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Pipelines for Development at Deep Water Fields

Master Thesis
Marine and Subsea Technology

Morten Langhelle
Spring 2011

Abstract

Oil and gas fields are today being developed at water depths characterized as ultra-deep waters, in this report limited to 3500 meters. Pipelines, which are major components of these developments, will experience challenges both in terms of design and installation. The installation processes require special focus, as heavy pipelines may exceed the lay vessels' tension capacities in these water depths.

A single steel pipeline is the most applied concept for deep water field developments due to its simple engineering concept, well known behavior and cost effectiveness. Pipe-in-Pipe solutions are thermally efficient and are a proven technology, but applications are limited due to economical and technical aspects restricting the sizes and weights applicable for installation in deep waters. Sandwich pipes can maintain a thermal and structural performance close to Pipe-in-Pipe systems, with a lower submerged weight. This is however a relatively new concept that demands further tests and studies in order to be applicable at ultra-deep water fields.

Design to withstand buckling during the installation process requires thick walled pipelines due to the combination of high external hydrostatic pressure affecting pipes at these depths and the bending during the pipe laying process. Given that existing lay vessels have limited tension capacities to reduce the bending radius, measures must be implemented, both in terms of pipeline design and lay vessel configurations, to allow for ultra-deep water installation.

The thesis comprises development of 14 inch, 20 inch and 28 inch steel pipelines for installation at water depths down to 3500 meters. Investigations are made on the effects of selecting pipelines with higher steel grades than the conventional X65. Static analysis studies are in addition made on the feasibility of installing these pipelines in deep- and ultra-deep waters, and to investigate limiting factors in the installation processes. Laying analyses are performed with OFFPIPE which provides results on bending moments, strains, and axial tensions affecting and limiting the layability. Further studies are performed on the effects an increased allowable overbend strain (up to 0,35%) will have on the installation process, and to understand the correlation between this factor and other parameters such as stinger radius, departure angle, top- and residual tension and bending moments.

Wall thickness parameter studies indicate that the use of higher steel grades will have a significant contribution in pipeline wall thickness reduction. The percentage reduction in wall thickness is greater for increasing water depths when higher steel grades are considered. This has a direct impact on the total weight of the pipeline segment to be installed in deep waters and thus selection of lay vessel. The associated cost reductions could also be substantial.

Static lay analyses show that large diameter pipelines have limited possibilities of being installed with existing lay vessels at ultra-deep waters down to 3500 meters. It can be concluded that increased allowable overbend strain have several advantages for the installation processes and will extend the water depths possible for pipe installation with existing S-lay vessels. Overbend strains are not an issue for J-lay vessels, where installation of large diameter pipelines can be performed to water depths of 3500 meters by increasing tensioning capacities of existing J-lay vessels.

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Morten B. Langhelle

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Nomenclature

Symbols

Latin characters

A	Ramberg-Osgood equation coefficient
B	Ramberg-Osgood equation exponent
b	Pipe buoyancy per unit length
C^{*}_{Y}	Peak horizontal load coefficient
C^{*}_{Z}	Peak vertical load coefficient
D	Outer diameter of the pipe, unless specified otherwise
D_{max}	Greatest measured inside or outside diameter
D_{min}	Smallest measured inside or outside diameter
E	Modulus of elasticity of the pipe steel, Young's Modulus
f_n	Natural frequency for a given vibration mode
f_o	Ovality (out-of-roundness)
f_u	Tensile strength
f_y	Yield stress
F^{*}_{Y}	Peak horizontal hydrodynamic load
F^{*}_{Z}	Peak vertical hydrodynamic load
g	Gravity acceleration
I_c	Cross sectional moment of inertia of the steel pipe
k	Thermal conductivity
κ	Pipe curvature
K_y	Pipe curvature at the nominal yield stress
L_{BA}	Buckle arrestor length
M	Bending moment
M_p	Plastic moment capacity
M_{Sd}	Design moment
M'_{Sd}	Normalized moment (M_{Sd}/M_p)
M_y	Pipe bending moment at the nominal yield stress; $M_y = 2\sigma_y I_c / D$
n	Hardening parameter
P	External pressure
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
R	Reaction force
r_{tot}	Load reduction factor
S_p	Plastic axial tension capacity

S_{Sd}	Design effective axial force
S'_{Sd}	Normalized effective force (S_{Sd}/S_p)
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
T_κ	Contact force
U	Global heat transfer coefficient
U^*	Oscillatory velocity amplitude for single design oscillation, perpendicular to pipeline
U_c	Mean current velocity normal to the pipe
V^*	Steady current velocity associated with design oscillation, perpendicular to pipeline
V_R	Velocity where vortex shedding induced oscillations can occur
W_s	Pipe submerged weight per unit length

Greek characters

α_c	Flow stress parameter
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_R	Ramberg- Osgood stress
σ_y	Nominal yield stress of the pipe steel

Abbreviations

ALS	Accidental Limit State
CP	Cathodic Protection
CRA	Corrosion Resistant Alloy
CWC	Concrete Weight Coating
DNV	Det Norske Veritas
DP	Dynamic Positioning
FBE	Fusion Bonded Epoxy
FLS	Fatigue Limit State
GPS	Global Positioning System
HFW	High Frequency Welding

HP	High Pressure
HT	High Temperature
LC	Load Controlled
LRFD	Load and Resistance Factor Design
PIP	Pipe-in-Pipe
PE	Polyurethane
PP	Polypropylene
ROV	Remotely Operated Vehicle
SAW	Submerged Arc Welding
SAWH	Submerged Arc Welding Helical
SAWL	Submerged Arc Welding Longitudinal
SLS	Serviceability Limit State
SMLS	Seamless Pipe
SMTS	Specified Minimum Tensile Strength
SMYS	Specified Minimum Yield Strength
SP	Sandwich Pipe
ULS	Ultimate Limit State
VIV	Vortex Induced Vibrations

CHAPTER 1 INTRODUCTION

1.1 Background

In recent years there has been an increased focus on oil and gas fields located in ultra-deep waters. Significant hydrocarbon reserves are present at these water depths, and due to increased energy needs, companies are starting to develop fields located in such areas. Considerations to pipeline design and installation must be made to overcome both technical and economical challenges arising at these depths.

As of today, projects have been done in water depths beyond 2000 meters and planned projects are ranging up to 3000 meters and more. The Medgaz project in the Mediterranean Sea has installed 24 inch pipelines at depths of 2155 meters, and a gas pipeline project between Oman and India had plans of pipelines at depths of nearly 3500 meters.

Significant challenges are present regarding pipelines for oil and gas field developments in deep waters. Methods of pipelaying, selection of pipeline concept and ability to do intervention are of large concern and set limitations to how deep a pipeline can be installed. Pipeline installations are limited by the laying vessels, but also technical solutions and the design are important in order to make pipeline installations and operations feasible at high water depths.

Single steel pipelines represent the most common pipeline concept. It is considered to be the simplest engineering concept, has well known behavior during installation for more shallow fields and costs are relatively low. Going to deeper waters has caused other concepts and solutions to be considered. Sandwich pipes and Pipe-in-Pipe are two alternative concepts to single steel pipelines for application in deep waters. For single steel pipelines, development of higher steel grades are explored and considered in order to reduce the required wall thicknesses and pipeline weights, which may improve layability at such depths.

1.2 Problem Statement

In this thesis pipelines in deep- and ultra-deep waters are to be studied. Based on requirements set by DNV (2007 a) and recommended practices pipelines shall be developed for water depths down to 3500 meters.

During installation at deep waters, pipelines will be subject to bending moments near the seabed, high external hydrostatic pressure, along with axial tension, affecting the installation process. Pipelines must be designed to withstand buckling during the installation, which is a greater problem with increasing water depths. When pipelines are installed empty, the concern of local buckling and hence propagation buckling will be significant.

Deep water pipelines will typically be thick walled pipes, which due to the high weight set limitations to installation depths applicable for existing vessels. In order to reduce the weight, pipelines with higher steel grades are considered, as increased yield strengths will decrease the required wall thicknesses.

1.3 Purpose and Scope

The purpose of this study is to study single steel pipelines for deep- and ultra-deep waters, and prove their layability with existing lay vessels, in addition to identify the effects increased allowable overbend strains will have on the installation process.

Scope of the thesis:

- Study relevant papers on deepwater pipeline challenges, -design and -installation.
- Identify main challenges for pipelines for development in deep- and ultra-deep waters.
- Wall thickness calculations.
- Study the effects of higher steel grades and ovality on wall thickness requirements.
- Decide pipeline coating design. Parameter study on the effect of the change in thermal conductivity from insulation coating thickness.
- Static pipeline laying study for water depths down to 3500 meters with the computer program OFFPIPE.
- Pipelay parameter study. This analysis shall provide results on the effects increased allowable overbend strains will have on the S-lay installation processes.
- Discuss and evaluate results.
- Conclusions.

1.4 Thesis Organization

Chapter 2 (Deepwater Pipelines) describes the subsea pipeline systems applicable for deep- and ultra-deep waters and discusses the main challenges connected to development of pipelines at these water depths.

Chapter 3 (Design Basis) provides the design basis for the pipelines being studied as part of case studies, including pipeline and coating properties, material data and stress-strain relationship, data about the physical environmental and design criteria, as well as on codes and standards applied in the thesis.

Chapter 4 (Design Methodology) discusses the code checks required for wall thickness design and installation analyses. DNV (2007 a) is the main standard used as design code.

Chapter 5 (Deepwater Pipeline Design and Case Studies) comprises some of the main aspects in the design processes to establish a layable and operative pipeline at deep waters. Theoretical studies and calculations of wall- and coating thicknesses, in addition to parameter studies on effects from higher steel grades on wall thicknesses and increased thermal conductivity on insulation coating thicknesses are provided.

Chapter 6 (Offshore Pipelaying) provides an understanding of pipeline laying methods relevant for deep waters. Selection of lay method will be done, based on a discussion of the advantages and disadvantages of the different concepts.

Chapter 7 (Pipeline Laying Study) covers results and evaluations on pipe layability studies of S- and J-lay to water depths of 3500 meters, and provides an understanding of pipelay parameters, -study input, and -assumptions made for the installation analyses. Results and discussions on the parameter studies with increased allowable overbend strain's effect on the installation process (with S-lay) are provided. The pipelaying system modeled with the finite element software OFFPIPE is also explained.

Chapter 8 (Conclusions and Further Studies) provides the conclusions and recommendations for further studies.

CHAPTER 2 DEEPWATER PIPELINES

Subsea pipelines are essential for the oil and gas industry throughout the world. Their ability to transport hydrocarbons between offshore fields, countries and continents are critical to maintain a sufficient import/export of oil and gas. Pipelines are constantly evolving to secure a safe and effective transportation of hydrocarbons, and to minimize the required human interference in form of maintenance and repairs.

As companies are pushing the boundaries for oil and gas recovery in increasing water depths, the need for safe and effective pipelines are critical for cost-effective and environmental reasons. Pipeline design and concepts in deep- and ultra-deep waters are being developed to fulfill the requirements given by standards and regulations.

In the following chapter general pipeline systems are highlighted, including concepts relevant for deep- waters, and discussions of main challenges related to pipelines for oil and gas field developments.

In this thesis deep- and ultra-deep waters will be defined according to NS-ES ISO 13628-1 (2005) as:

- Deep waters: water depths from 610m to 1830m
- Ultra-deep waters: water depths exceeding 1830m

2.1 Pipeline Systems

2.1.1 General

Pipeline sections extending from a start-off point, typically from a platform to an end point such as onshore facilities or another platform, are defined as a pipeline system (Braestrup, et al., 2005).

Parts of the pipeline system will typically include:

Risers
Vertical or near-vertical pipe segment connecting the subsea pipelines to above water facilities. Steel catenary-, flexible- and hybrid risers are variants applied for production and exportation purposes.

Valve assemblies
In-line valves such as check valves and ball valves, together with support structures and by-pass lines.

Isolation couplings
Devices that secure electrical isolation of two pipeline sections.

Shore approaches
Methods to connect subsea pipelines and onshore lines. This can be done by a beach pull, tunnel pull and horizontal drilling.

Pig launchers and receivers (pig traps)
Facilities connected to a pipeline to dispatch and receive pigs.

A variety of pipeline system configurations can be selected, based on factors such as location, water depth, environmental conditions, function and design life.

The different subsea pipelines can be classified as (Guo, Song, Chacko and Ghalambor, 2005) (figure 2-1):

- *Flowlines for oil and gas transport between subsea wells and -manifolds.*
- *Flowlines for oil and gas transport between subsea manifolds and production facility platforms.*
- *Infield flowlines for oil and gas transport between production facility platforms.*
- *Export pipelines for oil and gas transport between production facility platforms and shore.*
- *Flowlines for transport of water or chemicals between production facility platforms and injection wellheads.*

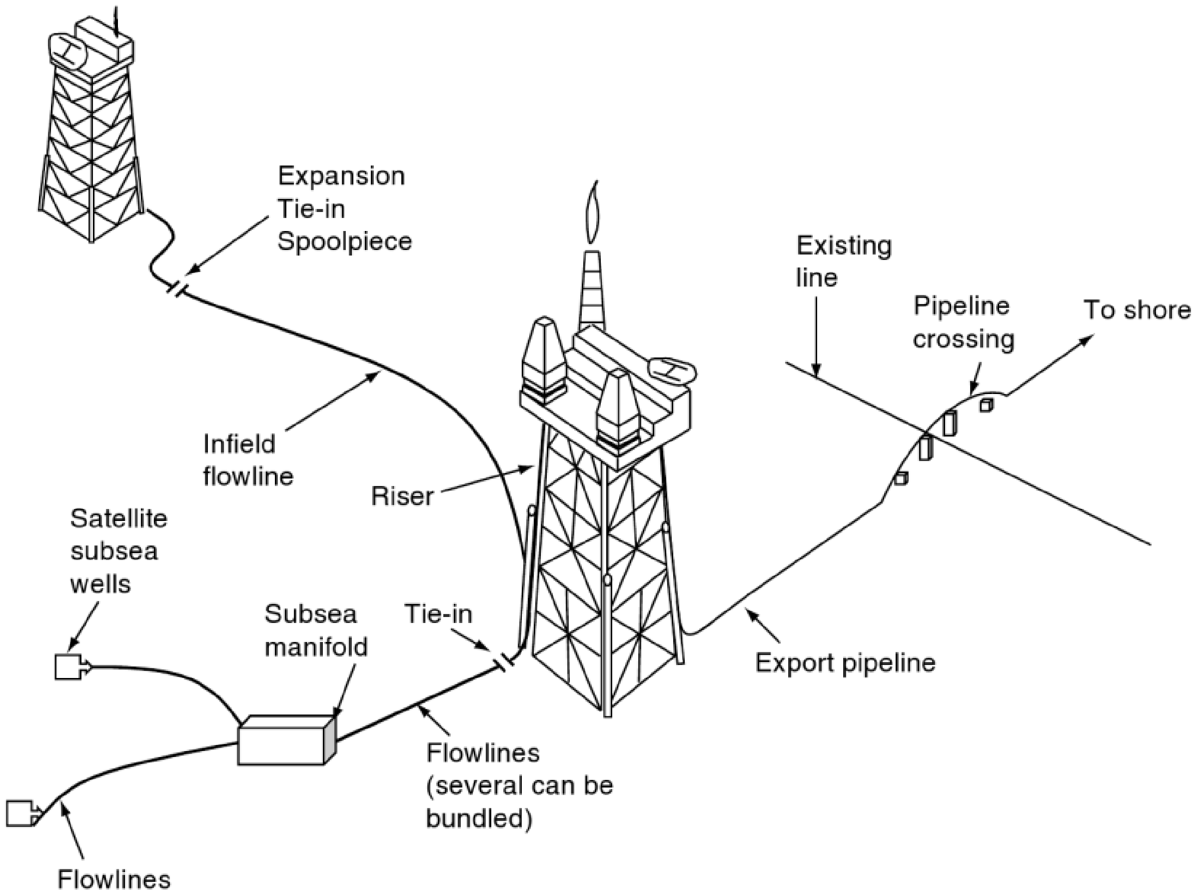


Figure 2-1 Offshore Pipelines [Guo, Song, Chacko and Ghalambor, 2005]

Flowlines are normally referred to as pipelines transporting untreated well fluids (single phase to multi-phase products). This can also include pipelines transporting chemicals for flow assurance purposes and pipelines with water or gas for injection into the reservoir to increase recovery of hydrocarbons. Pipeline diameter will normally increase further downstream to handle the expected pressure and flow.

