'SMYS'+str(int(smys/1e6)),depang,stgr)
                os.chdir(casename)
                run_simla(casename)
                run_simpost(casename)
                plotting_tool(casename)
                calc_dep_ang()
                os.chdir("..")
```

A.3 Post Processing Input File (SIMPOST)

```
GLPLOT   "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110" "AxialForce"    "KP [m]"    K-COR       "Axial
Force [N]"      ELFORCE-X      1     1200  1     1

GLPLOT    "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110"  "zmoment"            "KP  [m]"      K-COR
"Moment Z [Nm]"        ELMOM-Z        1     1200  1     1

GLPLOT    "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110"  "ymoment"            "KP  [m]"      K-COR
"Moment Y [Nm]"        ELMOM-Y        1     1200  1     1

GLPLOT     "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110"   "Strain_intp3"   "KP   [m]"        K-COR
"Strain-XX [-]"        STRAIN-XX      1     1200  1     1     1     3

GLPLOT     "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110"   "Strain_intp7"   "KP   [m]"        K-COR
"Strain-XX [-]"        STRAIN-XX      1     1200  1     1     1     7

GLPLOT    "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110"  "ECORvsY"           "Curvilinear  Element
Coordinate [m]" E-COR      "Y [N]"                Y-COR          1     1201  1     1

GLPLOT    "DeltaII-800-WT13_3mm_R=100m_D=800m-SMYS448-55-110"  "ECORvsZ"           "Curvilinear  Element
Coordinate [m]" E-COR      "Z [N]"                Z-COR          1     1201  1     1
```

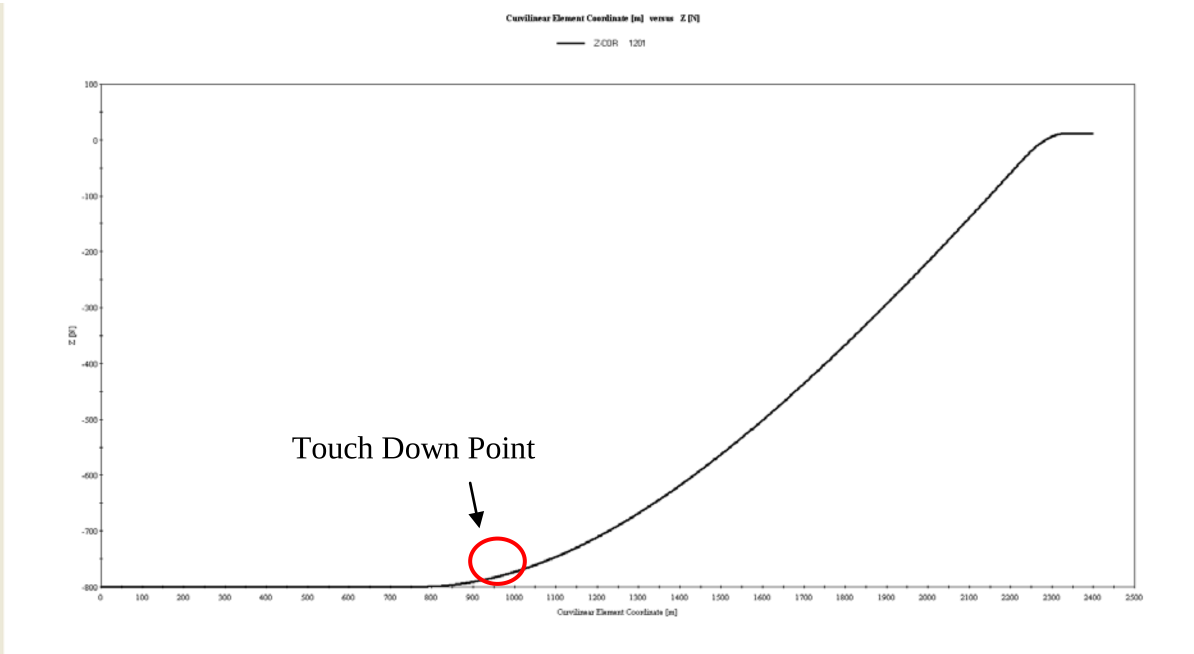
APPENDIX B OUTPUT FILES

This study carried out 112 cases pipe installation for each method, i.e. S-Lay and J-Lay methods. However this appendix only covers one example of the output file. The summary of results are presented in the main report chapter 5 and Appendix D.

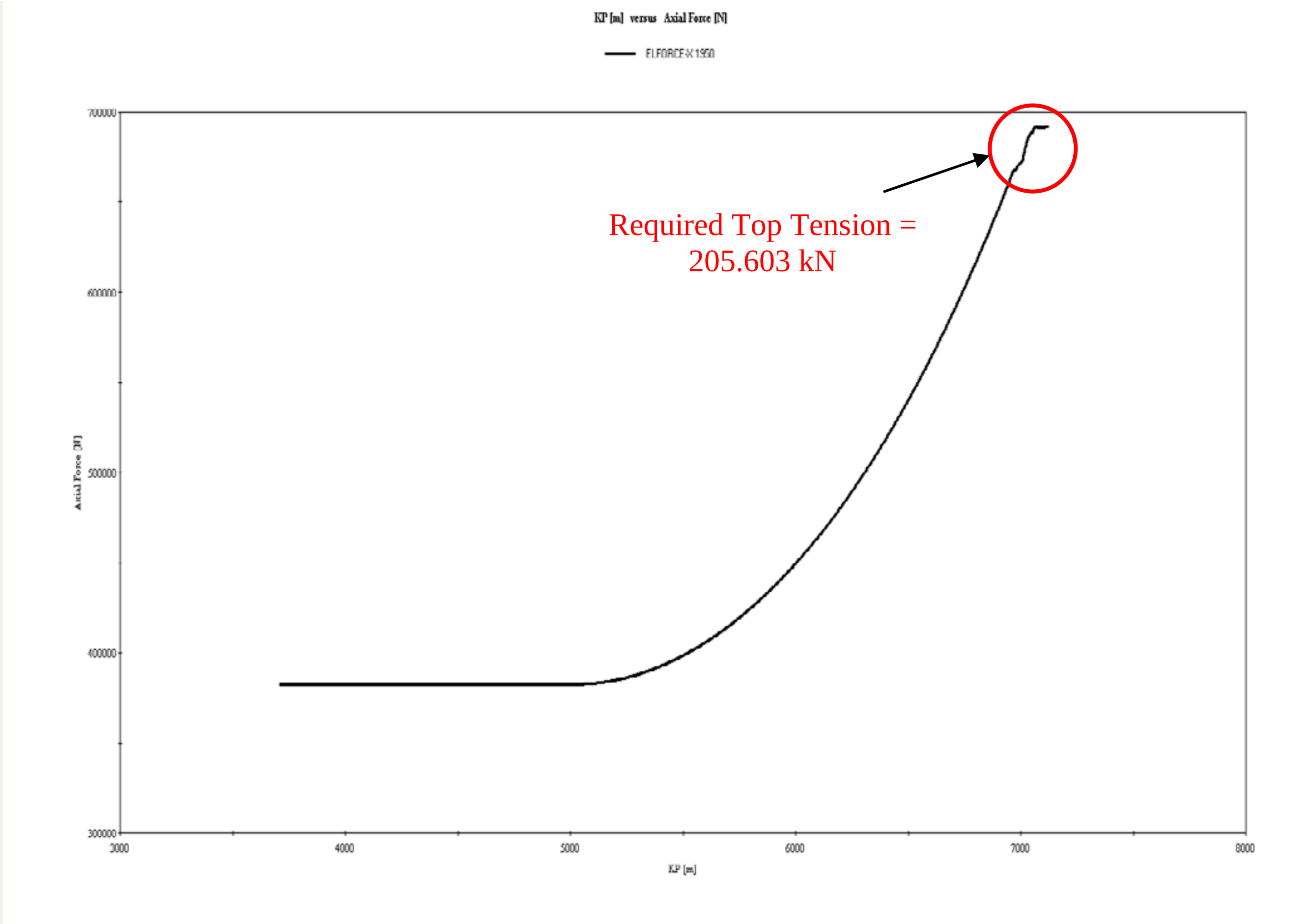
This example is for the 14 inch outer diameter pipeline at 800 m water depth installed by S-lay and J-Lay method

B.1 S-LAY

B.1.1 Configuration



B.1.2 Required Top Tension

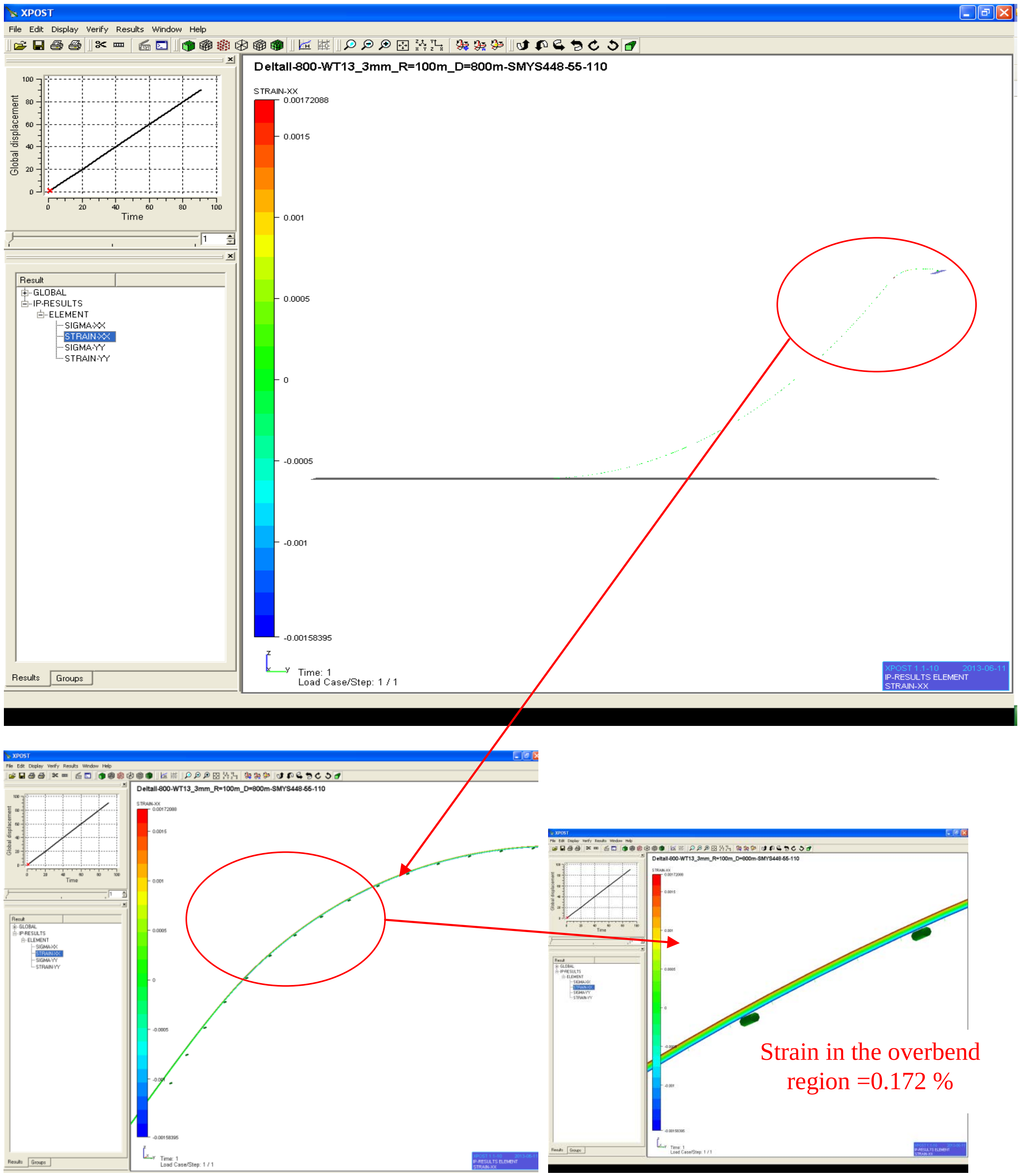


The output list of axial tension is presented in the following table.

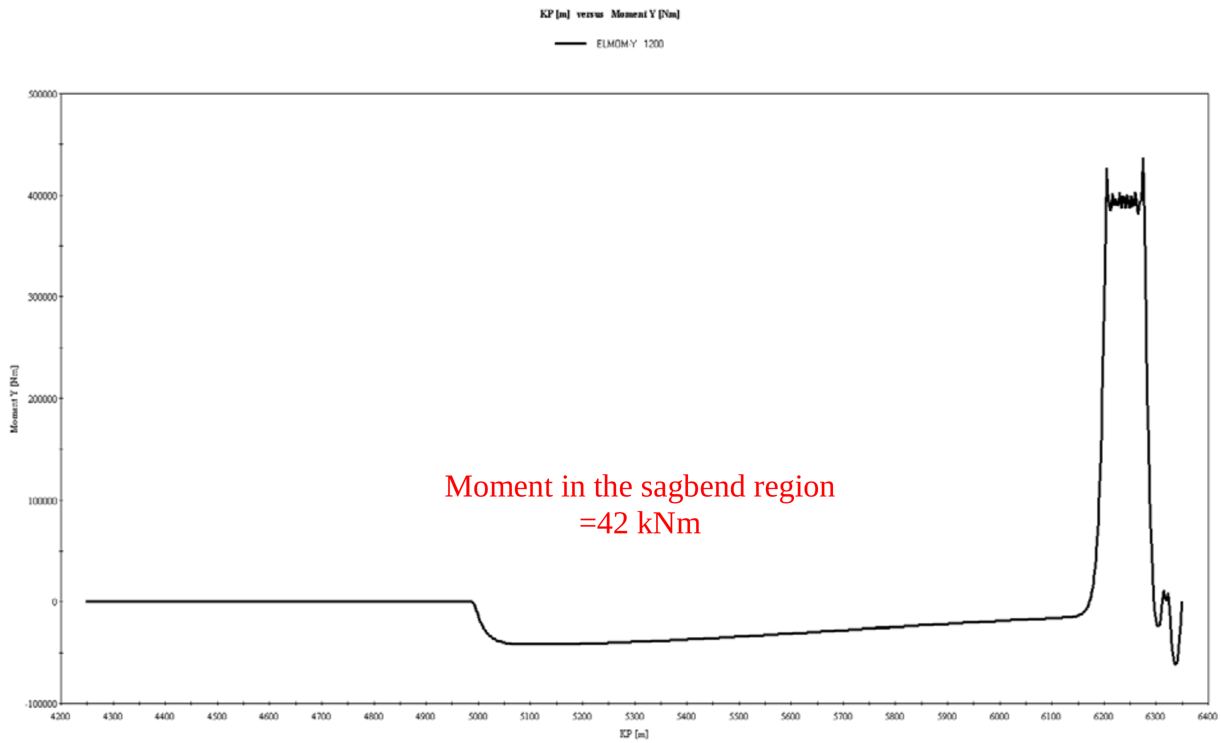
KP (m)	Required Top Tension (kN)	KP (m)	Required Top Tension (kN)
4247.97	106583	5116.32	107130
↓	↓	↓	↓
4952.14	106583	6276.9	202667
5048.35	106646	6282.89	204688
5050.35	106654	6284.89	204989
5052.35	106661	6286.89	205180
5054.36	106670	6288.89	205294
5058.37	106687	6292.89	205381
5060.37	106697	6294.89	205384
5062.37	106707	6296.89	205376
5064.37	106717	6298.89	205363
5066.38	106728	6300.89	205350
5068.38	106739	6302.89	205340
5070.38	106751	6304.89	205334
5072.38	106763	6306.9	205330
5078.39	106801	6312.9	205338
5080.39	106815	6314.9	205338
5082.39	106829	6316.9	205341
5084.39	106843	6318.9	205342
5086.39	106858	6320.9	205342
5088.38	106874	6322.9	205341
5090.38	106889	6324.9	205339
5092.38	106905	6326.9	205337
5094.38	106922	6328.9	205330
5096.38	106939	6330.9	205321
5098.37	106956	6332.9	205317
5100.37	106974	6334.9	205320
5102.36	106992	6336.9	205333
5104.36	107010	6338.9	205357