Export pipelines

Pipelines applied for exportation of oil and gas is typically divided into:

- ***Interfield pipelines***

  Interfield pipelines are lines used for oil and gas transport inside a limited area, such as between platforms or other offshore installations. These are normally small diameter pipelines.

- ***Trunklines (Transmission pipelines)***

  Trunklines are typically large diameter pipelines used for transport of hydrocarbons from a platform to shore, subsea to shore and between continents, usually for long distances. Treated mediums such as crude oil or sales gas are transported. One example is the Langeled trunkline delivering natural gas from Norway to England.

2.1.2 Flow Assurance

Common for pipelines transporting oil and gas is the focus on flow assurance. Pipelines operating in deep waters are, due to challenges arising regarding repair and interventions at these depths, particularly critical with respect to design for maintaining a satisfactory flow assurance.

Flow assurance is a significant aspect of any oil and gas transportation system where formation of hydrates, wax, scale deposits and asphaltenes can cause potential problems. Reduction in flow or blockage of flowlines in any part of the system will cause a non-optimal petroleum production, with potentially severe economical losses.

Several mitigating measures can contribute to flow blockage prevention. Thermal insulation of flowlines (use of materials with low thermal conductivity), chemical injections (methanol, glycol, inhibitors), active heating (with hot fluids or electrical heating) and pigging (removing fluids and deposits) are some examples. Flow assurance systems can in addition consist of equipment controlling temperature and pressure. For hydrate formation to be avoided, temperature in the flowlines should be kept above a given hydrate formation temperature. During shut-down and start-up the temperature may fall under this critical temperature. Insulation with external coatings can act as barriers from reaching the hydrate formation zone, and injection of chemicals such as glycol and methanol mitigates or prevent flowline blockage (further studies in section 2.2.7).

Necessary actions to secure flow assurance depend on properties of the transported materials, as well as water depth. Both concept selection and design are influenced by the required flow assurance for the given project. In deeper waters the changes in pressure and temperature are often higher, and the consequences of blockage more critical than for more shallow waters. This may require flowlines containing chemicals specifically aimed to maintain a sufficient flow.

- ***Chemical injection lines***

  In order to avoid potential hydrates, wax and paraffin blocking the pipelines, injection of chemicals such as MEG (monoethylene glycol) and methanol can be sufficient. Chemical injection lines can be independent flowlines, as for the Ormen Lange project (two 6” MEG lines), or as piggy-back lines (injection lines connected to a hydrocarbon pipeline).

2.1.3 Specific Solutions

Based on design and material selection, pipelines can be constructed as:

- rigid pipes
- flexible pipes
- composite pipes

Rigid Pipes

Rigid pipes include a number of pipelines made out of carbon steel and manganese and/or other alloying materials. Pipe-in-Pipe, Sandwich pipes and single steel pipelines are examples of rigid pipelines with potential of operation at deep water locations. Due to good mechanical properties and costs, rigid pipelines are the most common pipelines for production and export of hydrocarbons at deep water fields.

Single carbon steel pipelines are widely used for offshore fields, both for shallow and deep waters. Material grades are typically X60 (steel grade with yield strength of 413N/mm^2) to X70 (yield strength 482N/mm^2), selected for subsea pipelines based on water depth, cost and wanted mechanical design and properties.

Compared to flexible pipelines, rigid pipelines can be constructed in larger diameters and lengths, and are cheaper to produce. They can be used for high temperatures and pressures conditions, and have good characteristics for deep waters. Rigid pipelines with good mechanical properties such as strength, toughness, ductility and weldability are developed for application in many deep water projects throughout the world.

One of the challenges with rigid pipes is their lack of resistance against corrosion. Application of coating and cathodic protection on the outside, and corrosion resistant alloys on the inside, are measures to reduce the corrosion during the pipeline service life. Rigid pipelines may experience limited fatigue life, depending on the dynamic loads, compared to flexible pipelines.

As fields are developed at deeper waters, the industry is pushed to improve rigid-, including carbon steel pipelines to withstand loads and forces affecting the pipes at these depths. Colder and harsher environments along with restricted possibilities to perform interventions are setting requirements to pipeline design. Some of the areas studied are:

- Use of higher material grades – To reduce pipeline weight
- Pipe-in-pipe and Sandwich pipes – To improve flow assurance

Flexible Pipes

Flexible pipelines are made of different functioning layers of metal and thermoplastic materials. Carcass, liner, armor- to withstand radial- and axial tension loads, and an outer sheath are the typical inside to outside construction of flexible pipelines. Their high axial tensile stiffness combined with low bending stiffness (unbounded flexible pipes) is characteristics that make them applicable for spooling onto relatively small diameter spools.

Exportation and production of oil and gas between wellhead (manifolds) and rigid pipes are typical areas of use for flexible pipelines, but longer transportations have been done for specific fields (Palmer and King, 2008). Flexible pipes have also been applied as injection lines for gas and chemicals into reservoirs. Benefits (compared to rigid pipes) are related to ease and speed of installation, less free span distances, good insulating and corrosion properties, as well as no field joints which affect the probability of leakage and the ability to function in high dynamic motions.

Still, problems arising with use in deep waters usually exceed the advantages of selecting flexible pipelines. High costs combined with limitations to withstand external pressure are critical factors which so far have put limitations for use at deep waters.

Composite Pipes

Composite pipelines are constructed by two or more materials with different chemical or physical properties. Epoxy reinforced with glass fiber, carbon fiber or silicon nitride, are examples of composites developed to maintain a high strength combined with corrosion elimination. Characteristic for composite materials are their high strength in relation to weight. Still, concerns on making reliable joints with sufficient mechanical strength are present. According to Palmer and King (2008) a combination of corrosion resistant composite- and high strength low cost steel materials can make a well functioning pipeline, with composite typically as the internal corrosion protection.

2.1.4 Pipeline Concepts

Pipelines transporting oil, gas or other well fluids can be divided into concepts based on their structure and composition. Pipeline concepts most relevant for deep water applications are:

- **Pipe-in-Pipe (PIP) systems**

  PIP consists of concentric inner and outer pipes, where the inner pipe transports the fluids and is insulated, while the external pipe provides mechanical protection. The inner pipe is designed for internal pressure containment, and thermal insulation materials shall secure required temperature along the route. The outer pipe shall secure adequate protection from external pressure and other external loads affecting the system.

  Thermal insulation capacities of PIP make this concept a viable solution for HP/HT conditions, where flow assurance is a critical factor. This concept is however complex and costly, in addition to having a relatively high weight.

- **Bundle systems**

  Bundle systems have a configuration with an outer carrier pipe, inner sleeve pipe, internal flowlines and an insulation system. The carrier pipe acts as a mechanical protection and shall maintain a corrosion free environment for the flowlines. The sleeve pipe shall sustain internal flowlines with a dry pressurized compartment. Sleeve pipes are typically insulated and flowlines are gathered around heat-up lines to satisfy flow assurance for the system. This concept is relevant where several small flowlines are required for transportation of chemicals and other fluids.

- **Sandwich pipes (SP)**

SP are a relatively new concept which consists of an inner and outer steel pipe that is separated by a polymeric annulus. The structural concept will typically be two external thin and stiff layers, and a thick and flexible core in the center. A polymer between these layers is affecting the thermal and also the mechanical capacity of the pipe. This concept is promising for deep waters due to high strength, -insulation capacity and relatively low weight. But further studies are required for this concept to be an actual solution for deep water projects.

- **Single steel pipelines**

Single pipelines are the most common concept for transportation of oil and gas, where carbon steel is normally the main material. Typical steel grades are up to X65, but X70 have been used for offshore pipelines, and even higher grades are studied. Materials such as duplex- and super duplex steels can be possible substitutes. For single pipes the wall is designed to withstand both internal pressure containment and external loads and hydrostatic pressure. Insulation and corrosion are maintained by external and internal coatings.

2.2 Deep Water Challenges

Pipelines have been installed at depths close to 3000 meters and companies are working continuously to develop sustainable and secure projects at even greater depths. Characteristic for these projects are the increased focus on challenges, which are often comprehensive and critical at deep water locations. Pipeline installation, possibilities to do interventions and pipeline coating design are all challenges that get even greater as the water depth increase.

Projects comprising pipelines for oil and gas developments in deep waters have several challenges that need to be considered before and during project execution:

Environmental conditions, concept selection, design, material selection, pipe laying, increased hydrostatic pressure, flow assurance, corrosion, safety, economy, ability to do pipeline intervention, temperature, installation requirements, thermal management, ability to do seabed intervention, recovery factor, and so on.

2.2.1 Pipelaying

Installation of pipelines in deep waters is one of the most critical challenges, as this often is the governing factor for how deep a pipe can be laid. This is due to requirements on allowable bending moments and stresses/strains in the pipes. Installation method, lay vessel, size- and weight of the pipeline, pipe material and factors such as currents, waves and seabed conditions are all contributing to the challenges of safely installing a pipeline without exceeding the criteria set. Today there are a limited number of vessels performing pipelaying at ultra-deep waters. The vessels tensioning capacities required for deep water installations are high, especially for large and thick walled pipelines, which may be too costly to justify for. A high top tension may also result in large bottom tensions being left in the pipeline at the seabed, giving larger and more frequent freespans, especially for uneven seabeds (Bai and Bai, 2005).

S-lay is a commonly used pipe installation method, due to the speed of laying and ability to install large diameter pipelines. (See CHAPTER 6 for further information on offshore pipelaying). Some of the challenges linked to this method are the potential of exceeding acceptable strain values at the overbend and bending moments at the sagbend (figure 2-2). This is depending on the stinger length and -radius, tensioning capacity, tip slope, curvature of the pipeline and longitudinal trim of the vessel. These aspects will set the maximum depth of installation (Iorio, Bruschi and Donati, 2000). Heavy pipeline segments can also result in stinger and/or pipe damages due to pipe interaction with the stinger tip, typically from vessel movements caused by waves.

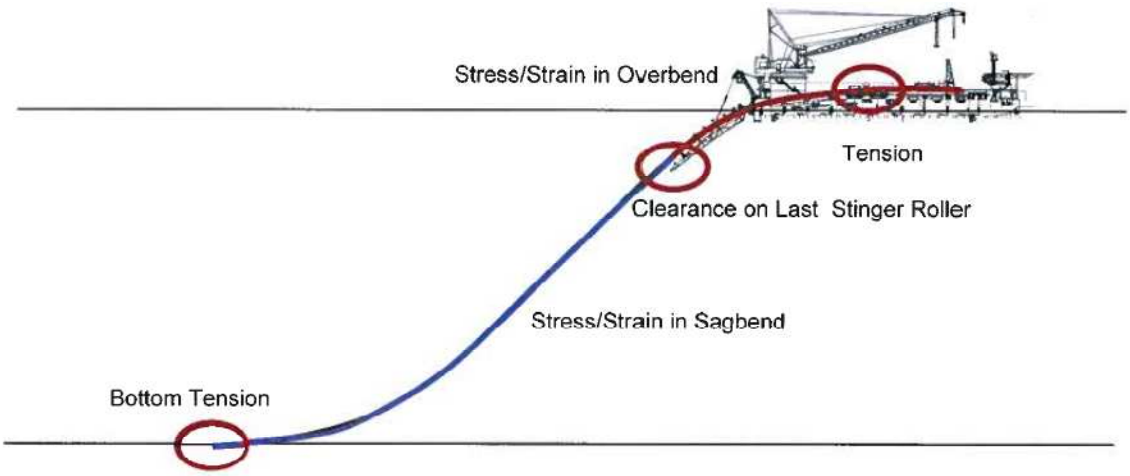


Figure 2-2 Critical Areas for S-Lay [Karunakaran, 2010 c]

To be able to install pipelines at a greater water depth several actions can be made. This could be increase of the stinger length and tensioning capacity. Still, this will have practical limitations due to waves and currents acting on the stinger, as well as the requirements to clamping actions which may damage the pipeline. Lay tensioning capacity requirements in ultra-deep waters are usually too high to handle even for the best S-lay vessels.

J-lay is a much applied technique for installation of pipelines in deep waters (figure 2-3). The pipeline is installed in a J-shape by welding the pipes together at a vertical position. Challenges related to this installation method are time consumption, due to only one or two work-stations, and limitations to pipe diameter. Another challenge is the need of dynamic positioning system (DP) for the installation vessel, which can be a severe problem in case of bad weather, where pipeline damage may occur due to the pipe curvature exceeding the allowable bending moments. Especially the curvature at the sagbend is a challenge and can lead to pipeline collapse due to buckling at great depths where the external pressure is high. In most cases J-lay is considered the best applicable installation method for pipelines in ultra-deep waters (Cavicchi and Ardavanis, 2003).

Iorio, Bruschi and Donati (2000) have discussed the use of higher graded steels to reduce pipeline weight and hence extend the layable water depths. Perinet and Frazer (2007 and 2008) investigate the benefits of steep S-lay, combined S- and J-lay and increased allowable strains in the overbend during installation.

The long free spans during deep water installations give potential of fatigue damage due to vessel response and vortex shedding. Critical loads can interfere with the long suspended pipe caused by the vessels response to wave actions, and vortex shedding induced oscillations may result in vibrations and potential high dynamic stresses, which is particularly critical for low tension added to the pipe during laying. Other factors of concern are the ability to lay pipelines accurately in the seabed corridors, and to predict the actual configuration on the seabed. This can be controlled in a better manner if integrated monitoring systems and use of ROV (Remotely Operated Vehicles) are applied as part of the installation processes.

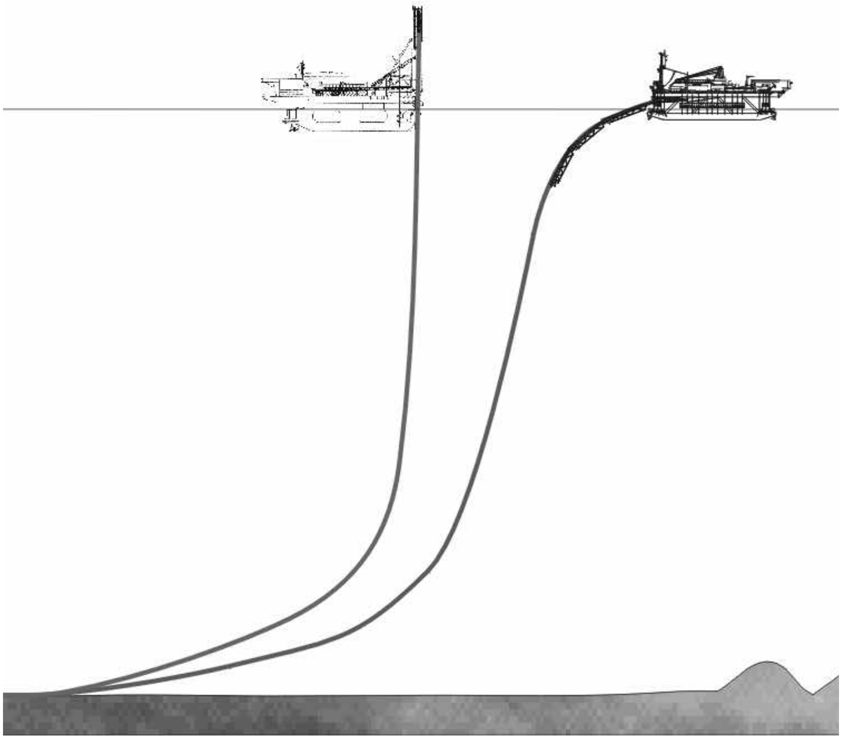


Figure 2-3 J-Lay vs. S-Lay at Deep Water [Iorio, Bruschi and Donati, 2000]

2.2.2 Material Selection and Wall Thickness Design

Materials and -compositions are significant aspects to develop sustainable pipes for oil- and gas recovery. Materials selected shall satisfy requirements to strength, corrosion and fracture toughness as well as requirements to weldability. Harsher environments will often be present at deeper waters, and loads affecting the pipelines will in many cases be more severe than for shallower waters. High temperatures and pressures of the transported fluids, along with aggressive chemistry, are factors requiring a special consideration for internal and external pipe materials. Stresses arising from temperature changes are often somewhat higher for deep water pipelines, due to low temperatures at the seabed and high internal temperatures. Higher stresses and strains affecting the pipes during the installation processes will also have an influence on the material selection.