5106.35	107029	6340.9	205392
5108.35	107049	6342.9	205437
5110.34	107068	6344.9	205490
5112.34	107089	6346.9	205547
5114.33	107109	6348.9	205603

Required Top Tension (N)

B.1.3 Strain In The Overbend Region

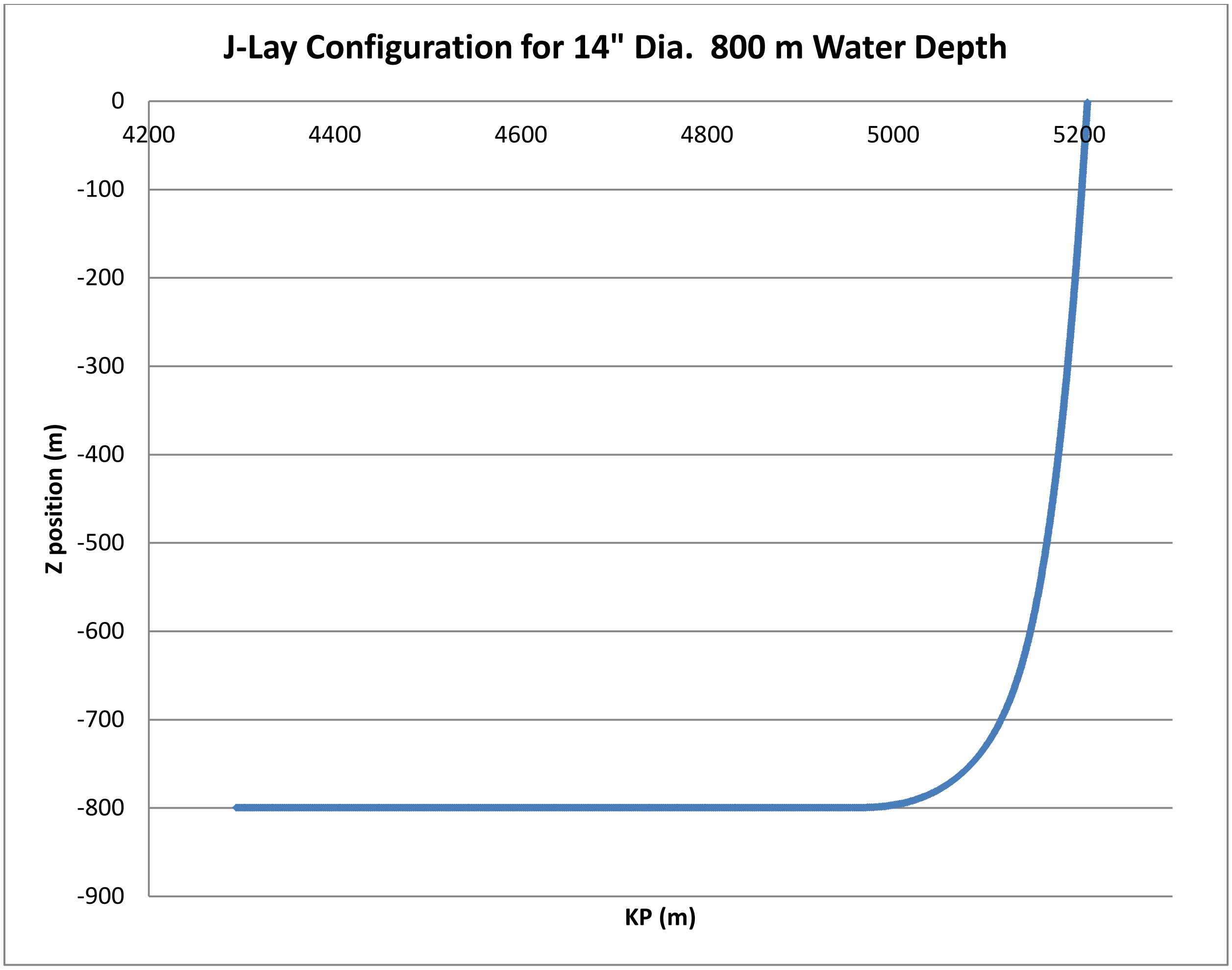


B.1.4 Bending Moment at The Sagbend Region

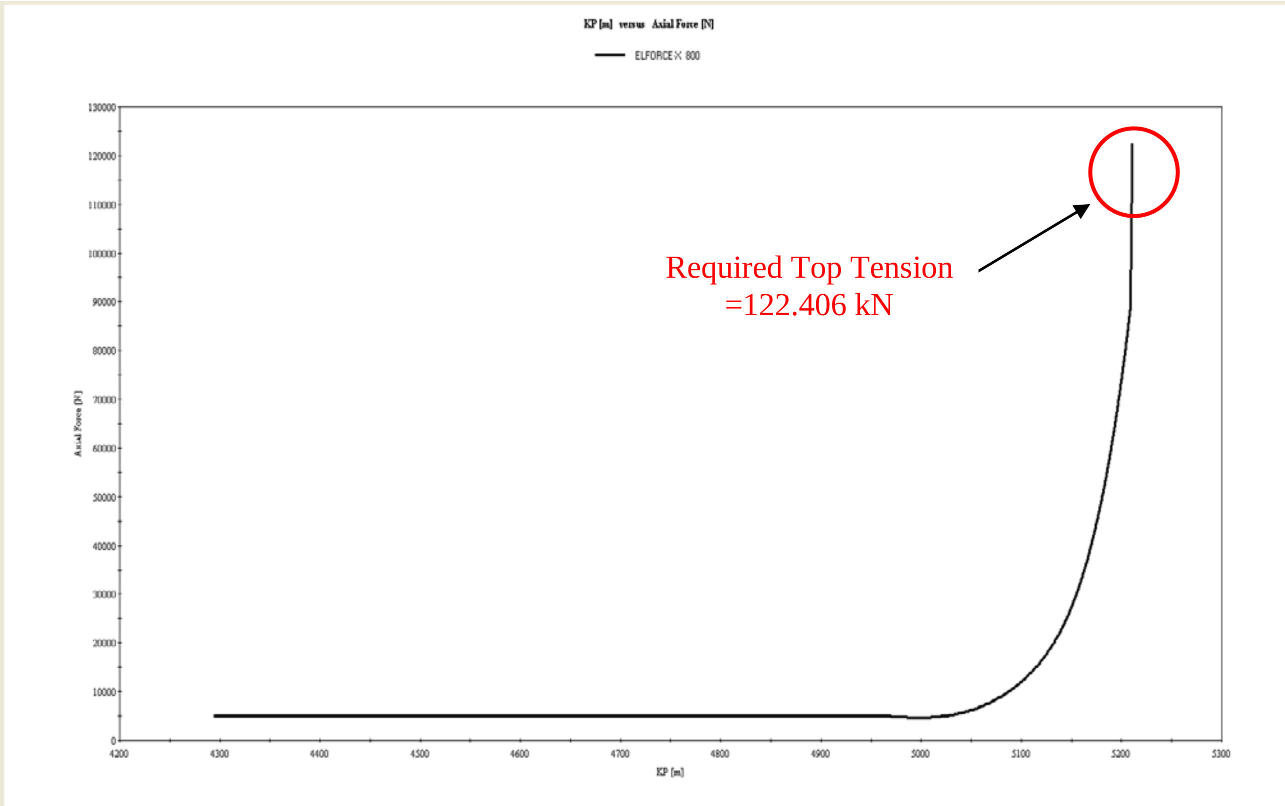


B.2 J-Lay

B.2.1 Configuration

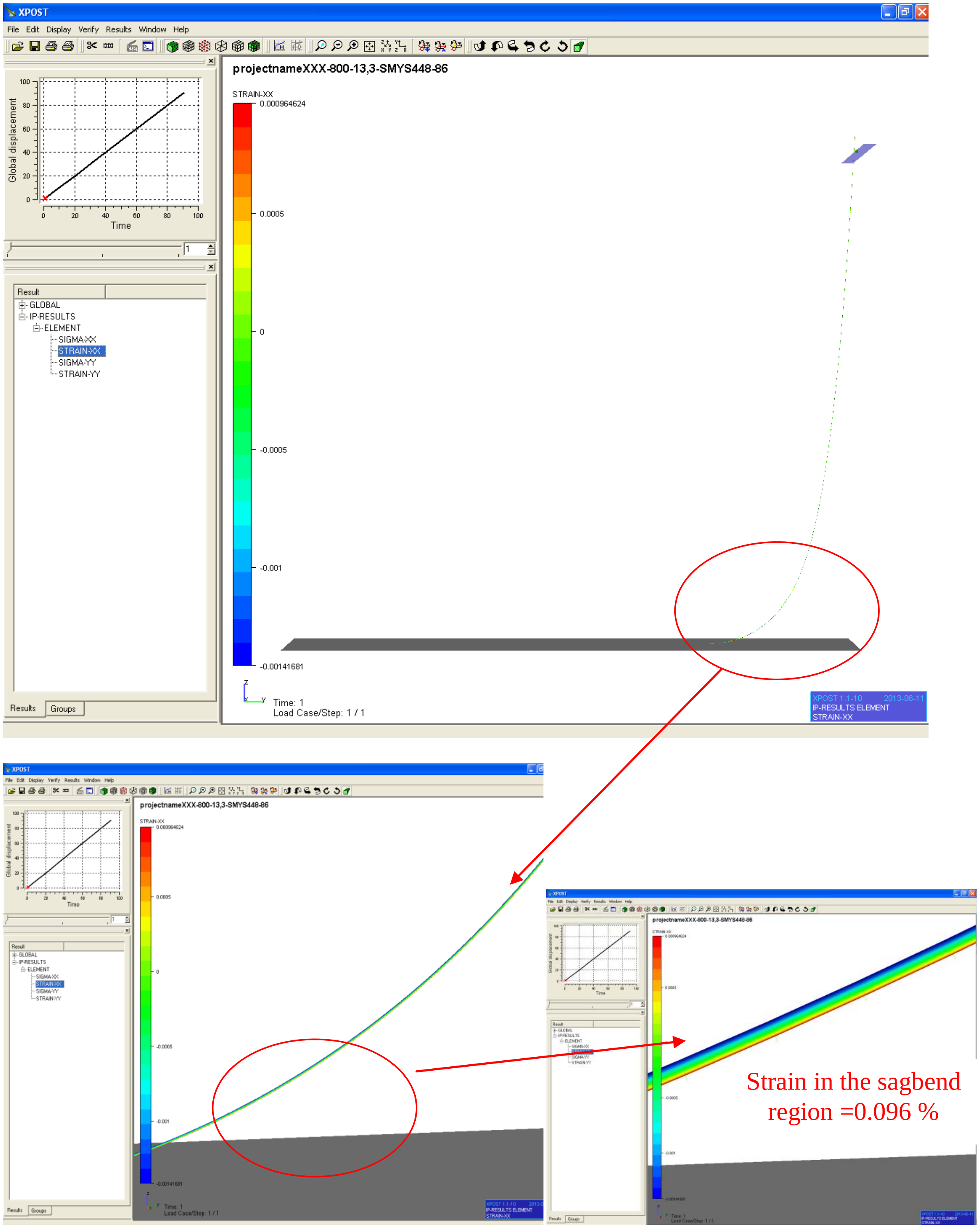


B.2.2 Required Top Tension

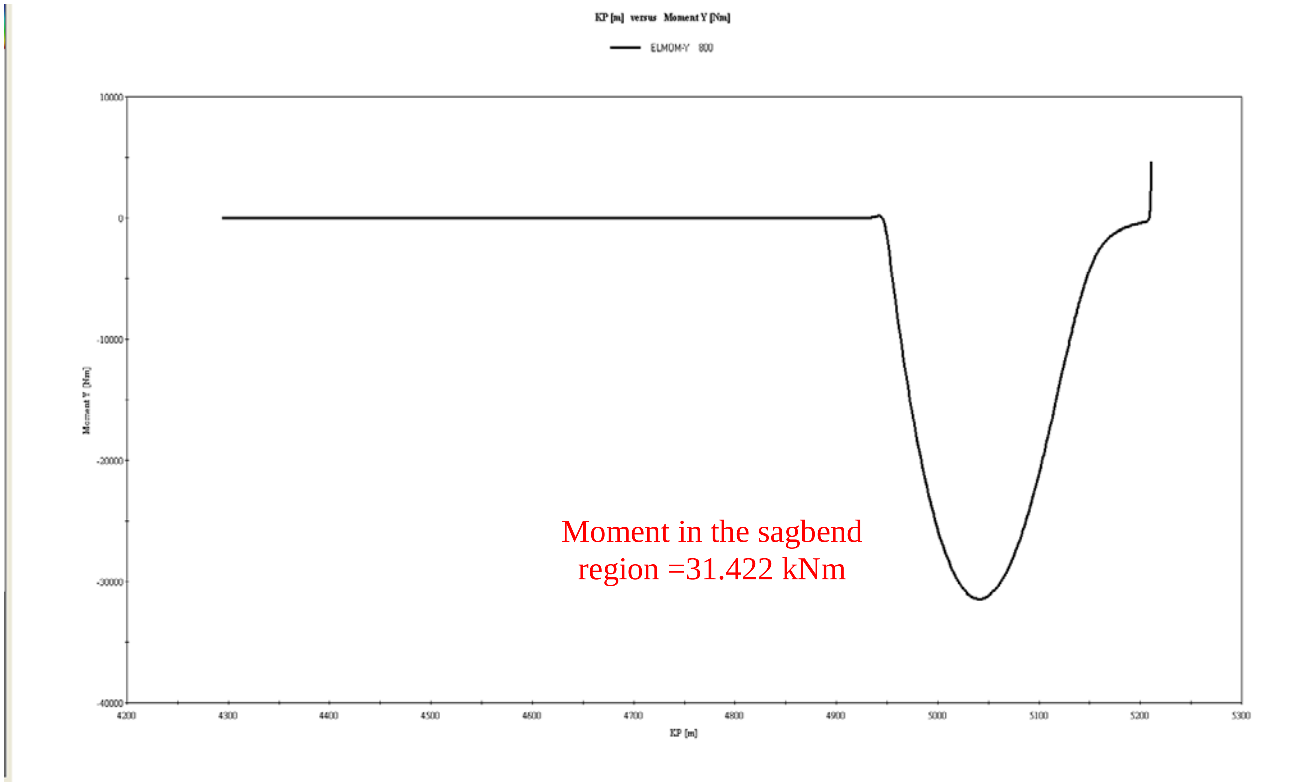


,KP (m)	Required Top Tension (kN)	KP (m)	Required Top Tension (kN)	KP (m)	Required Top Tension (kN)	KP (m)	Required Top Tension (kN)
4300	5098.26	5123.73	17297.9	5172.17	42034.9	5195.14	67056.7
4937.93	5098.25	5124.46	17500.8	5172.41	42242.9	5195.29	67265.5
4968.52	4941.85	5134.21	20555.6	5175.95	45363.8	5197.52	70399.1
4970.56	4915.69	5134.79	20759.8	5176.17	45571.9	5197.66	70608.1
4976.71	4837.29	5136.49	21373.3	5176.84	46196.5	5198.09	71234.9
4978.76	4812.36	5137.04	21577.8	5177.07	46404.7	5198.24	71443.8
4995.13	4678.36	5141.22	23216.4	5178.81	48070.8	5199.37	73115.5
5001.25	4674.75	5142.69	23831.9	5179.44	48695.7	5199.78	73742.4
5024.97	5026.86	5148.1	26298.1	5181.91	51196.4	5201.42	76250.4
5026.85	5084.03	5148.52	26503.9	5182.11	51404.8	5201.55	76459.4
5028.71	5145.69	5148.94	26709.8	5182.31	51613.2	5201.68	76668.5
5030.57	5211.81	5149.35	26915.7	5182.51	51821.7	5201.82	76877.5
5036.06	5436.79	5150.56	27533.7	5183.1	52447.1	5202.21	77504.6
5037.87	5520.53	5150.96	27739.8	5183.29	52655.6	5202.35	77713.6
5046.71	6003.24	5152.89	28770.7	5184.25	53698.2	5203	78758.8