Studies have been done on the effects of applying higher graded steels in pipeline design. This will reduce the required wall thickness due to higher yield strength, which in order will decrease the weight, making pipelaying in deep water more feasible. Even though selection of high graded steels (X70, X80, etc.) has its benefits, it also causes challenges. Weight reduction can result in less on-bottom stability, which may require use of implementing measures such as rock dumping, mats or anchors, to secure an adequate stability.

Use of higher steel grades is not optimal if welds are performed with a lower quality than the pipe itself, as this may cause possible failures during operation. Need of higher weld quality is a concern due to a decrease in lay rate, which already is a problem, especially for large diameter pipelines using the J-lay method for pipe installation. Another aspect of concern is corrosion. Decrease in wall thickness affects the possible corrosion before having to change the pipeline or parts of it, which is a costly and extensive operation, especially in deeper waters. Thinner walled pipelines are in addition more likely to be damaged due to extreme environmental loads and can get problems in rough sea bottoms (Iorio, Bruschi and Donati, 2000).

Wall thickness is the most relevant factor for a steel pipelines capacity to withstand loads imposed during installation and operation. A big concern for the pipeline design is the wall thickness requirements that affect the deep water pipelines. Due to high external pressure (in combination with bending), which increases with water depth, thick walled pipelines are needed to avoid collapse. Possibilities to perform installation for such heavy pipes, in addition to costs, will then be factors that comes into account for a go or no-go decision for the given project. Thick walled pipelines may experience difficulties to welding and problems concerning upheaval buckling. For the projected Oman-to-India gas pipeline the design studies concluded with the need of 30mm or thicker wall thicknesses for pipelines with a diameter of 20-26 inch in a water depth down to 3000 meters (Palmer and King, 2008).

External hydrostatic pressure is almost without exception the determining factor for pipeline wall thickness design in deep waters. Design to avoid initiating- and propagating buckling, as well as local buckling caused by the external pressure in combination with bending, is of extreme importance. Buckling can cause severe damage and even collapse of the pipeline if no counter-measures are put into action.

2.2.3 Concept Selection

Concept selection is a major part of making deep water fields economically feasible. Costs and technical challenges with the different concepts are governing for the final selection. Technical challenges are related to pipeline concepts which can withstand the external water pressure without exceeding the lay vessels tensioning capacities due to pipe segment weights. These shall in addition provide satisfactory flow assurance (reduce the chances of hydrates, wax, etc.), be able to transport the hydrocarbons with high enough rate and have the necessary strength to avoid deformation and damage during the laying operation.

Pipe-in-Pipe (PIP) and Sandwich pipes (SP) are two possible concepts besides standard single steel pipelines with insulation coatings. "One of the advantages of PIP system is the possibility of using materials with excellent thermal properties, considering that the structural integrity is provided independently by the outer and inner steel layers", Grealish and Roddy (2002) (referenced by Castello and Estefen, 2008). There are still challenges related to the costs and weight of this solution, which can problematic during pipelaying. The SP concept has benefits due to the possibility of obtaining good structural strength combined with a satisfactory flow assurance. Weight is also generally lower than for the PIP solution, due to use of less steel (Castello and Estefen, 2008). One of the challenges is that this is not a well known concept in ultra-deep waters, especially not ranging over more than 3000m. For single steel pipelines the challenges are related to the weight which may exceed the lay vessels tensioning capacities. This is due to the requirements to wall thicknesses to withstand collapse in deep waters. A heavier pipeline will increase the costs of the project by limiting the vessels capable of pipelaying.

2.2.4 Free spans

Spans occur where the pipe is moving over a depression in the seabed. Depending on the span length and height of the pipeline, this can cause potential problems to fatigue and overstresses. Problems can arise both due to static and dynamic loads. As deep water pipelines often are left with a high residual tension at the seabed, the probability of critical free spans increases.

Vortex induced vibrations (VIV) are able to cause fatigue damages to the pipelines if their natural frequencies are close to the vortex shedding frequency. Natural frequency is affected by the span length, mass, flexural rigidity, the boundary conditions, effective axial force, etc. of the pipeline. If the spans are long or the pipe mass is low, there is a higher probability of fatigue damages due to vibrations. Even though currents are generally lower for deeper waters there might exist so-called near bottom loop currents at these locations. Vibrations can then cause damages both to the pipeline, coating and welds. This effect can be reduced if VIV suppression devices, such as shroud and strake, are installed as part of the pipeline (Karunakaran, 2010 b).

Pipelines in free span may cause overstresses in the pipes due to unacceptable bending. This can cause local plastic deformation and buckling (figure 2-4). The weight of the pipe and content affects this issue, along with the drag- and lift force at the bottom which contributes to the static load.

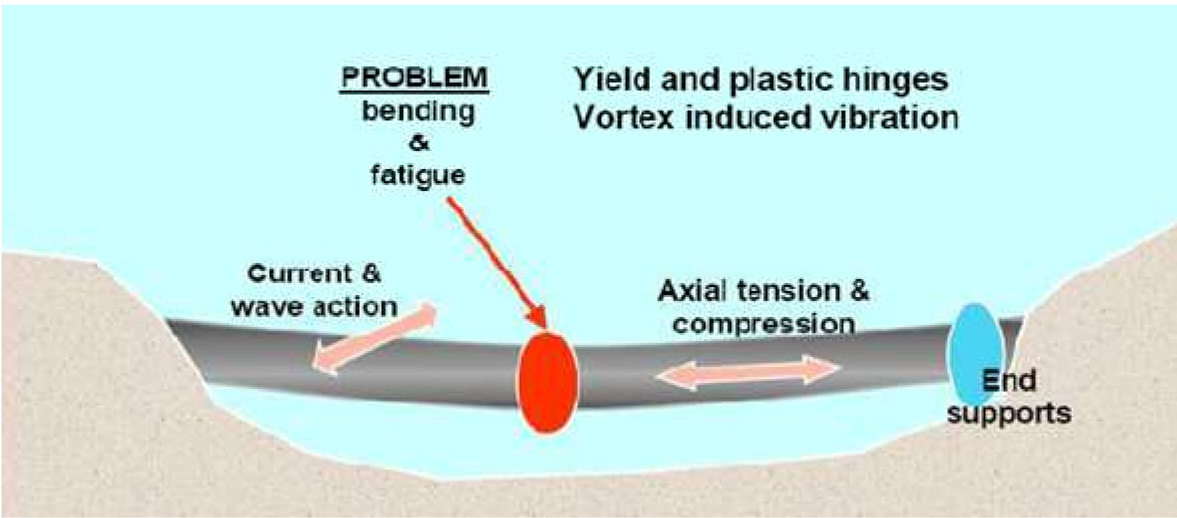


Figure 2-4 Span Problems [Karunakaran, 2010 b]

2.2.5 Pipeline Repair and Intervention

The ability to perform pipeline repair in deep waters are limited. As this is too deep for divers, there are more challenges in developing sufficient diverless methods of pipeline repair and intervention. Even though there are methods using mechanical connectors, there is still a way to go before this is an optimal solution for pipeline repair. In case of severe damage to the pipelines in operation mode, there are to this date few repair measures to implement. This shows the importance of well known survey information, in advance, to avoid these situations. Due to lack of methods and experience on pipeline repair in ultra-deep waters the costs are high, making it problematic for companies operating oil and gas fields in such depths (Abadie and Carlson, 1995) (McKinnon, 1999).

Lee (2002) indicates the importance of having repair plans in the early stages of a project. This is to minimize the downtime of the pipelines, which due to long waiting time for repair units can lead to potentially significant economical losses. Approximately 4-6 months waiting time is expected for spool piece repair units provided by diverless systems, from design to delivery. Repair clamps operated by ROVs, to stop leakages, may use 3-4 months. Connectors are in addition custom made based on wall thicknesses, steel grades, diameters and materials, and may not be kept in stock. During installations, where buckling or flooding are potential damage scenarios, reverse lay of the pipeline may be the most suitable measure to repair the area with defects.

2.2.6 Seabed Intervention

Seabed intervention is, as for pipeline repair and intervention, both more expensive and demanding as the water depth increases. Even if the seabed at deeper waters often has a smoother and a softer seafloor than shallower waters, other challenges can occur at these depths. This is related to landslips, mudflows and subsidence due to more unstable seabed. These situations are difficult to prevent, and are hence both costly and time consuming to avoid or rectify. Today there are many measures to stabilize and protect the pipelines at the seafloor by seabed intervention. Rock dumping, trenching, mechanical supports and anchors are some typical methods of intervention. Still, the lack of knowledge and limitations to these measures in deep waters is problematic and further study on the field is required (McKinnon, 1999).

2.2.7 Flow Assurance

Hydrate- and wax/gel formation are serious concerns for pipelines at deep water fields. Low sea bottom water temperature and high pressure are the two main factors that can cause challenges in deep water projects. An example is the Ormen Lange field in the Norwegian Sea where subzero temperatures at sea bottom are present at the deepest parts of the field (approx. 1000m). Even though subzero temperatures are unusual in deep waters, the temperature can be relatively low (2-4 degrees Celsius) and will in combination with high internal pressure cause hydrates and potential hydrate-plugs if inside the hydrate zone (figure 2-5). Given that deep waters often consist of soft seabeds and hilly terrain, the chances of hydrate accumulation are concerning due to low spots (Mehta, Walsh and Lorimer, 2000). Wax and hydrates have the potential to block pipelines, causing serious problems to flow assurance and production rates. Reduction in internal diameter and increased surface roughness reduce the throughput and increase the pressure. For temperatures where hydrates, wax etc. can become a problem, it may result in production stops and hence workovers to repair the damages. This is both time consuming and expensive processes. Use of wax inhibitors, MEG or methanol can prevent or reduce these severe problems, in addition to application of sufficient insulation coatings. Insulation materials that have been applied for shallower waters may have to be optimized to prove applicable for deep water environments.

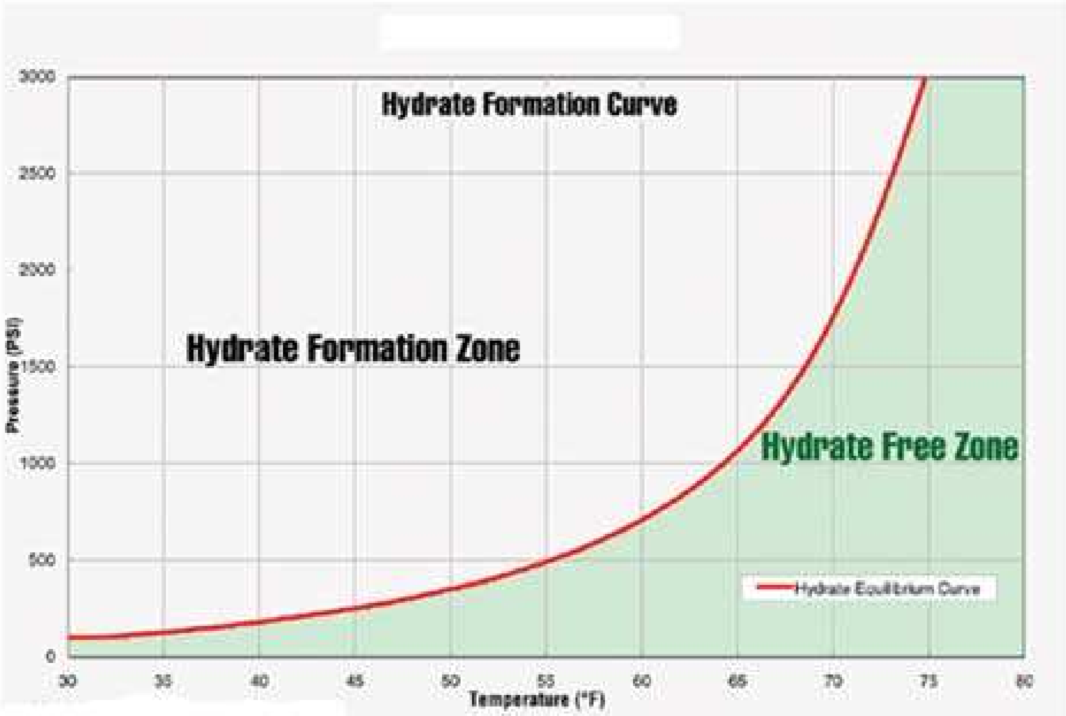


Figure 2-5 Hydrate Formation Zone [Toscano, 2007]

2.3 Summary

Rigid pipelines are, compared to flexible- and composite pipes, more applicable for deep waters due to their strength to withstand external pressure, in addition to the relatively low costs. Single steel pipes are beneficial for large diameter pipelines compared to Pipe-in-Pipe and Sandwich pipes which are limited by weight and lack of tests at ultra-deep waters, respectively. Single steel pipelines have a relatively simple construction, well known behaviors in installations, and are cost effective.

Several technical and environmental challenges are affecting the pipeline design and installation processes. Pipeline design due to high external pressure is, in combination with bending during pipelaying, possibly the most challenging aspects for deep water fields. Limitations in number of vessels able to perform S- and J-lay at these depths are pushing prices up. Pipeline insulation is also a challenge in order to secure a satisfactory flow assurance at deep waters where hard and cold environment can be present.

To improve pipeline layability, use of higher graded steels such as X70 and X80 has big potentials. Increasing steel grades will reduce the required wall thicknesses to avoid collapse and decrease pipeline weight. An overall cost reduction is most likely the outcome of increased steel grades.

CHAPTER 3 DESIGN BASIS

3.1 General

A design basis is developed by a number of considerations and calculations. To decide upon the following design basis, for pipelines in deep- and ultra-deep waters, the given standards and recommended practices have been applied:

- DNV-OS-F101 (2007) Submarine Pipeline Systems
- DNV-RP-F105 (2006) Free Spanning Pipelines
- DNV-RP-F109 (2007) On-bottom Stability Design of Submarine Pipelines

3.2 Water Depths

Pipeline design and installation in water depths of 800m, 1400m, 2000m and 3500m are considered in this study.

3.3 Pipeline and Coating Properties

3.3.1 Pipeline Data

Following pipeline data are given (table 3-1):

Nominal Diameter:	**14”**	**20”**	**28”**
Outer Diameter, *D*:	355,6 mm	508,0 mm	711,2 mm
External corrosion and insulation coating	Multilayer system: 0,3 mm FBE / 1300 kg/m^3 2,7 mm PP + Adhesive / 900 kg/m^3 Variable thickness PP foam / 620 kg/m^3 3,0 mm PP shield / 890 kg/m^3		
Ovality, f_o	1,5%	1,5%	1,0%
Wall thickness tolerance, t_{fab}	1,0 mm		

Table 3-1 Pipeline Data

U-value for the pipelines maximum of 5,0 W/m^{2}K.

3.3.2 Pipeline Material Data

Following pipeline material properties are given (table 3-2):

Characteristics	**Unit**	**Values**		
Carbon Steel Pipelines	inch	14	20, 28	
Material Grade	-	X65	X70	X80
Density	Kg/m^3	7850	7850	7850
SMYS	MPa	448	482	551
SMTS	MPa	530	565	620
Young's Modulus	MPa	$2{,}07 \times 10^5$	$2{,}07 \times 10^5$	$2{,}07 \times 10^5$
Poisson's Ratio	-	0,3	0,3	0,3
Max Yield Strength/Tensile Strength Ratio	-	0,93	0,93	0,93

Table 3-2 Material Properties

3.3.3 Stress- Strain Relationship

The stress-strain relationship is based on the Ramberg- Osgood relationship, which is used to characterize a material stress-strain response. Input data in table 3-3 and table 3-4 are chosen from two points on the stress- strain curve. These results in a hardening parameter, *n*, and the Ramberg-Osgood stress, σ_R, given in table 3-5 and table 3-6. The Ramberg-Osgood parameters are used in the further pipeline laying study (and to obtain the Moment-Curvature relationship (see APPENDIX D)).

	Stress (MPa)	Strain, ε (-)
SMYS (first point)	448	0,005
SMTS (second point)	530	0,200

Table 3-3 Ramberg- Osgood Input Data for X65

	Stress (MPa)	Strain, ε (-)
SMYS (first point)	482	0,005
SMTS (second point)	565	0,200

Table 3-4 Ramberg- Osgood Input Data for X70

Hardening parameter, *n*	25,24
Ramberg- Osgood stress, σ_R	428 MPa

Table 3-5 Ramberg- Osgood Parameters for X65

Hardening parameter, *n*	27,08
Ramberg- Osgood stress, σ_R	464 MPa

Table 3-6 Ramberg- Osgood Parameters for X70

3.4 Environmental Data

3.4.1 Seawater Properties

Seawater density is chosen as:
Density (at 10˚C): 1025 kg/m^3
Min. temperature: 5,0˚C

3.4.2 Seabed Friction

The seabed friction is assumed to be:
Seabed friction, axial: 0,3

3.5 Design Criteria

The following criteria are applied for installation analyses in this thesis:

- Sagbend: Moment criterion is in accordance with DNV (2007 a), assuming Load Controlled condition criteria.
- Overbend: The pipeline part on the stinger is assumed to be displacement controlled, with a maximum allowable strain of 0,25% (X65) and 0,27% (X70). Maximum allowable overbend strain criteria of 0,35% is set for the pipelay parameter study (section 7.5).

Material parameters (table 3-7) are based on the following location and safety class (DNV, 2007 a):

- Location class 1: Area of no frequent human activity.

- Safety class low: Low risk of human injury and minor environmental and economic consequences.

Factor	Class	Value
Material resistance factor, γ_m	SLS/ULS/ALS	1,15
Safety class resistance factor, γ_{SC} - Pressure containment	LOW	1,046
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

Table 3-7 Material Parameters

CHAPTER 4 DESIGN METHODOLOGY

4.1 General

The following methodology is applied to investigate:

- Wall thickness sizing
- On-bottom stability
- Pipeline installation feasibility

4.1.1 Limit States

DNV (2007 a) are set as the governing standard for the following pipeline design. Based on the Load and Resistance Factor Design (LRFD) given in this standard, the design load effects (L_{Sd}) shall in no failure modes exceed design resistance (R_{Rd}).

$$f\left(\frac{L_{Sd}}{R_{Rd}}\right)_i \leq 1 \tag{4.1}$$

Limit states are divided into following categories, according to DNV (2007 a):

*Serviceability Limit State (*SLS*): Pipeline must be functional when affected by routine loads to satisfy the SLS requirements.*
*Ultimate Limit State (*ULS*): ULS require that the pipeline does not collapse when subjected to the peak design loads.*
*Accidental Limit State (*ALS*): For ALS to be satisfied the pipeline shall withstand severe damages such as cracks due to unplanned loading conditions like dropped objects, fire and so on.*
*Fatigue Limit State (*FLS*): The pipeline shall be designed to withstand cyclic dynamic loads and accumulated fatigue through the life period.*

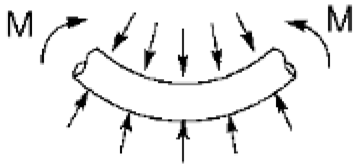
4.2 Ultimate Limit State

ULS design is set as the governing criteria for the pipeline design considered in this thesis. Exceeding the ULS may cause severe consequences, such as pipeline collapse. The pipeline must have a structural design with an integrity and strength, giving the required safety against failure in the ULS.

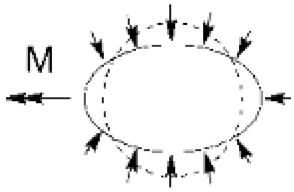
Ovalization

Ovalization results in the pipeline cross section changing from a circle into an elliptic shape. During installation the pipe will experience bending, either in the elastic or plastic range. If ovalization is going into the plastic range, the pipeline will have a reduced resistance against external pressure, which may affect both the collapse pressure and pigging abilities for the pipeline.

Figure 4-1 provides the mechanisms of ovalization during bending of the pipeline. Figure 4-1 (a) illustrates bending of a pipe length experiencing longitudinal stress during combined bending and external pressure. The upper elements go into compression, while tension is affecting the lower elements. This may result in ovality of the pipe, from the forces transferred to the cross section, given in figure 4-1 (b).



(a)



(b)

Figure 4-1 Ovalization during Bending [Kyriakides and Corona, 2007]

$$f_o = \frac{D_{max}-D_{min}}{D} \tag{4.2}$$

Where:

f_o	Initial ovality (out-of-roundness). Not to be taken < 0,005 (DNV, 2007 a)
D_{max}	Greatest measured inside or outside diameter
D_{min}	Smallest measured inside or outside diameter
D	Outer diameter of the pipe

According to DNV (2007 a) out-of-roundness tolerance from fabrication of the pipe shall not, together with flattening due to bending, in any case exceed 3%, except from where special design considerations are done (e.g. if corresponding reduction in moment resistance has been included).

$$f_o = \frac{D_{max}-D_{min}}{D} \leq 0{,}03 \tag{4.3}$$

4.2.1 Wall Thickness Design Criteria

On-Bottom Stability

The submerged weight of the pipeline must exceed the buoyancy force to avoid flotation.

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

$$\gamma_W \frac{b}{w_s+b} \leq 1{,}0 \tag{4.4}$$

Where:

$$b = \rho_W g \pi \frac{D^2}{4}$$

γ_w	Safety factor. Can be applied as 1,1 if a sufficiently low probability of negative buoyancy is not documented; 1,1
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

Local Buckling (System Collapse)

Local buckling may occur where there is high external hydrostatic pressure, typically for deep waters. Buckling may lead to pipe collapse failure and will first occur in the weakest point of the pipeline. Resulting in an ovalized pipe with danger of buckling propagation, this is a significant threat for deep water pipelines.

According to DNV (2007 a) the following criteria shall be met at any point along the pipeline, regarding external pressure:

$$p_e - p_{min} \leq \frac{p_c(t_1)}{\gamma_m \gamma_{SC}} \tag{4.5}$$

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 3-7
γ_{SC}	Safety class resistance factor; see table 3-7
p_c	Characteristic collapse pressure
t_1	Characteristic wall thickness; t-t_{fab} prior to operation

$$\left(p_c(t) - p_{el}(t)\right)(p_c(t)^2 - p_p(t)^2) = p_c(t)p_{el}(t)p_p(t)f_o\frac{D}{t} \tag{4.6}$$

Where:

p_{el} Elastic collapse pressure

$$p_{el}(t) = \frac{2E(\frac{t}{D})^3}{1-v^2} \tag{4.7}$$

p_p Plastic collapse pressure

$$p_p(t) = f_y \alpha_{fab} \frac{2t}{D} \tag{4.8}$$

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 are present.
t_{fab}	Fabrication thickness tolerance for wall thickness; 1,0 mm

D	Outer diameter of the pipe
E	Young's Modulus
v	Poisson's ratio

Propagation Buckling

Buckle propagation, which leads to contact between the upper and lower part of the pipe walls, may be initiated by local buckling, a dent, bending during installation or due to corrosion of the steel wall. Once local buckling has occurred a propagation buckling might continue to a part of the pipeline where the external pressure is too low to cause further buckling. Propagation buckling can be avoided if the pipelines are resistant to local buckling or buckle arrestors are installed.

Propagation buckling is critical in the installation phase where pipelines are subject to both bending and external pressure. The external collapse propagation pressure is lower than the external collapse pressure needed to collapse locally, typically only 15-20%, according to Omrani, Gharabaghi and Abedi (2009). Requirements to pipeline wall thicknesses, following the propagation criteria, are often very high. Due to both the weight and cost aspects, propagation buckling requirements for pipeline design are typically too expensive to satisfy by the wall thickness alone. Design made by propagation buckling is too conservative, and herby other measures should be set into action to avoid damages by propagation.

To reduce the probability of propagating buckling running along long distances, various types of buckle arrestors are installed on the pipelines (figure 4-2). One has to accept possibilities of propagation buckling over short distances, but the buckle will stop on each side of the buckle arrestor (Karunakaran, 2010 d).

According to DNV (2007 a) the following criteria for propagation buckling shall be satisfied:

$$p_e \leq \frac{p_{pr}}{\gamma_m \gamma_{SC}} \quad (4.9)$$

Where:

γ_m	Material resistance factor; see table 3-7
γ_{SC}	Safety class resistance factor; see table 3-7
p_e	External pressure
p_{pr}	Propagating pressure

$$p_{pr} = 35 f_y \alpha_{fab} \left(\frac{t_2}{D}\right)^{2,5} \qquad \frac{D}{t} < 45 \quad (4.10)$$

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

Buckle arrestors

Installation of buckle arrestors will increase the bending stiffness in the area of placement. By placing them at intervals along the pipeline, one reduces the damage by propagation by arresting the collapse propagation. Then a collapse cross-over pressure is necessary to have propagation through the arrestors (Toscano, et al., 2008).

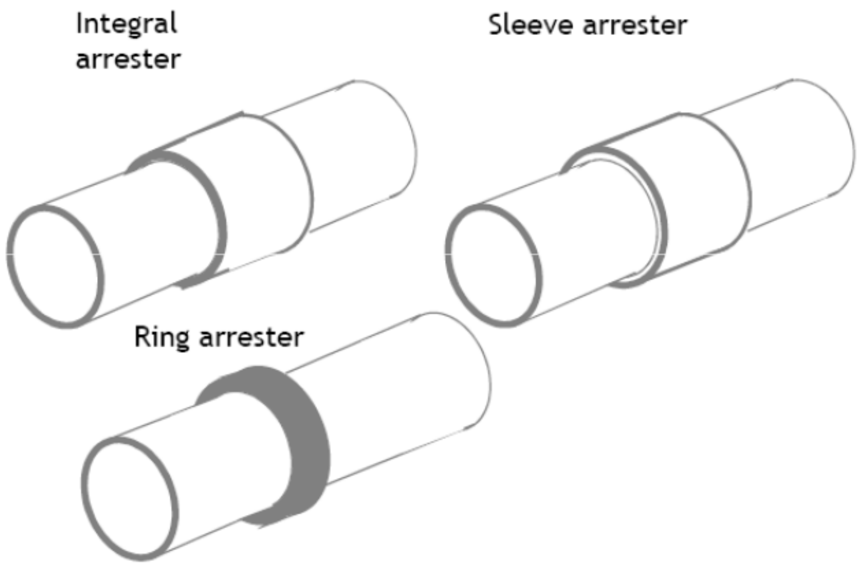


Figure 4-2 Three Types of Buckle Arrestors [Karunakaran, 2010 d]

According to DNV (2007 a) an integral buckle arrestor can be designed based on:

$$p_e \leq \frac{p_X}{1{,}1\gamma_m\gamma_{SC}} \tag{4.11}$$

Where:

γ_m	Material resistance factor; see table 3-7
γ_{SC}	Safety class resistance factor; see table 3-7
p_e	External pressure
p_X	Crossover pressure

$$p_X = p_{pr} + \left(p_{pr,BA} - p_{pr}\right)[1 - EXP\left(-20\frac{t_2 L_{BA}}{D^2}\right)] \tag{4.12}$$

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 will depend upon the propagation buckle resistance from the pipe and an infinite buckle arrestor, as well as the arrestor length (DNV, 2007 a).

According to DNV (2007 a) it is recommended to have a safety class higher for the buckle arrestors than for the propagating pressure.

4.2.2 Laying Design Criteria

Overbend

The pipelines shall be controlled against the simplified criteria in the overbend, according to DNV (2007 a).

Simplified laying criteria

In early design stages, the simplified laying criteria can, according to DNV (2007 a) section 13 H 300, be applied as a criteria for the local buckling check. This includes satisfactory strain in the overbend. Limit states for Concrete Crushing, Fatigue and Rotation shall also be satisfied, according to DNV (2007 a).

For static loading the calculated strain shall satisfy Criterion I in table 4-1. The strain shall include effects of bending, axial force 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 calculated strain shall satisfy criterion II in table 4-1. The strain shall include all effects, including varying stiffness due to field joints or buckle arrestors.

Simplified criteria, overbend				
Criterion	*X70*	*X65*	*X60*	*X52*
I	0,270%	0,250%	0,230%	0,205%
II	0,325%	0,305%	0,290%	0,260%

Table 4-1 Simplified Criteria, Overbend [DNV, 2007 a]

Sagbend

The pipelines shall be controlled against the load controlled condition criteria in the sagbend, according to DNV (2007 a).

Local Buckling – Combined Loading Criteria

Pipelines designed to withstand pure internal and external pressure will be controlled on their resistance against combined loading. For deep- and ultra-deep water pipelines this is normally design against buckling due to a combination of bending moment, axial force and external overpressure experienced during the installation process. This will govern the maximum allowable bending moments during lay operations.

Load Controlled condition (LC condition)

For the LC condition, where the structural response is mainly controlled by the imposed loads, the following equation shall be satisfied for the design, for pipelines affected by bending moment, effective axial force and external overpressure, according to DNV (2007 a):

$$\{\gamma_m \gamma_{SC} \frac{|M_{Sd}|}{\alpha_c M_p(t_2)} + \{\frac{\gamma_m \gamma_{SC} S_{Sd}}{\alpha_c S_p(t_2)}\}^2\}^2 + (\gamma_m \gamma_{SC} \frac{p_e - p_{min}}{p_c(t_2)})^2 \leq 1 \tag{4.13a}$$

$$\{\gamma_m \gamma_{SC} \frac{|M'_{Sd}(t_2)|}{\alpha_c} + \{\frac{\gamma_m \gamma_{SC} S'_{Sd}(t_2)}{\alpha_c}\}^2\}^2 + (\gamma_m \gamma_{SC} \frac{p_e - p_{min}}{p_c(t_2)})^2 \leq 1 \qquad (4.13b)$$

$\frac{D}{t} \leq 45 \quad p_i < p_e$

Where:

p_i	Internal pressure
p_{min}	Minimum internal pressure that can be sustained. Usually zero for as-laid pipelines
p_c	Characteristic collapse pressure; eq. 4.6
p_e	External pressure
M_{Sd}	Design moment; eq. 4.5 (DNV, 2007 a)
S_{Sd}	Design effective axial force; eq. 4.7 (DNV, 2007 a)
M_p	Plastic moment capacity of the pipe; $M_p(t_2)= f_y(D-t_2)^2 t_2$
S_p	Plastic axial tension capacity of the pipe; $S_p(t_2)= f_y \pi(D-t_2)t_2$
M'_{Sd}	Normalized moment; (M_{Sd}/M_p)
S'_{Sd}	Normalized effective force; (S_{Sd}/S_p)
t	Nominal pipe wall thickness (un-corroded)
t_2	Characteristic wall thickness; t for pipelines prior to operation
γ_m	Material resistance factor; see table 3-7
γ_{SC}	Safety class resistance factor; see table 3-7
α_C	Flow stress parameter

$$\alpha_c = (1-\beta) + \beta \frac{f_u}{f_y} \qquad (4.14)$$

$$\begin{aligned} \beta &= 0{,}5 && \text{for } \frac{D}{t_2} < 15 \\ \beta &= \frac{60 - D/t_2}{90} && \text{for } 15 < \frac{D}{t_2} < 60 \qquad (4.15) \\ \beta &= 0 && \text{for } \frac{D}{t_2} > 60 \end{aligned}$$

Where:

β	Factor used in combined loading criteria

CHAPTER 5 DEEPWATER PIPELINE DESIGN AND CASE STUDIES

Several considerations have to be done in order to develop a pipeline with the necessary design to be layable and operable for its required life cycle. This chapter will comprise some of the main aspects in the design processes to establish an operative pipeline in deep waters. In addition to theoretical studies, wall- and coating thicknesses are calculated in order to satisfy on-bottom stability and resistance to local buckling, and flow assurance, respectively. Parameter studies are provided to establish the effects on wall thicknesses by higher steel grades and ovality, and insulation coating design to obtain the effects of changing thermal conductivity on coating thicknesses.