5048.44	6112.11	5153.27	28977.0	5184.44	53906.7	5203.13	78967.8
5050.15	6224.96	5153.64	29183.4	5184.63	54115.3	5203.26	79176.8
5051.84	6341.61	5154.01	29389.9	5184.82	54323.8	5203.39	79385.9
5056.84	6714.0	5155.1	30009.3	5185.39	54949.5	5203.77	80013.0
5058.47	6845.21	5155.46	30215.8	5185.57	55158.1	5203.9	80222.1
5060.09	6979.83	5155.81	30422.4	5185.76	55366.7	5204.02	80431.1
5061.69	7117.77	5156.16	30629.0	5185.94	55575.3	5204.15	80640.2
5066.39	7550.48	5157.2	31249.2	5186.49	56201.2	5204.53	81267.4
5067.92	7700.67	5157.54	31455.9	5186.67	56409.8	5204.65	81476.5
5069.43	7853.62	5157.88	31662.6	5186.85	56618.4	5204.78	81685.6
5084.91	9691.56	5161.43	33939.4	5188.8	58913.7	5206.14	83985.5
5087.49	10050.7	5162.05	34353.8	5189.15	59331.1	5206.38	84403.7
5098.23	11731.3	5164.72	36219.5	5190.68	61209.7	5207.46	86285.7
5099.34	11923.2	5165.01	36426.9	5190.84	61418.5	5207.58	86494.8
5100.43	12116.0	5165.3	36634.3	5191.01	61627.3	5207.7	86703.9
5101.51	12309.5	5165.58	36841.8	5191.17	61836.0	5207.82	86913.0
5104.64	12894.6	5166.42	37464.4	5191.67	62462.3	5208.18	87540.4
5105.66	13090.8	5166.7	37671.9	5191.83	62671.1	5208.3	87749.5
5106.65	13287.6	5166.98	37879.5	5191.99	62879.9	5208.41	87958.6
5122.25	16892.7	5171.67	41619.1	5194.83	66638.9	5210.61	120172.0
5122.99	17095.2	5171.92	41827.0	5194.99	66847.8	5210.75	122406.0

B.2.3 Strain In The Sagbend Region



B.2.4 Bending Moment at The Sagbend Region



APPENDIX C CALCULATIONS

This appendix only covers one example of the calculation. It will be typical for different water depths, diameters, steel grades, and pipe ovalities.