5.1 Design Process

In advance of the design process, a design brief should be established. This will include operational requirements and should contain the following (Karunakaran, 2010 a):

- Chemical composition of the fluid transported (and if it will change during the design life).
- Maximum and minimum pressure at the upstream end.
- Maximum and minimum pressure at the downstream end.
- Maximum and minimum temperature at the upstream end.
- Maximum and minimum temperature at the downstream end.
- Location and heights of the end points.
- Available sources of bathymetric and topographic information.
- Available sources of geotechnical information about the seabed under the pipeline.
- Available sources of oceanographic information about the sea surrounding the pipeline.
- Known constraints (politics, environmental, other users of the seabed such as fishing, cables, navigation) for selection of route.

A design brief has to be established and is followed during design of pipelines based on the gathered information. Usually the design selection process is fixed in the given way:

1. Route selection (establishes maximum depth and length).
2. Type- and material selection (single or pipe-in-pipe, rigid or flexible, carbon steel or composite etc.).
3. Thermal and hydraulic analysis to determine diameter, temperature and pressure profile, need of thermal insulation and if heat tracing or cooling are required.
4. Material selection for internal coating, concrete weight coating, external anti-corrosion coating, and thermal insulation (if required).
5. Wall-thickness selection.
6. Stability design; if the weight is sufficient to have a stable pipeline or if it has to be trenched etc.
7. Cathodic protection system design.
8. Confirm that the pipeline is constructible.

5.2 Route Selection

The pipeline route is selected by a number of factors and considerations. Some of the most important is safety, protection of environment, and probability of damage to new and already existing equipment and facilities. From the technical point of view this includes location of host and destination of the pipeline, along with factors that affect the routing of the pipeline (DNV, 2007 a):

- Environment
  - Areas of natural conservation
  - Archaeological sites
  - Exposure to environmental damage
  - Etc.

- Seabed characteristics
  - Unstable seabed
  - Uneven seabed
  - Soil properties
  - Seismic activity

- Facilities
  - Subsea structures and well heads
  - Obstructions
  - Existing pipelines and cables
  - Offshore installations

- Third party activities
  - Dumping areas
  - Fishing activities
  - Ship traffic
  - Mining activities

- Landfall
  - 3^{rd} party requirements
  - Environmental sensitive areas
  - Limited construction period
  - Local constraints

In addition construction limitations, politics and costs are influencing the pipeline routing. Construction limitations can be a challenge to overcome, especially for ultra-deep water areas, where vessels able to perform installations are limited.

A pipeline route survey will be required to obtain sufficient data for pipeline design. This include the whole route with special investigations for areas of concern, such as landfalls, areas of increased geological activities and other areas that may influence installation, stability and seabed intervention performance.

For companies to optimize the route there are a number of steps that must be performed. Depending on the project location, available data and requirements etc., these steps will have different emphasis. The deepwater pipeline routing for the Mardi Gras project in the Gulf of Mexico used e.g. the following methodology (Tootill, Vandenbossche and Morrison, 2004):

1. Define data- and pipeline route requirements to select a route.
2. Desktop study based on available (company, public) information.
3. Assess regional data for selection of corridor for high resolution survey.
4. AUV survey for the pipeline route corridor.
5. Survey result assessment, modeling of areas of concern, and acceptance of general route.
6. Survey at ultra high resolution for areas of concern/interest.
7. Geotechnical evaluation of the route including slope stability analysis and sampling.
8. Visual inspection of contacts with ROV for selected areas.
9. Final selection of pipeline route.

At deep waters the need for sufficient and accurate survey data are particularly important. This is due to considerations on repair and seabed interventions, which tends to be both more costly and challenging than for shallow waters. In addition, as deep water fields tend to have soft seabeds, pipeline sinking can be a problem in relation to inspections and repair.

Bonnell, Blackmore and Tam (1999) present a procedure for pipeline routing at ultra-deep waters, where the governing issues related to a successful routing and survey are examined. Particularly the importance of detailed desktop studies and geohazard analyses prior to route selection are highlighted, as these have a significant effect on success and cost of the upcoming surveys, and ultimately the entire pipeline. The costs of installing mechanical span supports and additional pipeline to avoid geohazards or spanning problems showed the importance of detailed desktop studies and surveys to find the optimal route in terms of cost and safety.

An earlier planned pipeline from Oman to India, reaching a depth of 3500m, was found to have a technically feasible route for installation (Mullee, 1995). For the pipeline which would go through critical areas, the use of survey vessels and equipment to perform swath bathymetry showed very effective for routing of pipelines through unexplored and complex deep water terrain.

The pipelines considered in this thesis are installed along a route with relatively flat seabed and few pipeline crossings.

5.3 Type- and Material Selection

Concept and material selection are based on factors such as:

- Water depth
- External hydrostatic pressure
- Internal pressure
- Fluid characteristics
- Environmental conditions
- Weight requirements
- Installation analysis
- Seabed topography
- Cost

The main goal is to find concepts and materials which satisfy the standards and regulations for the given project and optimize the costs. Pipeline concepts are chosen based on laying analysis, flow assurance and costs, among other factors. Material selection is based on material strength, -weldability, -ductility, -toughness, corrosion resistance (knowing the fluid characteristics) and cost.

5.3.1 Pipeline Concepts

Pipe-in-Pipe

Pipe-in-pipe (PIP) concept consists of one pipe inside a larger external pipe (figure 5-1). The space between the two pipes, the annulus, is used for isolation purposes to protect the transported material inside the inner pipe. Insulation materials can typically be some kind of gas, gel, foam, wool or other materials that have the required thermal insulation for a given project. Air or circulating hot water is also used in some pipeline annuluses. The main focus of the PIP concept is to increase the thermal effect to withstand the low outside sea water temperatures that can cause hydrates or wax, and which may cause blockage of the pipeline (Castello and Estefen, 2008).

The external pressure will set the requirements to the outer pipe, which has to withstand the hydrostatic pressure to protect the insulation and hence the inner pipe. The inner pipe, on the other hand, must be resistant to the pressure from the transported hydrocarbons.

As insulating materials don’t have to withstand neither the internal- nor the external pressure, the insulation material can be selected primarily based on its thermal capacity. Materials with excellent thermal abilities can be chosen, which makes the PIP concept well applicable for deep waters, based on thermal capability. Chances of hydrates and wax formation are hence considerably decreased for cold and harsh environments.

To optimize the PIP configuration, considerations have to be made to gap thickness between the internal and external pipes (maintain heating), thermal stability and overall feasibility, according to Bai and Bai (2005).

One of the challenges with the PIP concept is the relatively high weight, which affects the laying process. Installation will be difficult, especially in ultra-deep waters, due to the high vessel tension required. Additional challenges for PIP installation, compared to single pipelines, comprise complex processes of multi-jointing, offshore pipe production, and movements of the inner pipe during welding.

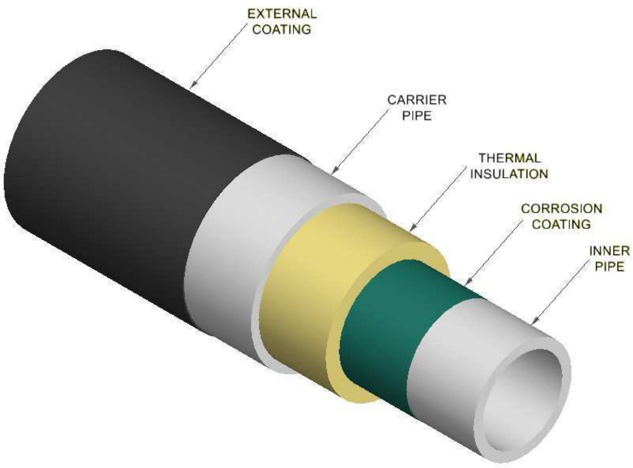


Figure 5-1 Typical Pipe-in-Pipe Composition [Braga de Azevedo, Solano and Lacerda, 2009]

Focus and study on PIP for development at deep waters is increasing along with the trend of increased number of deep water projects. Design of pipelines will in several cases be based on very stringent insulation and cool-down criteria, which benefits the PIP system.

Based on structural behavior PIP systems are categorized by their method of load transfer between the internal and external pipe:

- **Compliant**

Continuous load transfer between the two consecutive pipes is present, with no relative displacement between them.

- **Non-compliant**

System force transfers at discrete locations between the pipes.

Two main types of PIP systems are relevant for installation:

- **Sliding PIP**

Sliding PIP system consists of an inner pipe and coating which are uncoupled from the external pipe. The inner pipe is standing freely inside the outer pipe during installation, and bulkheads are used to connect these two pipes. Both the inner- and outer pipe will require offshore welding (Harrison and McCarron, 2006).

- **Bonded PIP (Single-weld PIP)**

Bonded PIP are providing PIP systems where the outer and inner pipes are fully bonded by the insulation, which is controlling the bonding strength. This solution makes the inner and outer pipe only able of making small movements relative to each other. This method requires only one offshore weld for each pipe stalk, as the connection between the inner- and outer pipe are typically made onshore (O’Grady, Bakkenes, Lang and Connaire, 2008).

Active Heating of PIP

In addition to insulation by passive systems, studies have been done on active heating of pipelines to sustain a satisfactory flow assurance at deep waters. Passive insulation may in itself not be sufficient to avoid wax and hydrate formation etc. during operation. Active heating can be applied constantly or during shut-down to increase the cool down time. An electrically heated PIP, combining active and passive insulation has been developed by Coflexip Stena Offshore (now Technip) for ultra-deep water locations (figure 5-2) (Denniel and Laouir, 2001). Results of system testing by Denniel and Laouir (2001) showed that sufficient flowline temperature could, with low power inputs (20 to 40W/m pipe), maintain satisfactory flow assurance for a 20km long tie-back. The potential of this solution is tremendous for situations where passive insulation is not sufficient to give sufficient flow assurance.

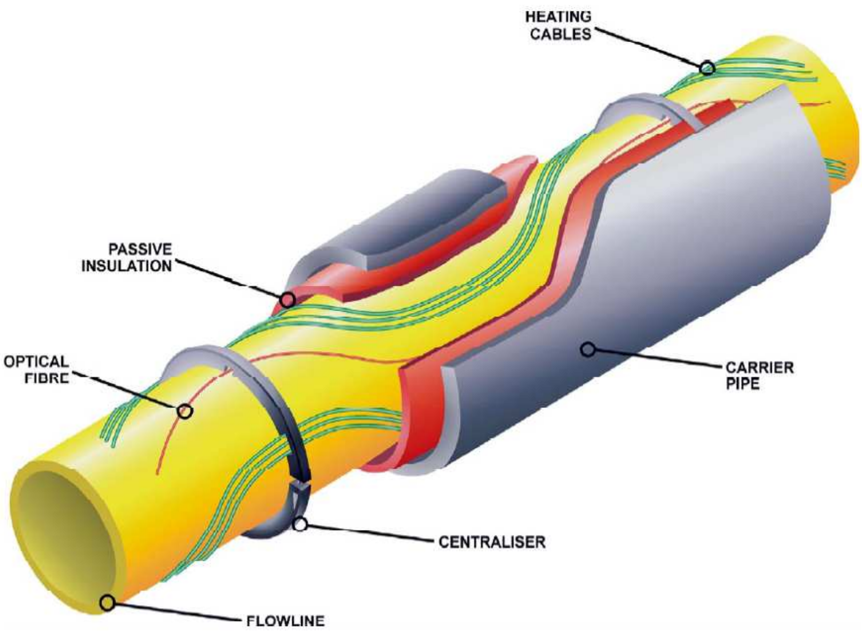


Figure 5-2 Active Heating System for PIP [Denniel and Laouir, 2001]

Sandwich Pipes

Sandwich pipes (SP), which is a relatively new pipeline concept, consist of two concentric steel pipes that are separated by a polymeric annulus (figure 5-3). The structural concept will typically be two external thin and stiff layers, and a thick and flexible core in the center. A polymer between these layers is affecting the thermal and also the mechanical capacity of the pipe. Load transfers between the components are made possible by the bonding of the external layers and the core, and will result in a higher structural strength. It has also been found that the adhesion property has a large effect on the external pressure the pipe can withstand, due to the displacement between the layers.

Figure 5-3 Sandwich Pipe [Castello and Estefen, 2008]

The concept has potential to create pipes with good thermal insulation combined with high structural strength. Both mechanical and thermal capabilities required for deep waters can be met simultaneously. Compared to PIP lines, less steel is required for SP to obtain a similar structural and thermal capacity. This will also result in lighter pipelines which is beneficial for the installation process.

As of 2008, studies and tests using a combination of bending and external pressure have shown good results for SP ultimate strength for water depths down to 3000m (Castello and Estefen, 2008). Still, there are challenges regarding which materials to use for insulation. There are few insulation materials that have the required combination of mechanical strength and thermal capacity. For situations that require greater thermal capabilities, SP would be dependent on active heating by electrical cables.

Tests have been done by Castello and Estefen on three variants of SP and one PIP in 2500m water depth, with the following diameters, wall thicknesses and compositions (table 5-1):

Type	Inner diameter (in)	Inner wall thickness (mm)	Outer diameter (in)	Outer wall thickness (mm)
SP PP	6 5/8	4,775	16	4,775
SP EP	6 5/8	4,369	12 3/4	4,369
SP PI	6 5/8	6,35	10 3/4	6,35
PIP PUF	6 5/8	6,35	8 5/8	12,7

Table 5-1 Geometric Properties of Pipelines [Castello and Estefen, 2008]

PP, EP, PI and PUF are polypropylene, syntactic epoxy foam, polyimide foam and polyurethane foam, respectively.

The results of the study concerning heat transfer coefficient (U) compared to total weight, submerged weight compared to steel weight, and annular thickness versus steel to total weight ratio, are as follows (figure 5-4, figure 5-5 and figure 5-6, respectively):

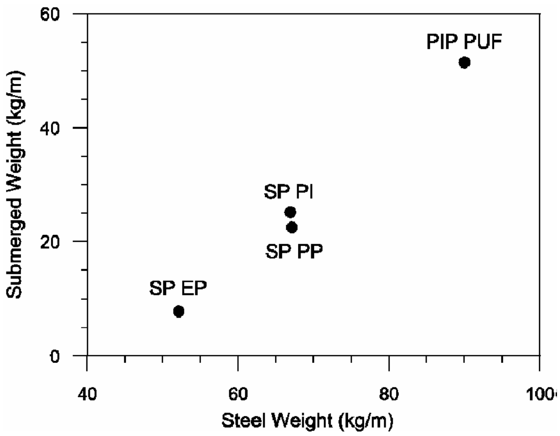


Figure 5-4 Submerged Weight vs. Steel Weight [Castello and Estefen, 2008]

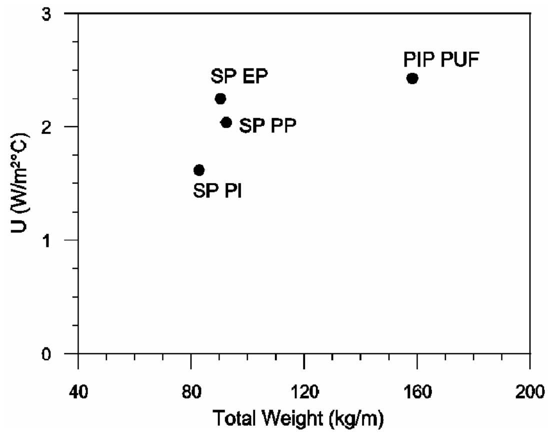


Figure 5-5 U-value vs. Total Weight [Castello and Estefen, 2008]

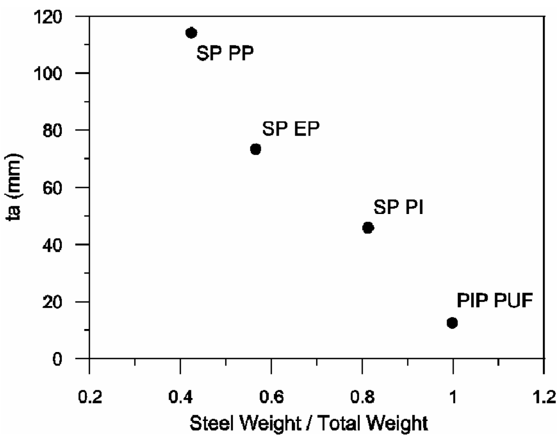


Figure 5-6 Annular Thickness vs. Steel to Total Weight Ratio [Castello and Estefen, 2008]

Results from the studies performed by Castello and Estefen show that the PIP has a better thermal insulation than the SP considered (figure 5-5). This is due to use of a more sufficient material for thermal insulation in the PIP case. The weight, however, is lower for the sandwich pipelines (figure 5-4) as they have thinner walls, and the submerged weight is lower due to less steel and higher buoyancy (affected by higher outer diameter of the pipes). Figure 5-6 indicates that PIP has a better insulation design than the SP and a smaller annular thickness, but a much higher weight due to steel.