C.1 Local Buckling (System Collapse Calculation) in the Overbend Area – DCC Check

SLAY OVERBEND CHECK (DCC Check)

Calculation for 800 m water depth, 14 inch diameter X65

Outer Diameter $D := 355.6\text{mm}$

Wall thickness $t := 13.3\text{mm}$

$ratio := \frac{D}{t}$ $\frac{D}{t} = 26.737$

Fabrication allowance $t_{fab} := 1\text{mm}$

Characteristic w.t $t_1 := t - t_{fab}$

$(DNV - OS - F101 - Table5 - 2)$ $t_1 = 0.012\,\text{m}$

$t_2 := t$ $t_2 = 0.013\,\text{m}$

Elastic Modulus $E := 200000\text{MPa}$

Steel Quality X65

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

Note: Ksi=6.895 MPa; 1 MPa =0.145 ksi;1 ksi=1000 psi

Yield Stress $SMYS := 448\text{MPa}$

Tensile Strength $SMTS := 500\text{MPa}$

Material Strength Factor $\alpha_u := 0.96$ (DNV – OS – F101 – Table5 – 6)

Material Strength Factor, α_u		
Factor	Normally	Supplementary Requirement α_u
α_u	0.96	1.00

Fabrication Factor $\alpha_{fab} := 0.85$ (DNV – OS – F101 – Table5 – 7)

Maximum Farication Factor, α_{fab}			
Pipe	Seamless	UO&TRB&ERW	UOE
α_{fab}	0.96	0.93	0.85

Derating on yield stress $f_{ytemp} := 0$

Derating on tensile strength $f_{utemp} := 0$

Characteristic Material Strength $f_y := (SMYS - f_{ytemp}) \cdot \alpha_u$

$f_y = 4.301 \times 10^8 \, Pa$

$f_u := (SMTS - f_{utemp}) \cdot \alpha_u$

$f_u = 4.8 \times 10^8 \, Pa$

Poisson Ratio $\nu := 0.3$

Gravity Constant $g = 9.807 \frac{m}{s^2}$

Water Density $\rho_w := 1025 \frac{kg}{m^3}$

Water Depth $h := 800m$

External Pressure $P_e := \rho_w \cdot g \cdot h$

$P_e = 8.041 \times 10^6 \, Pa$

Minimum Internal Pressure $P_{min} := 0$

Out of Roundness $f_0 := 0.015$ (Ovality1.5%)

Material Resistance Factor $\gamma_m := 1.15$

Material Resistance Factor, γ_m		
Limit State Category	**SLS/ULS/ALS**	**FLS**
γ_m	1.15	1.00

Safety Class Resistance Factor $\gamma_{sc} := 1.046$

Safety Class Resistance Factors. γ_{SC}			
Safety Class	**Low**	**Medium**	**HIgh**
Pressure Containment	1.046	1.138	1.308
Other	1.04	1.14	1.26

Condition Load Effect Factor $\gamma_C := 1.07$

Condition Load Effect Factor, γ_c	
Condition	γ_c
Pipeline Resting on Uneven Seabed	1.07
Continuously Stiff Supported	0.82
System Pressure Test	0.93
Otherwise	1.00

LOCAL BUCKLING : COLLAPSE DUE TO EXTERNAL PRESSURE

Elastic Collapse Pressure

$$P_{el} := 2 \cdot E \cdot \frac{\left(\frac{t}{D}\right)^3}{1 - \nu^2}$$

$$P_{el} = 2.3 \times 10^7 \, Pa$$

Plastic Collapse Pressure

$$P_p := f_y \cdot \alpha_{fab} \cdot \frac{2(t)}{D}$$

$$P_p = 2.735 \times 10^7 \, Pa$$

Load Combination

Pipe Functional Strain $\varepsilon_F := 0.00187$

Strain in the overbend area due to functional load (from SIMLA output)

Pipe Environmental Strain $\varepsilon_E := 0\text{kN}\cdot\text{m}$

Environmental load is not considered in static analysis, therefore strain due to environmental load = 0

Pipe Interference Strain $\varepsilon_I := 0$

Pipe Accidental Strain $\varepsilon_A := 0$

Acidental Load Factor $\gamma_A := 0$

Design Factor (functional load effect factor - system check) $\gamma_F := 1.2$

Load Effect Factor for Environmental Load $\gamma_E := 0.7$

Limit State/Load Combination	Design Load Combination		Functional Loads 1)	Environmental Load	Interference Loads	Accidental Loads
			γ_F	γ_E	γ_E	γ_A
ULS		System Check 2)	1.2	0.7		
		Load Check	1.1	1.3	1.1	
FLS			1.0	1.0	1.0	
ALS			1.0	1.0	1.0	1.0

Design Strain

$$\varepsilon_{sd} := \varepsilon_F \cdot \gamma_F \cdot \gamma_C + \varepsilon_E \cdot \gamma_E + \varepsilon_I \cdot \gamma_F \cdot \gamma_C + \varepsilon_A \cdot \gamma_A \cdot \gamma_C$$

$$\varepsilon_{sd} = 2.401 \times 10^{-3}$$

System Collapse Check

Pipeline's Resistance to External Pressure $\left(P_c - P_{el}\right)\left(P_c^{\,2} - P_p^{\,2}\right) = \blacksquare \cdot P_c \cdot P_{el} \cdot P_p \cdot f_0 \cdot \frac{D}{t - t_{fab}}$

Based on DNV-OS-F101 (2007) Section 13 E700 Local Buckling - Collapse Pc(t) can be obtained by solving third degree of polynomial with following solution :

$$P_c := y - \frac{1}{3} \cdot b$$

Where :

$$b := -P_{el} \qquad b = -2.3 \times 10^{7}\,\text{Pa}$$

$$c_1 := -1 \cdot \left(P_p^{\,2} + P_p \cdot P_{el} \cdot f_0 \cdot \frac{D}{t}\right) \qquad c_1 = -1 \times 10^{15}\,\text{Pa}^2$$

$$d := P_{el} \cdot P_p^{\,2} \qquad d = 1.72 \times 10^{22}\,\text{Pa}^3$$

$$u := \frac{1}{3}\left(\frac{-1 \cdot b^2}{3} + c_1\right) \qquad u = -3.921 \times 10^{14}\,\text{Pa}^2$$

$$v := \frac{1}{2} \cdot \left(\frac{2}{27} b^3 - \frac{1}{3} b \cdot c_1 + d\right) \qquad v = 4.315 \times 10^{21}\,\text{Pa}^3$$

$$\Phi_1 := \operatorname{acos}\left(\frac{-v}{\sqrt{-u^3}}\right) \qquad \Phi_1 = 2.16$$

$$y := -2\sqrt{-u} \cdot \cos\left(\frac{60\pi}{180} + \frac{\Phi_1}{3}\right) \qquad y = 7.73 \times 10^{6}\,\text{Pa}$$

So the pressure collapse :

$$P_c := y - \frac{1}{3} \cdot b$$

$$P_c = 1.54 \times 10^{7}\,\text{Pa}$$

Local Buckling Combined Loading Criteria

For Displacement Controlled Condition:

Based on DNV-OS-F101 Section 5 D600, pipe members that subjected to bending moment, axial force, and external overpressure shall satisfy :

$$\left(\frac{\varepsilon_{sd}}{\frac{\varepsilon_c(t_2, 0)}{\gamma_\varepsilon}}\right)^{0.8} + \frac{P_e - P_{min}}{\frac{P_c}{\gamma_m \cdot \gamma_{SC}}} \le 1$$

Where

$$\alpha_h = \left(\frac{R_{t0,5}}{R_m}\right)_{max}$$, Table 7.5

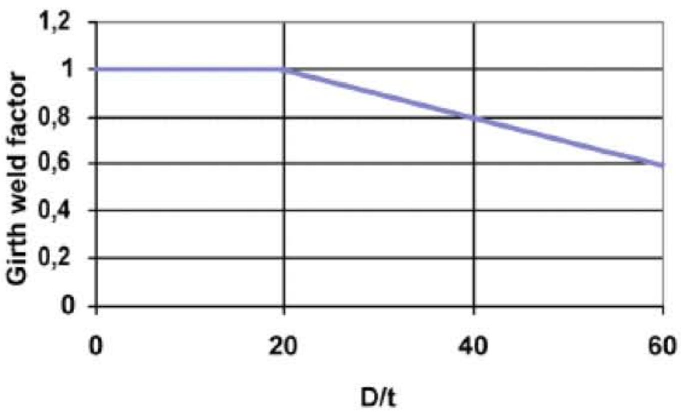
$\alpha_h := 0.93$ Minimum strain hardening

Table 7-5 C-Mn steel pipe, mechanical properties										
	Yield strength $R_{t0,5}$ [MPa]		*Tensile strength* Rm [MPa]		*Ratio* $R_{t0,5}/R_m$	*Elongation in 50.8 mm* A_f [%]	*Hardness* [HV10]		*Charpy V-notch energy (KVT)* [1) [J]	
							BM, WM	*HAZ*		
SMYS	*min.*	*max.*	*min.* [2)	*max.*	*max.*	*min.*	*max.*		*average*	*min.*
245	245	450 [3)	415	760	0.93	Note 4)	270	300	27	22
290	290	495	415	760			270		30	24
320	320	520	435	760			270		32	27
360	360	525	460	760			270		36	30
390	390	540	490	760			270		39	33
415	415	565	520	760			270		42	35
450	450	570	535	760			270		45	38
485	485	605	570	760			300		50	40
555	555	675	625	825			300		56	45

Girth Weld Factor

$$\alpha_{gw} := \begin{cases} 1 & \text{if } \frac{D}{t} \le 20 \\ -0.01\cdot\frac{D}{t} + 1.25 & \text{if } \frac{D}{t} > 20 \end{cases}$$

$\alpha_{gw} = 0.983$



$$\varepsilon_c := 0.78\cdot\left(\frac{t}{D} - 0.01\right)\cdot(1 + 5\cdot 0)\cdot\alpha_h^{-1.5}\alpha_{gw}$$

$\varepsilon_c = 0.023$

Requirement to be satisfied

$$\left(\frac{\varepsilon_{sd}}{\frac{\varepsilon_c}{\gamma_E}}\right)^{0.8} + \frac{P_e - P_{min}}{\frac{P_c}{\gamma_m \cdot \gamma_{sc}}} = 0.75$$

DCC check < 1, Hence OK

C.2 Local Buckling (System Collapse Calculation) in the Sagbend Area – LCC Check

SLAY SAGBEND CHECK (LCC Check)

Calculation for 800 m water depth, 14 inch diameter X65

Outer Diameter $D := 355.6\text{mm}$

Wall thickness $t := 13.3\text{mm}$

$ratio := \frac{D}{t}$ $\frac{D}{t} = 26.737$

Fabrication allowance $t_{fab} := 1\text{mm}$

Characteristic w.t $t_1 := t - t_{fab}$

(DNV – OS – F101 – Table5 – 2) $t_1 = 0.012\,\text{m}$

$t_2 := t$ $t_2 = 0.013\,\text{m}$

Elastic Modulus $E := 200000\text{MPa}$

Steel Quality X65

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

Note: Ksi=6.895 MPa; 1 MPa =0.145 ksi;1 ksi=1000 psi

Yield Stress $SMYS := 448\text{MPa}$

Tensile Strength $SMTS := 500\text{MPa}$

Material Strength Factor $\alpha_u := 0.96$ (DNV – OS – F101 – Table5 – 6)

Material Strength Factor, α_u		
Factor	**Normally**	**Supplementary Requirement α_u**
α_u	0.96	1.00

Fabrication Factor $\alpha_{fab} := 0.85$ (DNV – OS – F101 – Table5 – 7)

Maximum Farication Factor, α_{fab}			
Pipe	**Seamless**	**UO&TRB&ERW**	**UOE**
α_{fab}	0.96	0.93	0.85

Derating on yield stress $f_{ytemp} := 0$

Derating on tensile strength $f_{utemp} := 0$

Characteristic Material Strength $f_y := (SMYS - f_{ytemp}) \cdot \alpha_u$

$f_y = 4.301 \times 10^8 \, Pa$

$f_u := (SMTS - f_{utemp}) \cdot \alpha_u$

$f_u = 4.8 \times 10^8 \, Pa$

Poisson Ratio $\nu := 0.3$

Gravity Constant $g = 9.807 \dfrac{m}{s^2}$

Water Density $\rho_w := 1025 \dfrac{kg}{m^3}$

Water Depth $h := 800m$

External Pressure $P_e := \rho_w \cdot g \cdot h$

$P_e = 8.041 \times 10^6 \, Pa$

Minimum Internal Pressure $P_{min} := 0$

Out of Roundness $f_0 := 0.015$ (Ovality1.5%)

Material Resistance Factor $\gamma_m := 1.15$

Material Resistance Factor, γ_m		
Limit State Category	**SLS/ULS/ALS**	**FLS**
γ_m	1.15	1.00

Safety Class Resistance Factor $\gamma_{sc} := 1.046$

Safety Class Resistance Factors. γ_{SC}			
Safety Class	**Low**	**Medium**	**HIgh**
Pressure Containment	1.046	1.138	1.308
Other	1.04	1.14	1.26

Condition Load Effect Factor $\gamma_C := 1.07$

Condition Load Effect Factor, γ_C	
Condition	γ_C
Pipeline Resting on Uneven Seabed	1.07
Continuously Stiff Supported	0.82
System Pressure Test	0.93
Otherwise	1.00

LOCAL BUCKLING : COLLAPSE DUE TO EXTERNAL PRESSURE

Elastic Collapse Pressure

$$P_{el} := 2 \cdot E \cdot \frac{\left(\frac{t}{D}\right)^3}{1 - \nu^2}$$

$$P_{el} = 2.3 \times 10^7 \, Pa$$

Plastic Collapse Pressure

$$P_p := f_y \cdot \alpha_{fab} \cdot \frac{2(t)}{D}$$

$$P_p = 2.735 \times 10^7 \, Pa$$

Load Combination

Pipe Functional Bending Moment $M_F := 38.7kN \cdot m$

Bending moment in the sagbend area due to functional load (from SIMLA output)

Pipe Environmental Bending Moment $M_E := 0kN \cdot m$

Environmental load is not considered in static analysis, therefore bending moment due to environmental load = 0

Pipe Interference Bending Moment $M_I := 0$

Pipe Accidental Bending Moment $M_A := 0$

Acidental Load Factor $\gamma_A := 0$

Pipe Functional Axial Force $S_F := 90kN$

Axial force in the sagbend area due to functional load (from SIMLA output)

Pipe Environmental Axial Force $S_E := 0kN$

Environmental load is not considered in static analysis, therefore axial force due to environmental load = 0

Pipe Interference Axial Force $S_I := 0$

Pipe Accidental Axial Force $S_A := 0$

Design Factor (functional load effect factor - system check) $\gamma_F := 1.2$

Load Effect Factor for Environmental Load $\gamma_E := 0.7$

Limit State/Load Combination	Design Load Combination		Functional Loads 1)	Environmental Load	Interference Loads	Accidental Loads
			γ_F	γ_E	γ_E	γ_A
ULS		System Check 2)	1.2	0.7		
		Load Check	1.1	1.3	1.1	
FLS			1.0	1.0	1.0	
ALS			1.0	1.0	1.0	1.0

Design Moment

$$M_{sd} := M_F \cdot \gamma_F \cdot \gamma_C + M_E \cdot \gamma_E + M_I \cdot \gamma_F \cdot \gamma_C + M_A \cdot \gamma_A \cdot \gamma_C$$

$$M_{sd} = 4.969 \times 10^4 \, J$$

Design Effective Axial Forces

$$S_{sd} := S_F \cdot \gamma_F \cdot \gamma_C + S_E \cdot \gamma_E + S_I \cdot \gamma_F \cdot \gamma_C + S_A \cdot \gamma_A \cdot \gamma_C$$

$$S_{sd} = 1.156 \times 10^5 \, N$$

System Collapse Check

Pipeline's Resistance to External Pressure $\left(P_c - P_{el}\right)\left(P_c{}^2 - P_p{}^2\right) = \blacksquare \cdot P_c \cdot P_{el} \cdot P_p \cdot f_0 \cdot \dfrac{D}{t - t_{fab}}$

Based on DNV-OS-F101 (2007) Section 13 E700 Local Buckling - Collapse Pc(t) can be obtained

by solving third degree of polynomial with following solution :

$$P_c := y - \frac{1}{3} \cdot b$$

Where :

$$b := -P_{el} \qquad b = -2.3 \times 10^7 \, Pa$$

$$c_1 := -1 \cdot \left(P_p{}^2 + P_p \cdot P_{el} \cdot f_0 \cdot \frac{D}{t}\right) \qquad c_1 = -1 \times 10^{15} \, Pa^2$$

$$d := P_{el} \cdot P_p{}^2 \qquad d = 1.72 \times 10^{22} \, Pa^3$$

$$u := \frac{1}{3}\left(\frac{-1 \cdot b^2}{3} + c_1\right) \qquad u = -3.921 \times 10^{14} \, Pa^2$$

$$v := \frac{1}{2} \cdot \left(\frac{2}{27} b^3 - \frac{1}{3} b \cdot c_1 + d\right) \qquad v = 4.315 \times 10^{21} \, Pa^3$$

$$\Phi_1 := \operatorname{acos}\left(\frac{-v}{\sqrt{-u^3}}\right) \qquad \Phi_1 = 2.16$$

$$y := -2\sqrt{-u} \cdot \cos\left(\frac{60\pi}{180} + \frac{\Phi_1}{3}\right) \qquad y = 7.73 \times 10^6 \, Pa$$

So the pressure collapse :

$$P_c := y - \frac{1}{3} \cdot b$$

$$P_c = 1.54 \times 10^7 \,\text{Pa}$$

Based on DNV-OS-F101 Section 5 D400, at any point along the pipeline shall satisfy :

$$P_e - P_{min} \le \frac{P_c}{\gamma_m \cdot \gamma_{SC}}$$

Where :

$$P_e = 8.041 \times 10^6 \,\text{Pa}$$

$$P_{min} = 0$$

$$P_e - P_{min} = 8.041 \times 10^6 \,\text{Pa}$$

$$\frac{P_c}{\gamma_m \cdot \gamma_{sc}} = 1.28 \times 10^7 \,\text{Pa}$$

$$\text{check} := \begin{vmatrix} \text{"ok"} \quad \text{if } P_e - P_{min} < \dfrac{P_c}{\gamma_m \cdot \gamma_{sc}} \\ \text{"not ok"} \quad \text{otherwise} \end{vmatrix} = \text{"ok"}$$

$$\text{check} = \text{"ok"}$$