Single Pipes

Single pipes are normally steel pipelines designed with steel grades up to X65 (due to weldability etc.), but have in recent years been considered with use of higher graded steels. The steel wall must provide resistance against both internal pressure, external loads and -hydrostatic pressure. Single pipelines can consist of no more than steel walls, but are typically designed with different types of coatings. Depending on the environmental issues, a pipeline may have insulation coatings, concrete coatings and other external coatings.

Deep water steel pipes most often have external insulation coating in order to secure flow assurance. Hydrates, wax and hence pressure drop are limited along the pipeline by use of sufficient insulating material. This is obtained by thermal materials that reduce the impact made by low outer temperature by maintaining the operating temperature of the fluid. Various types of insulation coatings are used, depending on environment, wanted thermal conductivity and mechanical properties. Multilayer coatings are a commonly used insulation method, made by anticorrosion coating to withstand the temperature, an insulating foam, and an external protection layer.

5.3.2 Materials

Pipelines have to withstand loads acting on them during operation and installation, as well as the effect of transported fluids and external environment. These are the main drivers for development and selection of pipeline materials. According to DNV (2007 a) selection of pipeline system materials are based on several characteristics:

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

Also ductility is an important material property. The steel must have the sufficient strength to resist transverse tensile and longitudinal forces during operation and installation. Ductility is critical to absorb overstresses by deformation. The pipelines should also have materials with sufficient toughness to withstand impact loads and to tolerate defects. Weldability is critical to assure that the pipeline can be welded with the same strength and toughness as the rest of the pipe, and also due to economical reasons (Palmer and King, 2008). Balancing the given factors in a way that assure the required properties for pipelines in deep waters can be difficult, but is crucial from both a technical, environmental and economical point of view.

There will be costs and benefits by selection one material above the others. Carbon steel have high corrosion rate. Duplex may experience strength de-rating in high pressure and temperature conditions. Cladded carbon steel pipes tend to be costly and there is limited experience with 13% Chrome pipelines.

Steel Grades

The previous given properties are directly affected by steel grades. In addition to these factors, steel grades are selected based on:

- Weight requirements
- Cost

Typical steel grades used for pipeline design are strengths up to X65, from API 5L (2004). In recent years steel pipelines have been made with higher steel qualities, typically X70 and X80, but also X100 are being considered. This provides weight reduction, due to a decrease in wall thickness. Reduced weight is beneficial for installation of pipelines in deep waters, and hence a higher steel grade will allow the pipeline to be laid in deeper waters.

For deep waters both X65 and higher steel grades have been applied. The Medgaz project, with a max water depth of 2 155 meters, is one of the ultra-deep fields which has used X70 steel grade (Chaudhuri, Pigliapoco and Pulici, 2010). One reason for choosing an X70 steel grade is to reduce the wall thickness requirements, as the wall thickness can be lowered when yield strength is increased. This is in connection with the decrease in pipeline weight compared to using lower steel grades, which will be beneficial for pipeline installation. Thinner wall thickness is beneficial for welding, as the cooling rate of the weld will decrease, reducing the potential problems with hardness, fracture toughness and cold cracking (Bai and Bai, 2005). This due however require the welds to be made with the same strength as the rest of the pipe, which has been a challenge for higher steel grade pipes, and there is a limited number of contractors with proven experience. As it is more difficult to get a weld with the same strength as the pipe itself for high strength steel pipelines, this may decrease the laying speed during installation.

Cost studies for the Britannia gas pipelines showed a significant reduction by selecting X70 rather than X65 (Bai and Bai, 2005). Transportation, welding equipment rentals and overall lay time are other potential cost savers.

Carbon Steel

Carbon steel pipelines are constructed with various alloying 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, according to Braestrup, et al. (2005). The selection of composition and content of the different alloys determine the steel grade, and hereby strength, weldability, toughness and ductility of the given pipe.

Corrosion resistance, which is a problematic area for carbon steels, can be improved 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 corrosion resistant alloys (CRA) may exist in solid form or used as internal lining in carbon steel pipes. The CRA have various strengths and weaknesses, and the selection between them is depending on the transported fluid properties and conditions. CRA are normally applied to increase internal corrosion resistance, as the external corrosion resistance may be fulfilled by the cathodic protection (CP) and external coatings.

5.3.3 Fabrication Methods

Pipelines are defined into types based on their manufacturing process. Wall thickness, diameter, mechanical properties and water depth are among the factors affecting the choice of pipeline type.

Oil and gas pipelines are typically divided into the following pipeline types:

- **Seamless (SMLS)**
  Construction of seamless pipes is done by a hot forming process without welding. No welds, in addition to the good track record in service are advantages for seamless pipes (Palmer and King, 2008). On the other side, disadvantages due to wall thickness variation (+15% to -12,5%) along the pipe length, out-of-roundness and –straightness are present. For large diameter pipelines this process may also be more expensive than the following processes. Usually seamless pipes are delivered to a diameter of 16 inches, but Guo, Song, Chacko and Ghalambor (2005) states that seamless pipes should be used for 12 inch diameter pipes and less.
- **Submerged Arc Welded (SAW)**
  Construction of SAW pipes is either done with a longitudinal or a helical seam, including a minimum of one welding pass on both the inside and outside of the pipe.
  - **Longitudinal seam (SAWL)**
    SAWL pipes are typically made by the UOE process; crimping of plate edges, U- and O pressing before the pipe is expanded (E) for circularity reasons. Due to good out-of-roundness (+/- 1%) and wall thickness tolerance (+12%, - 10%) this is an excellent choice for large diameter and high-pressure pipelines (Palmer & King, 2008). For pipe-diameters in the region from 14 to 28 inches, UOE (SAWL) pipes can be a good substitute for seamless pipes.
  - **Helical seam (SAWH) (Spiral weld)**
    Strips or steel bands are rolled into cylindrical form and SAW welded (inside- and outside weld), where the stip/band width, angle and curvature sets the diameter. Wall thickness tolerance is close to the UOE pipes, but as the ovality tolerance is often higher, and (long) welded areas of pipe are intersecting with the most corrosion exposed areas (at the bottom), it has some disadvantages compared to the above pipe types. Guo, Song, Chacko and Ghalambor (2005) states that this type should be kept to low pressure water or outfall lines. SAWH pipes are used for large-diameter pipelines both for oil and gas transportation, but limited wall thickness sets limitations for use in deep waters (figure 5-7).
- **High Frequency Welded (HFW)**
  HFW pipes are formed by strips into an U and O shape from a continuous rolling process, before one longitudinal weld are made by high frequency current (Braestrup, et al., 2005). Cold expansion, hot stretching or sizing may be executed to get the required diameter and wall thickness of the pipe. Advantages due to wall thickness tolerances (typically +/- 5%) and cost compared to seamless pipes are making it a competitor. Smaller tolerance in wall thickness and ovality are also beneficial for laying, due to less welding problems and faster setup at the vessel (cost reductions). Experience is limited for pipelines beyond 16 inches and 16 mm wall thickness, but experience in process and use is improving, and has made these pipes available for higher diameters (figure 5-7).

The UOE manufacturing process significantly degrades the collapse resistance of high strength line pipes. This has led to several tests being performed to investigate the effects of thermal aging (heat treatment) during pipe fabrication processes, in order to recover pipe strength. DeGeer, et al. (2004) investigated the effect this would have on pipeline strength and collapse resistance for an X65 UOE 28 inch pipeline installed as part of the Mardi Gras Transportation System in ultra-deep water. Results indicated a significant increase in circumferential compressive yield strength and pipes collapse strength. The thermal treatment will harden the material, leading to increased hoop compressive yield strength and collapse resistance. It was shown that the DNV fabrication factor could be increased from 0,85 to 1,0, which will have a major effect on the required wall thickness.

Al-Sharif and Preston (1996) obtained similar results for their study on a potential UOE manufactured Oman India pipeline. Their investigations predicted an average of 23% increase in collapse pressure due to thermal aging. A significant improvement in collapse resistance of low D/t, high strength line pipes manufactured by the UOE, as a result of thermal aging, was concluded. The greatest increase in compressive yield strength occurs from 175˚C - 250˚C. For an ultra- deep water pipeline this will lead to improved reliability when subjected to high external pressure, which can reduce the required wall thickness.

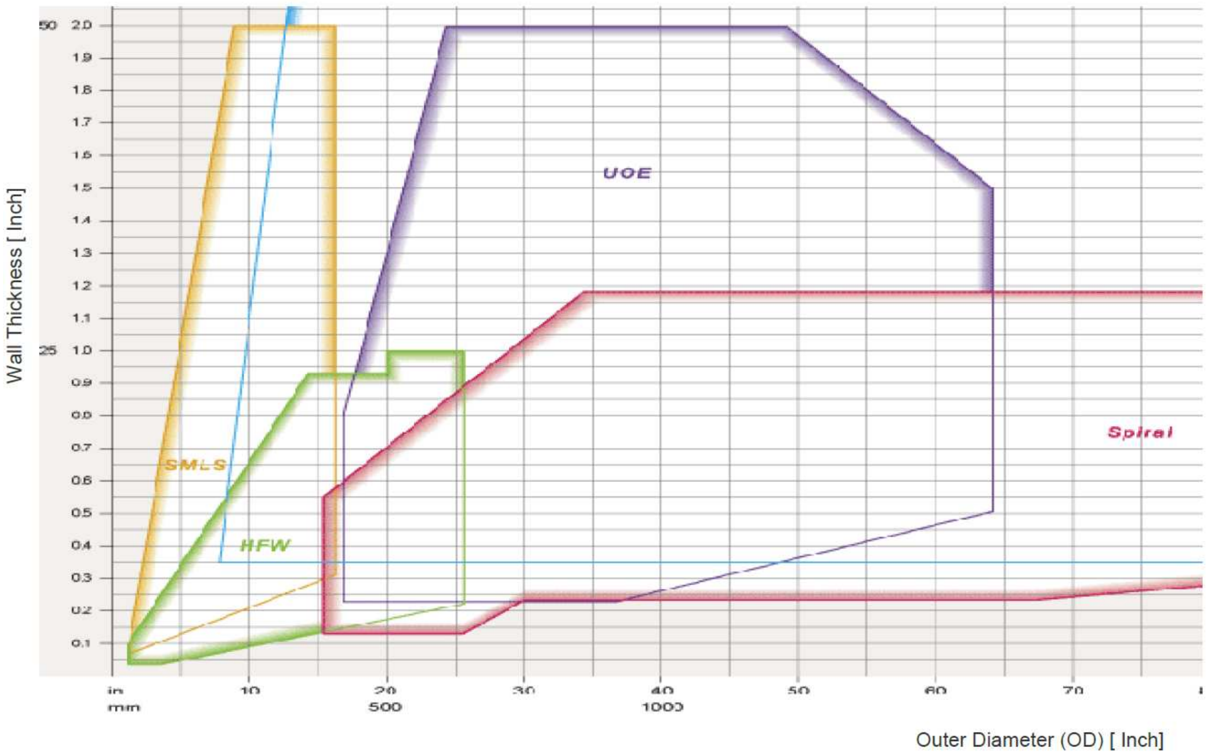


Figure 5-7 Pipeline Types based on Pipe Diameter and Wall Thickness [Haldorsen, 2010]

The pipeline concept, material, fabrication method and steel grades applied in this thesis have all been selected based on the factors studied in the given section.

5.4 Diameter, Temperature and Pressure Profile

Pipe diameter size is selected based on several factors, including:

- Fluid and/or gas properties
- Annual flow
- Availability of the system
- Required pressure at pipeline end

Information about properties (density, viscosity, compressibility, thermal conductivity, etc.) of the hydrocarbons transported in the pipeline system are essential in order to calculate pipe size based on required pressure at delivery, as well as need for corrosion and thermal insulation coatings.

An economic evaluation both concerning capital costs (CAPEX) and operational costs (OPEX) for the whole pipeline system, acts as a part of overall picture for diameter determination.

Establishing a temperature and pressure profile is critical to evaluate flow conditions in the pipeline, as well as sacrificial anode design, free span evaluation and pipeline expansion, according to Braestrup, et al. (2005). Pipeline wall thickness, insulation, hydrocarbon properties and temperature, pipe material, etc., are all influencing the temperature and pressure profile for a pipeline system during operation.

The pipeline diameters of 14 inch, 20 inch and 28 inch are all considered to be chosen based on the mentioned factors and profiles.

5.5 Material Selection for Coatings and Insulation

Materials used for coatings and insulation must be developed to fulfill their function for the required time horizon. To fulfill corrosion protection requirements either a single-layer coating or a multi-layer coating is applied, depending on the external environment and location of use. If the pipeline is in a continuous static, laterally stable condition and laying on a soft seabed, single-layer coatings will usually be the case. For environments with high probabilities of wearing out the external coating, multi-layer coatings are recommended. Thermal insulation- and mechanical protection coatings may also be included in the pipe design to avoid flow assurance problems and pipe damage respectively.

Pipeline coatings are used to protect and secure the integrity of the pipeline during its service life (figure 5-8). They are applied to maintain certain parts of the pipeline and have function as:

- Corrosion protection
- Thermal insulation
- Mechanical protection
- Weight coating (On-bottom stability)
- Internal drag reduction

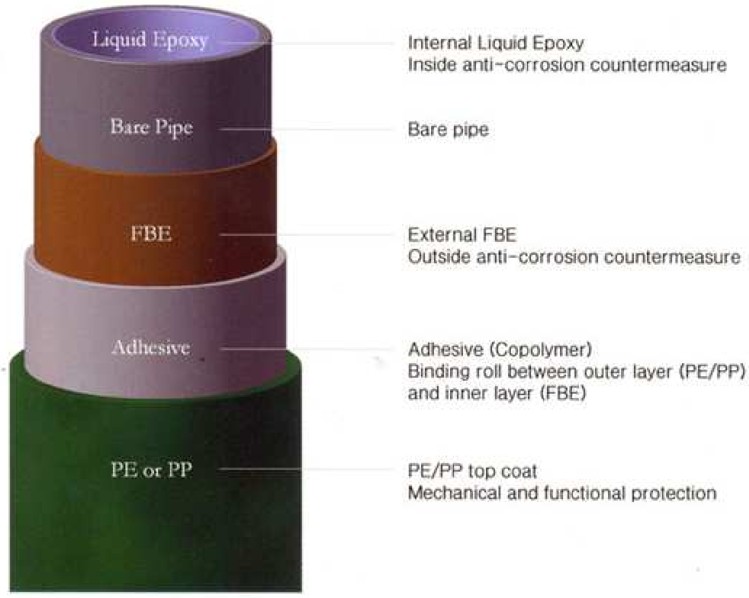


Figure 5-8 3-layer PE/PP Coating [Harve Group, 2006]

Internal coatings can be applied to reduce or resist internal corrosion and erosion. For deep water pipelines it will be important to minimize the needed wall thickness, as it affects both laying requirements (pipeline weight) and costs. The coating may also reduce flow resistance in the pipe. External coatings such as Fusion Bonded Epoxy (FBE) are used for anticorrosive purposes, while foams such as polypropylene (PP) and polyurethane (PE) are applied as thermal insulation. This is to maintain flow assurance by reducing wax deposition and hydrate formation. Thermal insulation coatings are often part of deep water pipelines, as water tends to be cold and high pressure fluids can be present. The outer layer, which can be a PP shield, is acting as a mechanical protection against loads affecting the pipeline. An outer concrete weight coating may be used to secure stability on the seabed and act as a mechanical protection layer. The latter layer is not common for ultra-deep waters as the weight increase can have a negative influence on the installation process, and thick steel walls will in most cases be sufficient to secure on-bottom stability.