Local Buckling Combined Loading Criteria

Based on DNV-OS-F101 Section 5 D600, pipe members that subjected to bending moment, axial force, and external overpressure shall satisfy :

For Load Controlled Condition:

$$\left[\left(\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{sd1}|}{\alpha_C}\right) + \left(\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{sd1}}{\alpha_C}\right)^2\right]^2 + \left(\gamma_m \cdot \gamma_{SC} \cdot \frac{P_e - P_{min}}{P_c}\right)^2 \le 1$$

$$\frac{D}{t} < 45 \qquad\qquad P_{min} < P_e$$

Where

Plastic Moment Capacity of the Pipe

$$M_p := f_y \cdot (D - t)^2 \cdot t$$

$$M_p = 6.702 \times 10^5\,J$$

Plastic Axial Tension Capacity of The Pipe

$$S_p := f_y \cdot \pi \cdot (D - t) \cdot t$$

$$S_p = 6.151 \times 10^6\,N$$

Flow Stress Parameter for 15<D/t<60

$$\beta := \begin{cases} 0.5 & \text{if } \dfrac{D}{t_2} < 15 \\ \left(\dfrac{60 - \dfrac{D}{t_2}}{90}\right) & \text{if } 15 \le \dfrac{D}{t_2} \le 60 \\ 0 & \text{otherwise} \end{cases}$$

$$\beta = 0.37$$

$$\alpha_C := (1 - \beta) + \beta \cdot \frac{f_u}{f_y}$$

$$\alpha_C = 1.043$$

Normalized Moment

$$M_{sd1} := \frac{M_{sd}}{M_p}$$

$$M_{sd1} = 0.074$$

Normalized Effective Axial Force

$$S_{sd1} := \frac{S_{sd}}{S_p} \qquad S_{sd1} = 0.019$$

Requirement to be satisfied

$$\left[\left(\gamma_m \cdot \gamma_{sc} \cdot \frac{|M_{sd1}|}{\alpha_C}\right) + \left(\frac{\gamma_m \cdot \gamma_{sc} \cdot S_{sd1}}{\alpha_C}\right)^2\right]^2 + \left(\gamma_m \cdot \gamma_{sc} \cdot \frac{P_e - P_{min}}{P_c}\right)^2 = 0.402$$

LCC check < 1, Hence OK

C.3 Propagation Buckling

WALL THICKNESS DESIGN BASED ON BUCKLE PROPAGATION CRITERIA

Calculation for 800 m water depth, 14 inch diameter X65

Outer Diameter $D := 355.6\text{mm}$

Wall thickness $t := 21.018\text{mm}$

$\text{ratio} := \frac{D}{t}$ $\frac{D}{t} = 16.919$

Fabrication allowance $t_{fab} := 1\text{mm}$

Characteristic w.t $t_1 := t - t_{fab}$

$(\text{DNV} - \text{OS} - \text{F101} - \text{Table5} - 2)$ $t_1 = 0.02\,\text{m}$

$t_2 := t$ $t_2 = 0.021\,\text{m}$

Elastic Modulus $E := 200000\text{MPa}$

Steel Quality X65

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

Note: Ksi=6.895 MPa; 1 MPa =0.145 ksi;1 ksi=1000 psi

Yield Stress $\text{SMYS} := 448\text{MPa}$

Tensile Strength $\text{SMTS} := 500\,\text{MPa}$

Material Strength Factor $\alpha_u := 0.96$ (DNV – OS – F101 – Table5 – 6)

Material Strength Factor, α_u		
Factor	**Normally**	**Supplementary Requirement α_u**
α_u	0.96	1.00

Fabrication Factor $\alpha_{fab} := 0.85$ (DNV – OS – F101 – Table5 – 7)

Maximum Farication Factor, α_{fab}			
Pipe	**Seamless**	**UO&TRB&ERW**	**UOE**
α_{fab}	0.96	0.93	0.85

Derating on yield stress $f_{ytemp} := 0$

Derating on tensile strength $f_{utemp} := 0$

Characteristic Material Strength $f_y := (SMYS - f_{ytemp}) \cdot \alpha_u$

$$f_y = 4.301 \times 10^8 \, Pa$$

$$f_u := (SMTS - f_{utemp}) \cdot \alpha_u$$

$$f_u = 4.8 \times 10^8 \, Pa$$

Gravity Constant $g = 9.807 \frac{m}{s^2}$

Water Density $\rho_w := 1025 \frac{kg}{m^3}$

Water Depth $h := 800m$

External Pressure $P_e := \rho_w \cdot g \cdot h$

$$P_e = 8.041 \times 10^6 \, Pa$$

Material Resistance Factor $\gamma_m := 1.15$

Material Resistance Factor, γ_m		
Limit State Category	**SLS/ULS/ALS**	**FLS**
γ_m	1.15	1.00

Safety Class Resistance Factor $\gamma_{sc} := 1.046$

Safety Class Resistance Factors. γ_{SC}			
Safety Class	**Low**	**Medium**	**HIgh**
Pressure Containment	1.046	1.138	1.308
Other	1.04	1.14	1.26

$$P_{pr} := 35 \cdot f_y \cdot \alpha_{fab} \cdot \left(\frac{t_2}{D}\right)^{2.5}$$ for D/t2 <45

$$P_{pr} = 1.087 \times 10^7 \text{ Pa}$$

$$\frac{P_{pr}}{\gamma_m \cdot \gamma_{sc}} = 9.034 \times 10^6 \text{ Pa}$$

$$\text{Check} := \begin{cases} \text{"OK"} & \text{if } P_e < \dfrac{P_{pr}}{\gamma_m \cdot \gamma_{sc}} \\ \text{"NOT OK, Increase the thickness"} & \text{otherwise} \end{cases}$$

Check = "OK"

C.4 On-Bottom Stability Calculation

ON BOTTOM STABILITY CHECK

Stability Check for 14 inch pipe diameter

Outer Diameter	$D := 355.6mm$
Specific Gravity	$\gamma_w := 1.1$
Gravity Constant	$g = 9.807 \frac{m}{s^2}$
Water Density	$\rho_w := 1025 \frac{kg}{m^3}$
Steel Density	$\gamma_s := 7850 \frac{kg}{m^3}$

Pipe Buoyancy per unit length

$$b := \rho_w \cdot g \cdot \pi \cdot \frac{D^2}{4}$$

$$b = 998.293 \frac{kg}{s^2}$$

According to DNV (2007), the following criteria shall be met to ensure vertical stability:

$$\gamma_w \cdot \frac{b}{b + w_s} < 1$$

$$\gamma_w \cdot \frac{b}{b + w_{dry} - b} < 1$$

$$\gamma_w \cdot \frac{b}{\left[\frac{\pi}{4} \cdot D^2 - \frac{\pi}{4} \cdot (D - 2 \cdot t)^2\right] \cdot \gamma_s \cdot g} < 1$$

Try :

Wall thickness	$t := 13.3mm$

$$\text{Check} := \gamma_w \cdot \frac{b}{\left[\frac{\pi}{4}\cdot D^2 - \frac{\pi}{4}\cdot(D - 2\cdot t)^2\right]\cdot\gamma_s\cdot g}$$

$\text{Check} = 0.997$

$$\text{Stability} := \left|\begin{array}{l}\text{"OK, This wall thickness satisfy the requirement for stability"} \quad \text{if Check} < 1 \\ \text{"Not OK, Increase the thickness"} \quad \text{otherwise}\end{array}\right.$$

Stability = "OK, This wall thickness satisfy the requirement for stability"

C.5 Catenary Calculation

CATENARY CALCULATION

Calculation for J-Lay method in 2000 m water depth, 14 inch diameter

Water Depth $h := 2000\,m$

Total Length $s := 2150\,m$

Outer Diameter $D := 0.3556\,m$

Thickness $t := 0.0175\,m$

Steel Density $\gamma_s := 7850\dfrac{kg}{m^3}$

Water Density $\gamma_w := 1025\dfrac{kg}{m^3}$

Dry Weight :

$$w := \frac{\pi\left[D^2 - (D - 2\cdot t)^2\right]\cdot\gamma_s}{4} \qquad w = 145.916\frac{kg}{m}$$

Bouyancy Weight :

$$b := \frac{1}{4}\cdot\pi\cdot D^2\cdot\gamma_w \qquad b = 101.798\frac{kg}{m}$$

Submerged Weight :

$$w_s := w - b \qquad w_s = 44.118\frac{kg}{m}$$

Horizontal Forces :

$$H := \frac{w_s\cdot\left(s^2 - h^2\right)}{2\cdot h} \qquad H = 6.866\times 10^3\,kg$$

Vertical Forces :

$V := w_s \cdot s$ $\quad\quad$ $V = 9.485 \times 10^4\,kg$

Tension Forces:

$T := \sqrt{V^2 + H^2}$ $\quad\quad$ $T = 9.51 \times 10^4\,kg$

APPENDIX D SUMMARY OF ANALYSIS RESULTS

This appendix only covers one example of the input file. It will be typical for different water depths, diameters, steel grades, and pipe ovalities.

D.1 14 Inch Pipe Diameter Results

S-Lay X70

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	DCC Check	LCC Check
800	54	"110/120"	13.30	205.6	0.172	0.029	0.75	0.40
1300	54	"110/120"	14.00	503.232	0.192	0.079	0.77	0.42
2000	54	"110/120"	17.30	2192.11	0.235	0.103	0.95	0.69
2500	60	"100/120"	20.00	3152.06	0.268	0.110	0.99	0.77
3000	63	"100/120"	23.00	4752.78	0.291	0.100	0.94	0.96
3500	63	"100/120"	25.40	6302.32	0.293	0.111	0.98	0.95
4000	65	"110/140"	27.20	8128.08	0.319	0.110	1.00	0.00

J-Lay X70

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress UC	LCC Check
800	86	13.30	122.41	0.096	210.00	419.34	0.50	0.40
1300	86	13.30	178.93	0.062	124.00	419.34	0.30	0.97
2000	86	15.50	643.013	0.040	80.00	419.34	0.19	1.17
2500	86	19.00	1545.06	0.050	100.00	419.34	0.24	0.88
3000	86	21.80	2549.46	0.065	130.00	419.34	0.31	0.85
3500	86	23.90	3572.06	0.082	164.00	419.34	0.39	0.89
4000	86	27.20	5270.4	0.103	206.00	419.34	0.49	0.84

S-Lay X80

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	DCC Check	LCC Check
800	54	"110/120"	13.30	205.60	0.17	0.03	0.48	0.17
1300	54	"110/120"	13.80	454.31	0.19	0.08	0.69	0.32
2000	54	"110/120"	16.8	1821.29	0.228	0.116	0.95	0.67
2500	60	"100/120"	18.8	2329	0.262	0.117	0.97	0.72
3000	63	"100/120"	21	3914.07	0.282	0.118	0.97	0.98
3500	63	"100/120"	23	6050.23	0.322	0.119	0.96	0.99
4000	65	"110/140"	25	7300	0.31	0.121	0.94	0.93

D.2 20 Inch Pipe Diameter Results

S-Lay X70

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	DCC Check	LCC Check
800	55	"110/120"	19.10	630.00	0.18	0.05	0.54	0.17
1300	60	"100/120"	20.50	1200.51	0.22	0.08	0.79	0.42
2000	60	"100/120"	25.40	4414.83	0.30	0.11	0.99	0.71
2500	60	"100/120"	29.00	6702.33	0.34	0.11	0.99	0.74
3000	60	"100/140"	33.00	10657.10	0.35	0.08	0.98	0.78
3500	65	"110/140"	36.20	14844.40	0.39	0.09	0.96	0.76
4000	68	"130/170"	41.00	18129.10	0.38	0.10	0.00	0.00

J-Lay X70

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilization	LCC Check
800	86	19.10	258.86	0.13	250.0	419.34	0.60	0.39
1300	86	19.10	380.67	0.062	124.0	419.34	0.30	0.95
2000	86	22.00	1275.95	0.040	80.0	419.34	0.19	1.21
2500	86	26.20	2866.42	0.050	100.0	419.34	0.24	0.99
3000	86	30.80	5080.09	0.065	130.0	419.34	0.31	0.86
3500	78	35.00	8973.90	0.082	164.0	419.34	0.39	0.83
4000	78	41.00	13478.20	0.11	206.0	419.34	0.49	0.59

S-Lay X80

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	DCC Check	LCC Check
800	55	"110/120"	19.10	630.00	0.18	0.05	0.49	0.13
1300	60	"100/120"	20.00	1016.45	0.24	0.08	0.49	0.32
2000	60	"100/120"	24.20	3785.52	0.30	0.12	0.96	0.65
2500	60	"100/120"	27.50	5876.21	0.34	0.12	0.97	0.67
3000	60	"120/140"	30.50	9027.78	0.34	0.13	0.96	0.71
3500	60	"150/170"	33.50	12796.00	0.35	0.12	0.96	0.74
4000	60	"130/170"	37.00	17630.40	0.39	0.12	0.96	0.77

D.3 28 Inch Pipe Diameter Results

S-Lay X70

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	DCC Check	LCC Check
800	41	"150/120"	26.60	1389.00	0.24	0.04	0.78	0.40
1300	38	"160/120"	28.80	2398.24	0.24	0.08	0.80	0.42
2000	60	"120/140"	36.00	7650.90	0.38	0.10	0.98	0.70
2500	60	"150/170"	41.50	13823.80	0.40	0.10	0.97	0.68
3000	63	"135/170"	46.50	21103.00	0.43	0.11	0.97	0.72
3500	65	"135/170"	52.00	30403.40	0.43	0.11	0.97	0.77
4000	65	"135/170"	57.20	40893.90	0.45	0.11	0.00	0.00

J-Lay X70

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilization	LCC Check
800	86	26.60	481.90	0.153	306.0000	419.34	0.73	0.40
1300	86	26.60	711.02	0.062	124.0000	419.34	0.30	0.98
2000	86	32.00	2915.08	0.040	80.0000	419.34	0.19	1.04
2500	86	38.00	6176.18	0.050	100.0000	419.34	0.24	0.88
3000	86	44.00	10394.0	0.065	130.0000	419.34	0.31	0.82
3500	86	50.00	15540.6	0.082	164.0000	419.34	0.39	0.79
4000	80	55.00	23597.6	0.103	206.0000	419.34	0.49	0.82

S-Lay X80

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend	Strain in Sagbend	DCC Check	LCC Check
800	41	"150/120"	26.60	1389.00	0.24	0.04	0.50	0.12
1300	38	"160/120"	28.00	1988.31	0.24	0.08	0.72	0.63
2000	60	"120/140"	34.20	6526.93	0.37	0.12	0.98	0.62
2500	60	"120/140"	39.00	11899.60	0.39	0.11	0.95	0.63
3000	63	"135/170"	43.00	17927.00	0.42	0.12	0.98	0.68
3500	65	"135/170"	47.50	25704.20	0.42	0.12	0.00	0.00
4000	65	"135/170"	52.20	32000.00	0.45	0.12	0.96	0.71

J-Lay X80

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	Top Tension (kN)	Strain in Sagbend	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	UC Stress	LCC Check
800	80	26.60	527.12	0.177	314.233	479.37	0.656	0.648
1300	86	26.60	946.47	0.145	250.488	479.37	0.523	0.85
2000	86	29.1	2958.43	0.114	215.862	479.37	0.450	0.96
2500	86	35	5469.46	0.102	211.239	479.37	0.441	0.93
3000	86	39.5	8663.87	0.098	216.132	479.37	0.451	0.92
3500	86	45	12534.3	0.092	218.795	479.37	0.456	0.91
4000	86	50	16164.2	0.078	224.842	479.37	0.469	0.94

D.4 30 Inch Pipe Diameter Results

S-Lay X70

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend	Strain in Sagbend	DCC Check	LCC Check
800	41	"150/120"	28.50	1593.26	0.26	0.05	0.56	0.16
1300	38	"160/120"	31.00	2799.77	0.25	0.08	0.81	0.42
2000	60	"120/140"	38.60	8795.10	0.40	0.10	0.99	0.66
2500	60	"150/170"	44.30	15675.60	0.42	0.10	0.95	0.63
3000	63	"135/170"	50.00	24399.70	0.44	0.11	0.98	0.00
3500	65	"135/170"	56.00	35219.50	0.45	0.11	0.96	0.76
4000	65	"135/170"	61.50	47208.00	0.47	0.11	0.00	0.00

J-Lay X70

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	Sress Utilization	LCC Check
800	86	28.50	551.76	0.1	0.000	389.760	0.00	0.41
1300	86	28.50	1674.83	0.062	124.00	389.760	0.32	0.98
2000	86	34.00	3239.35	0.040	80.00	389.760	0.21	1.07
2500	86	42.00	7672.42	0.050	100.00	389.760	0.26	0.80
3000	86	47.00	11854.8	0.065	130.00	389.760	0.33	0.83
3500	86	54.00	18103.0	0.082	164.00	389.760	0.42	0.78
4000	85	59.00	24560.4	0.103	206.00	389.760	0.53	0.82

S-Lay X80

Water Depth (m)	Departure Angle (deg)	Stinger Radius/Stinger Length	Wall Thickness (mm)	Top Tension (kN)	Strain in Overbend (%)	Strain in Sagbend (%)	DCC Check	LCC Check
800	41	"150/120"	28.50	1593.26	0.26	0.05	0.51	0.12
1300	38	"160/120"	30.00	2800.00	0.25	0.08	0.73	0.32
2000	60	"120/140"	37.00	7726.17	0.38	0.11	0.00	0.00
2500	60	"150/170"	41.50	15866.00	0.41	0.11	0.96	0.58
3000	63	"135/170"	46.20	24006.00	0.44	0.12	0.96	0.63
3500	65	"135/170"	51.00	32146.00	0.43	0.12	0.96	0.71
4000	65	"135/170"	56.00	40286.20	0.47	0.12	0.96	0.70

J-Lay X80

Water Depth (m)	Departure Angle (deg)	Wall Thickness (mm)	Top Tension (kN)	Strain in Sagbend (%)	Stress Equivalent in Sagbend (Mpa)	Allowable Stress (Mpa)	UC Stress	LCC Check
800	80	28.5	741.589	0.175212	312.73	479.37	0.65	0.86
1300	86	28.5	1109.53	0.16411	284.27	479.37	0.59	0.54
2000	86	32	4627.11	0.129	229.23	479.37	0.48	0.72
2500	86	37.5	9187	0.122	223.13	479.37	0.47	0.78
3000	86	43	13746	0.095	217.12	479.37	0.45	0.96
3500	86	48.5	18305	0.078	228.52	479.37	0.48	0.99
4000	86	53.5	22862.4	0.067	241.10	479.37	0.50	0.99