External coating materials for deep water pipelines corrosion protection should have good properties regarding the following factors (Guo, Song, Chacko and Ghalambor, 2005 and DNV, 2007 a):

- Resistance against corrosion due to seawater absorption, gases and salts
- Resistance to chemical, biological and physical degradation
- Resistance to cathodic disbondment
- Flexibility and adhesion, during installation and operation
- Resistance against abrasion and impacts
- Cathodic protection compatibility
- Resistance to weathering
- Ease of application
- Adequate temperature stability
- Ease of repair at damaged areas

Multi-layer coatings are often preferred as single-layer coatings can provide insufficient capabilities for some of these properties required.

Where single-layer coatings are used for deep water pipelines however, FBE is the most applied coating. Due to high adhesion to steel, ease of repair, -coating application, good functions with operating temperatures and being an extremely cost effective coating, FBE is the preferred coating for several pipelines in deep water (Guo, Song, Chacko and Ghalambor, 2005). One example is the Mardi Gras pipelines using FBE anti-corrosion coating (Karlsen, McShane, Rich and Vandenbossche, 2004). FBE coating is applied after heating the pipe to 250-260˚C, typically including use of an etch primer as a first step to increase coating adhesion (European practice).

Multi-layer coatings can typically include dual-layer FBE and three-layer extruded coatings. For situations where an outer layer is required to protect against high temperatures, abrasion and so on, dual-layer FBE coatings with FBE base coat and an outer layer of polypropylene acting as mechanical protection may be selected. Three-layer coatings of epoxy or FBE, thermoplastic adhesive coating and either PP or PE can provide further corrosion resistance for deep water pipelines. Since PP and PE coatings have a very low CP current requirement and high dielectric strength this can provide a good combination with cathodic corrosion protection systems.

Insulation coating materials are selected based on properties such as:

- Thermal conductivity
- Specific heat capacity
- Affect on these properties by high external pressure and internal fluid temperature

Coating insulating properties, given as W/m˚C from the thermal conductivity (*k*), should be low enough to minimize the risk of wax, hydrate and asphaltene formation which degrades the flow assurance of the system, in addition to enhance flow properties and increase cool-down time. Table 5-2 provides the thermal conductivity for different materials relevant for pipeline developments.

Material	Thermal conductivity, *k* (W/m˚C)
Linepipe steel	45
Seabed soil	1,2-2,7
Concrete coating	1,5
High density polyolefins	0,43
Fusion bonded epoxy	0,3
Polychloroprene	0,27
Solid polyolefins	0,12-0,22
Asphalt enamel	0,16
Syntactic foams	0,1-0,2
Alumina silicate microspheres	0,1
Polyolefin foams	0,039-0,175

Table 5-2 Thermal Conductivities for typical Pipeline Materials [Braestrup, et al., 2005]

Polyolefins (polyethylene, polypropylene and polyurethane), polychloroprene and epoxy are used for pipeline insulation, where polyolefins are the most common. Due to excellent thermal conductivity, these polyolefins are applied in different compositions in for instance three- and four-layer coatings. Typical polyurethane foams can have thermal conductivity as low as 0,04 W/m˚C, making this a more widely used insulating material for deepwater piplines, according to Guo, Song, Chacko and Ghalambor (2005). Polyolefins are wet insulations and do not require an external steel barrier for protection, in contrast to dry insulations (mineral wool, fiberglass etc.) used for Pipe-in-Pipe.

Syntactic versions of PE and PP insulation coatings applying plastic or glass matrix are used to improve insulation and capabilities at deeper waters. Watkins and Hershey (2001) have studied use of syntactic foam for thermal insulation of ultra-deep water oil and gas pipelines, and results have shown several advantages. Testing was done on syntactic foams consisting of fine-grained glass microsphere fillers, which is preferred over plastic as they better maintain their strength at elevated temperatures. Some of the advantages by syntactic foams, according to Watkins and Hershey (2001), were low densities (reduce weight which is preferable for installation), low thermal conductivity (require less thickness to satisfy U-values, leading to smaller diameters), great compressive strength (resistant to crushing and mechanical damage during handling and laying), and cost-effectiveness (often lowest cost solution for insulation). The potential of syntactic foams are huge, but some technical challenges are present and further studies are required.

5.5.1 Coating Design

The pipelines relevant for this study shall apply a multilayer PP system based on FBE, PP + adhesive, PP Foam and PP shield for external corrosion protection and thermal insulation. Thermal insulation shall satisfy the requirement of a maximum U-value of 5,0 W/m^{2}K given for the pipelines.

Following properties (table 5-3) are present for the coating layers to be applied in the given project:

Item	Density (kg/m^3)	Thermal conductivity (W/mK)	Thickness (mm)
FBE	1300	0,301	0,3
PP + Adhesive	900	0,221	2,7
PP Foam	620	0,148	Variable
PP shield	890	0,206	3

Table 5-3 Coating Properties

Based on these properties, evaluation of the system is performed in order to secure adequate thicknesses for the different coating layers. This shall provide the required thicknesses necessary to stay within the given U-values for the pipelines.

Results of the required PP foam thickness analyses for the different pipeline wall thicknesses are given in table 5-4, table 5-5 and table 5-6.

Water depth (m)	Wall thickness (mm)	PP foam thickness (mm)	U-value (W/m^{2}K)
800	13,3	34	4,89
1400	15,1	34	4,97
2000	17,8	35	4,95
3500	25,3	38	4,95

Table 5-4 14” Pipe: Required Insulation Coating Thicknesses

Water depth (m)	Wall thickness (mm)	PP foam thickness (mm)	U-value (W/m^{2}K)
800	19,0	31	4,99
1400	20,8	32	4,92
2000	24,4	33	4,89
3500	33,9	35	4,91

Table 5-5 20” Pipe: Required Insulation Coating Thicknesses

Water depth (m)	Wall thickness (mm)	PP foam thickness (mm)	U-value (W/m^{2}K)
800	26,6	30	4,98
1400	27,7	31	4,87
2000	32,3	31	4,94
3500	45,1	33	4,91

Table 5-6 28” Pipe: Required Insulation Coating Thicknesses

Results from the analyses show that the maximum U-value of 5,0 W/m^{2}K given for this thesis was satisfied for all pipelines. The results are representative for exposed pipelines, as these pipes are not buried.

APPENDIX A provides the calculation method used to achieve the pipelines U-values.

Insulation Coating

Insulation coating thicknesses for the different pipes and water depths are summarized in table 5-7:

Pipe diameter	Water depth (m)	PP foam thickness (mm)	Total coating thickness (mm)
14 inch	800	34	40
	1400	34	40
	2000	35	41
	3500	38	44
20 inch	800	31	37
	1400	32	38
	2000	33	39
	3500	35	41
28 inch	800	30	36
	1400	31	37
	2000	31	37
	3500	33	39

Table 5-7 Coating Design

5.5.2 Thermal Insulation Parameter Study

In order to reduce the required insulation coating thicknesses, materials with lower thermal conductivities are required. A parameter study is performed to investigate the effects changes in thermal conductivity will have on the required insulation coating thicknesses for the deep water pipelines. The thermal conductivity range for PP foam given in table 5-2 is taken into consideration.

Results of the study are given in figure 5-9, figure 5-10 and figure 5-11 for the effects of changing the thermal conductivity of the insulating material for the 14 inch, 20 inch and 28 inch pipelines, respectively.

14 inch pipeline

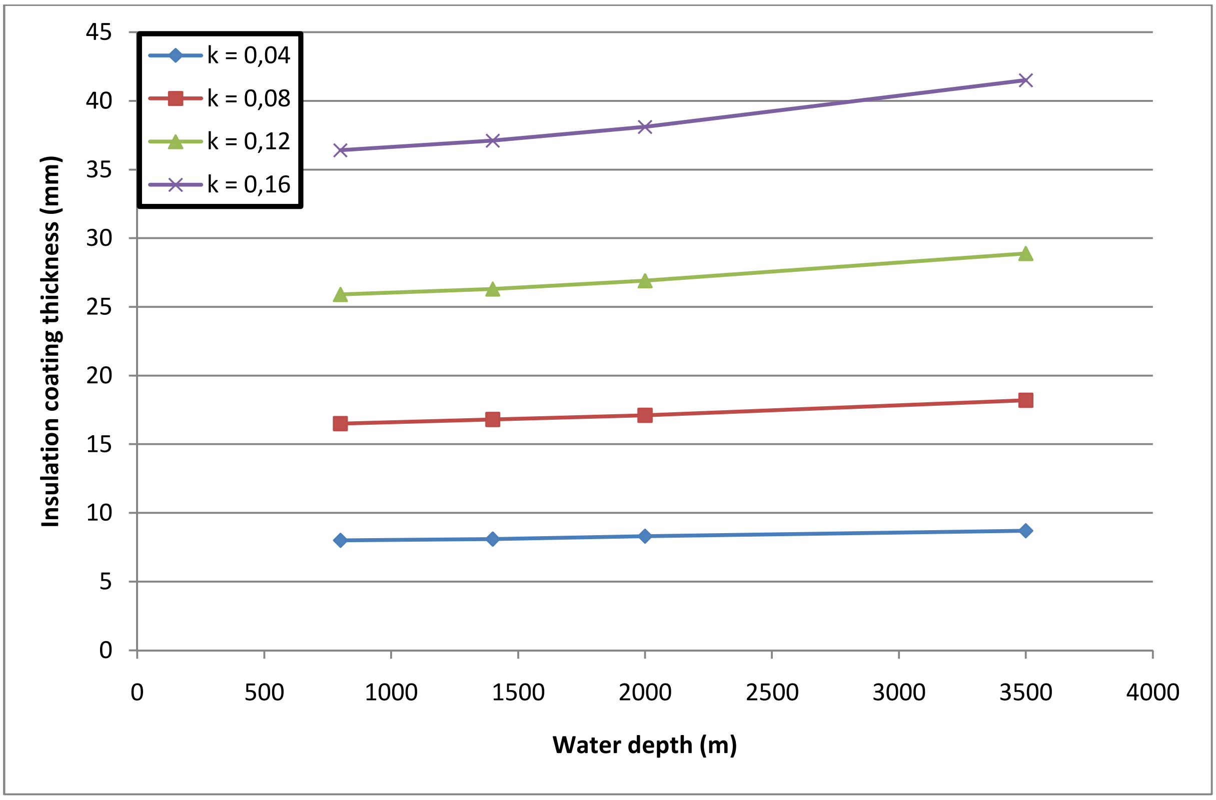


Figure 5-9 14" Pipe: Insulation Coating Thickness vs. Thermal Conductivity

20 inch pipeline

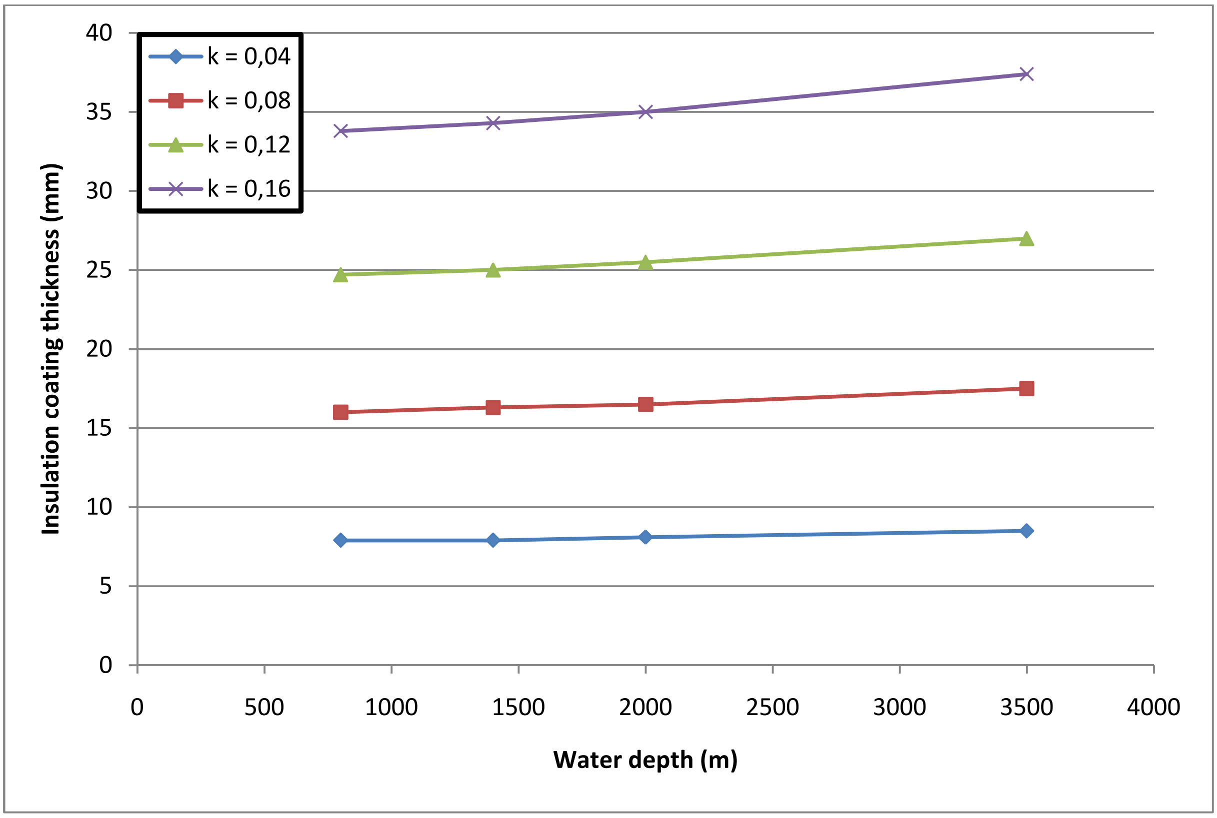


Figure 5-10 20" Pipe: Insulation Coating Thickness vs. Thermal Conductivity

28 inch pipeline

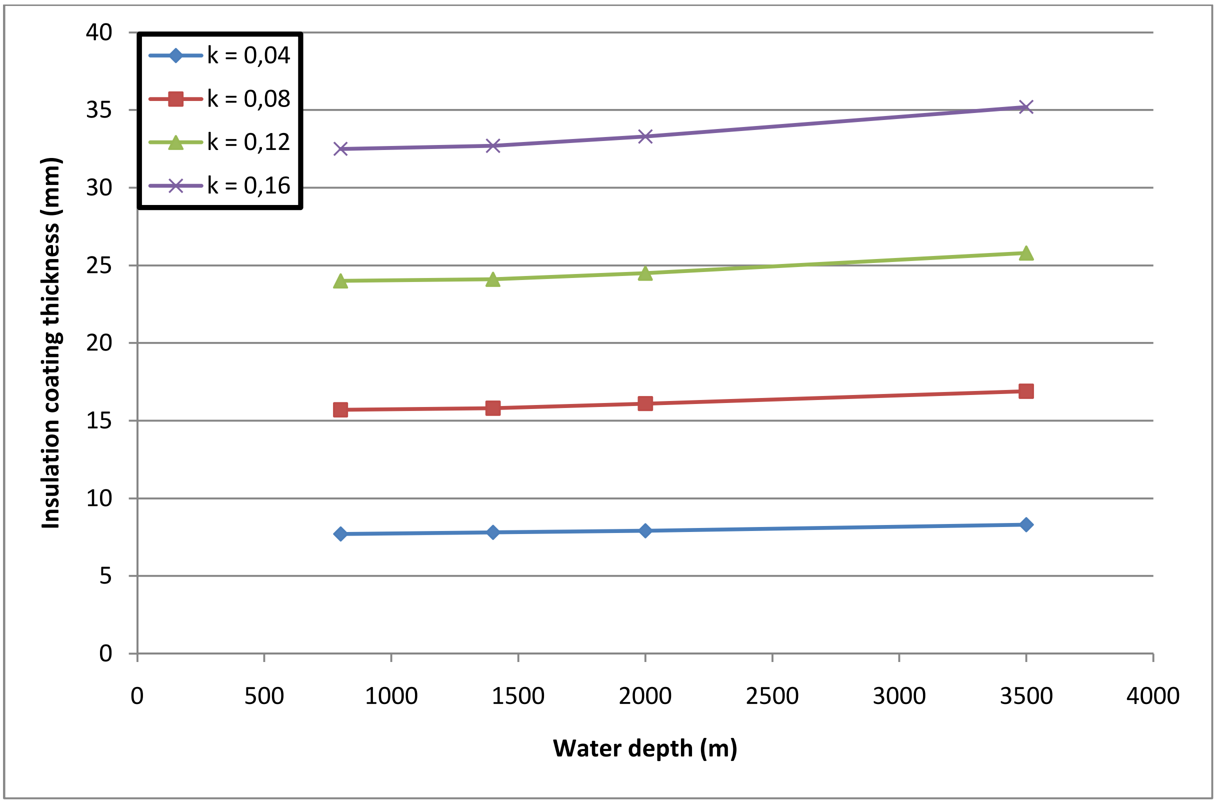


Figure 5-11 28" Pipe: Insulation Coating Thickness vs. Thermal Conductivity

5.5.3 Effect by Change in Thermal Conductivity

In 800 meter water depth the required insulation coating thickness will decrease by:

- 28,4 mm or 78,0% for a 14 inch pipeline
- 25,9 mm or 76,6% for a 20 inch pipeline
- 24,8 mm or 76,3% for a 28 inch pipeline

as the thermal conductivity decreases from 0,16W/mK to 0,04W/mK

In 1400 meter water depth the required insulation coating thickness will decrease by:

- 29,0 mm or 78,1% for a 14 inch pipeline
- 26,4 mm or 76,9% for a 20 inch pipeline
- 24,9 mm or 76,2% for a 28 inch pipeline

as the thermal conductivity decreases from 0,16W/mK to 0,04W/mK

In 2000 meter water depth the required insulation coating thickness will decrease by:

- 29,8 mm or 78,2% for a 14 inch pipeline
- 26,9 mm or 76,9% for a 20 inch pipeline
- 25,4 mm or 76,3% for a 28 inch pipeline

as the thermal conductivity decreases from 0,16W/mK to 0,04W/mK

In 3500 meter water depth the required insulation coating thickness will decrease by:

- 32,8 mm or 79,0% for a 14 inch pipeline
- 28,9 mm or 77,3% for a 20 inch pipeline
- 26,9 mm or 76,4% for a 28 inch pipeline

as the thermal conductivity decreases from 0,16W/mK to 0,04W/mK

5.5.4 Discussions and Conclusions

Results from the parameter study show that the effect of selecting insulation materials with lower thermal conductivity will lead to a significant reduction in required insulation coating thickness. The change in required insulation thickness is limited between the water depths, as the steel has only a small negative influence on the required insulation coating thickness.

Optimal insulation coating designs are not based entirely on the thermal conductivity, but are affected by factors such as cost and weight required to secure on-bottom stability. Materials with low thermal conductivity are generally more costly and reduce the weight of the pipelines. This indicates that for deep water pipelines where on-bottom stability is a limited problem, use of materials with low thermal conductivity would be preferred. Reduction in weight would also have a positive influence on layability of the given pipe, as less tension capacity is required.

For pipes with a given internal diameter, a reduction in insulation coating thickness will reduce the outer diameter. This may be preferable for pipeline installation, as well as pipes required to be within a given size to make them layable with specific vessels.

Based on the results from the parameter study it can be concluded that:

- Use of insulating materials with low thermal conductivity will reduce the required coating thickness significantly.
- The reduction in insulation thickness increases (in terms of percentage) the lower the thermal conductivity goes.
- Reduction in insulation material thickness is relatively higher for smaller diameter pipelines.
- The required insulation coating thickness is little influenced by water depth.

5.6 Wall Thickness Selection

Pipeline wall thickness design is one of the most critical design considerations that have to be done before pipeline construction. This will affect the pipes resistance against internal- and external pressure, the allowed corrosion, the influence of longitudinal stress, bending and indentation, as well as the cost aspect.

The pipeline wall thicknesses shall as a minimum satisfy a design in order to avoid (DNV, 2007 a):

- Bursting (pressure containment)
- Local buckling (collapse) due to external pressure only, as given in eq. 4.5
- Propagation buckling for external pressure only, as given in eq. 4.9

At deep waters the wall thicknesses will typically be set by the external hydrostatic pressure. Due to the high cost of selecting wall thicknesses based on propagation buckling, installation of buckle arrestors are often done to provide a wall thickness governed by the system collapse criterion. Corrosion allowance is also a factor to be considered during wall thickness design, as the pipelines may initially exceed the wall thicknesses required to avoid collapse (or bursting) during its service life. Installation loading, bending loads and external impacts may also influence the required wall thicknesses, where the latter is usually a limited problem in deep waters.

For deep waters the required pipeline wall thicknesses may be governed by the effect of combined loading, i.e. the combination of external pressure and imposed bending moments during laying operations. The required wall thickness to avoid collapse will depend on the allowable bending moment in combination with the external pressure, assuming the load condition is load controlled. This is the situation for the sagbend area during installation, and the wall thickness must be increased in order to allow for additional bending capacity of the pipe. In this thesis the wall thicknesses are assumed to be governed by the collapse due to external pressure only, in addition to requirements for on-bottom stability (specific weight ratio of 1,1) (section 5.7). These wall thicknesses are controlled against the load controlled condition criteria during laying, to assure that these wall thicknesses are adequate to satisfy the allowable bending moments in the sagbend (section 7.4).

Hydrostatic pressure is increasing linearly as the water depth increase, and it is hereby given that as one goes deeper, the impact made by the external pressure rises. This will, in deep waters, increase the wall thicknesses necessary to withstand collapse.

Minimum wall thicknesses, for the steel grades of X65, X70 and X80, are calculated based on the system collapse check and propagation buckling check (section 4.2.1), and are given in table 5-8 and table 5-9 respectively, for water depths of 800m, 1400m, 2000m and 3500m. APPENDIX B provides the detailed calculations used to obtain wall thicknesses from local buckling (system collapse) and propagation buckling calculations.

Local Buckling (System Collapse)

Wall thickness (mm)			
W.D. 800 m			
Diameter (inches)	***Steel grade***		
	X65	***X70***	***X80***
14”	12,2	12,1	12,0
20”	17,0	16,9	16,7
28”	22,7	22,6	22,4
W.D. 1400 m			
14”	15,1	14,9	14,6
20”	21,1	20,8	20,4
28”	28,1	27,7	27,3
W.D. 2000 m			
14”	17,8	17,4	16,8
20”	25,0	24,4	23,5
28”	33,0	32,3	31,4
W.D. 3500 m			
14”	25,3	24,0	22,3
20”	35,6	33,9	31,4
28”	47,5	45,1	41,6

Table 5-8 Wall Thicknesses by Local Buckling

Discussions and conclusions on the influence on wall thickness of changing steel grades are given in section 5.6.4.

Propagation Buckling

Wall thickness (mm)			
W.D. 800 m			
Diameter (inches)	***Steel grade***		
	X65	***X70***	***X80***
14”	20,1	19,5	18,5
20”	34,4	33,4	31,6
28”	40,1	38,9	36,9
W.D. 1400 m			
14”	25,1	24,4	23,1
20”	43,0	41,8	39,6
28”	50,2	48,7	46,2
W.D. 2000 m			
14”	28,9	28,1	26,6
20”	49,6	48,2	45,6
28”	57,9	56,2	53,3
W.D. 3500 m			
14”	36,2	35,1	33,3
20”	62,1	60,2	57,1
28”	72,4	70,3	66,6

Table 5-9 Wall Thicknesses by Propagation Buckling

Wall thickness requirements based on propagation buckling are assumed too costly to satisfy. Buckle arrestors are installed to avoid propagation buckling during installation and operation for the given pipelines.

For this thesis integral ring arrestors (figure 5-12) are selected, due to their suitability in combination with deep water pipelines (further information in Langner, 1999). Integral arrestors consist of a ring with the same inner diameter as the pipe, but are thicker than the pipe itself. These arrestors directly increase the wall strength by welding it to the pipe and hereby increasing the thickness of this section. This is a well suited buckle arrestor for deep water pipelines installed by S- and J-lay.

The integral arrestors should have a crossover pressure to withstand the collapse pressure of the pipe, and hereby secure the pipeline wall thickness not to be governed by the propagation buckling criteria.

Integral Ring arrestors are designed based on installation method. Length to thickness ratio for the buckle arrestor (L_{BA}/t_{BA}) should be in the range of (Langner, 1999):

- **0,5 – 2,0** for J-lay, where they also act as a collar for suspended span support.
- **> 2,0** for S-lay, to avoid problems for arrestors passing through tensioners and stinger rollers.

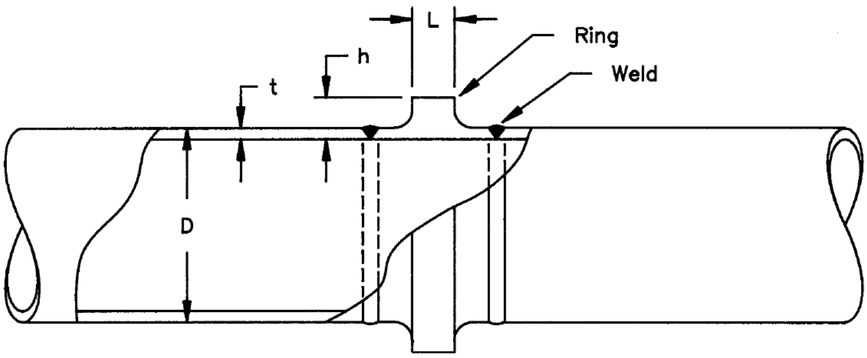


Figure 5-12 Integral Buckle Arrestor [Langner, 1999]

The following wall thicknesses have been selected based on the system collapse check (table 5-10):

Nominal Diameter:	**14”**	**20”**	**28”**
Outer Diameter, *D*:	355,6 mm	508,0 mm	711,2 mm
	Wall thicknesses (mm):		
800m depth:	13,3[1]	19,0[1]	26,6[1]
1400m depth:	15,1	20,8	27,7
2000m depth:	17,8	24,4	32,3
3500m depth:	25,3	33,9	45,1

Table 5-10 Wall Thicknesses

Note 1: Wall thicknesses given by requirements to specific weight from on-bottom stability calculations (section 5.7).

5.6.1 Wall Thickness Parameter Studies

The wall thickness required for deep water pipelines are, as previously mentioned, a huge cost driver for oil and gas projects in deep waters. Due to the effect on both cost and weight, a decrease in wall thickness may have great benefits for the overall cost of the project, as this requires less steel and has a positive effect on pipeline layability (less tension required).

Parameter studies based on changes in steel grades and ovalities of the pipelines have been done to obtain the effects these parameters have on the wall thickness requirements.

5.6.2 Effect by Change in Steel Grades

Pipelines installed in deep waters can be provided in different steel grades. This analysis show the effects by an increase in steel grades from X65 to X70 and X80 on the wall thickness required from local buckling. At 800m water depth however, the wall thicknesses are given from the specific weight ratio of 1,1 (section 4.2.1).

Figure 5-13, figure 5-14 and figure 5-15 show the required wall thicknesses to avoid system collapse for water depths varying from 800m to 3500m, for a 14 inch, 20 inch and 28 inch pipe respectively. As the results indicate; a higher steel grade will have low impact on minimum wall thickness requirements for a water depth of 800m. However, as the water depth increases the increase in steel grade will have a higher effect on this matter (criteria given by local buckling).

In 800 meter water depth the required wall thickness will decrease by:

- 0,2 mm or 1,6% for a 14 inch pipeline
- 0,3 mm or 1,8% for a 20 inch pipeline
- 0,3 mm or 1,3% for a 28 inch pipeline

as the material grade increases from X65 to X80.

In 1400 meter water depth the required wall thickness will decrease by:

- 0,5 mm or 3,3% for a 14 inch pipeline
- 0,7 mm or 3,3% for a 20 inch pipeline
- 0,8 mm or 2,8% for a 28 inch pipeline

as the material grade increases from X65 to X80.

In 2000 meter water depth the required wall thickness will decrease by:

- 1,0 mm or 5,6% for a 14 inch pipeline
- 1,5 mm or 6,0% for a 20 inch pipeline
- 1,6 mm or 4,8% for a 28 inch pipeline

as the material grade increases from X65 to X80.

In 3500 meter water depth the required wall thickness will decrease by:

- 3,0 mm or 11,9% for a 14 inch pipeline
- 4,2 mm or 11,8% for a 20 inch pipeline
- 5,9 mm or 12,4% for a 28 inch pipeline

as the material grade increases from X65 to X80.

14 inch pipeline

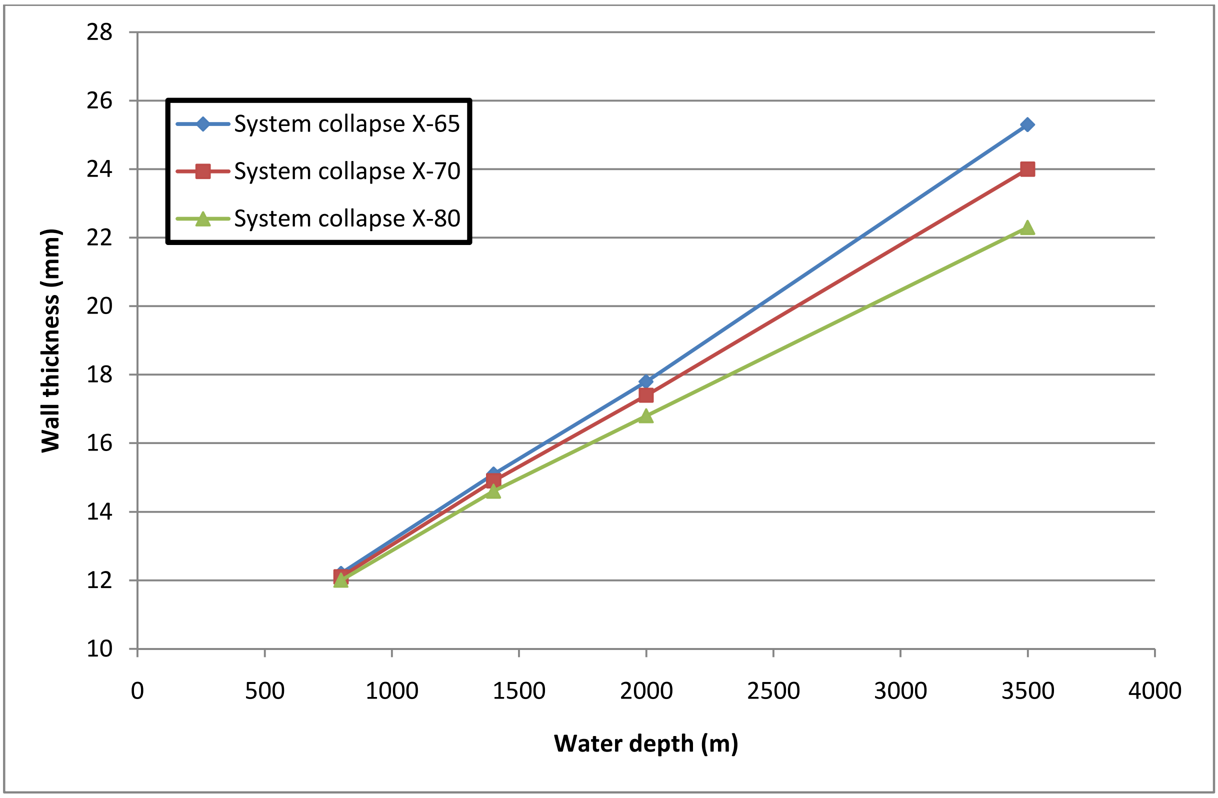


Figure 5-13 14" Pipe: Wall Thickness vs. Steel Grades

20 inch pipeline

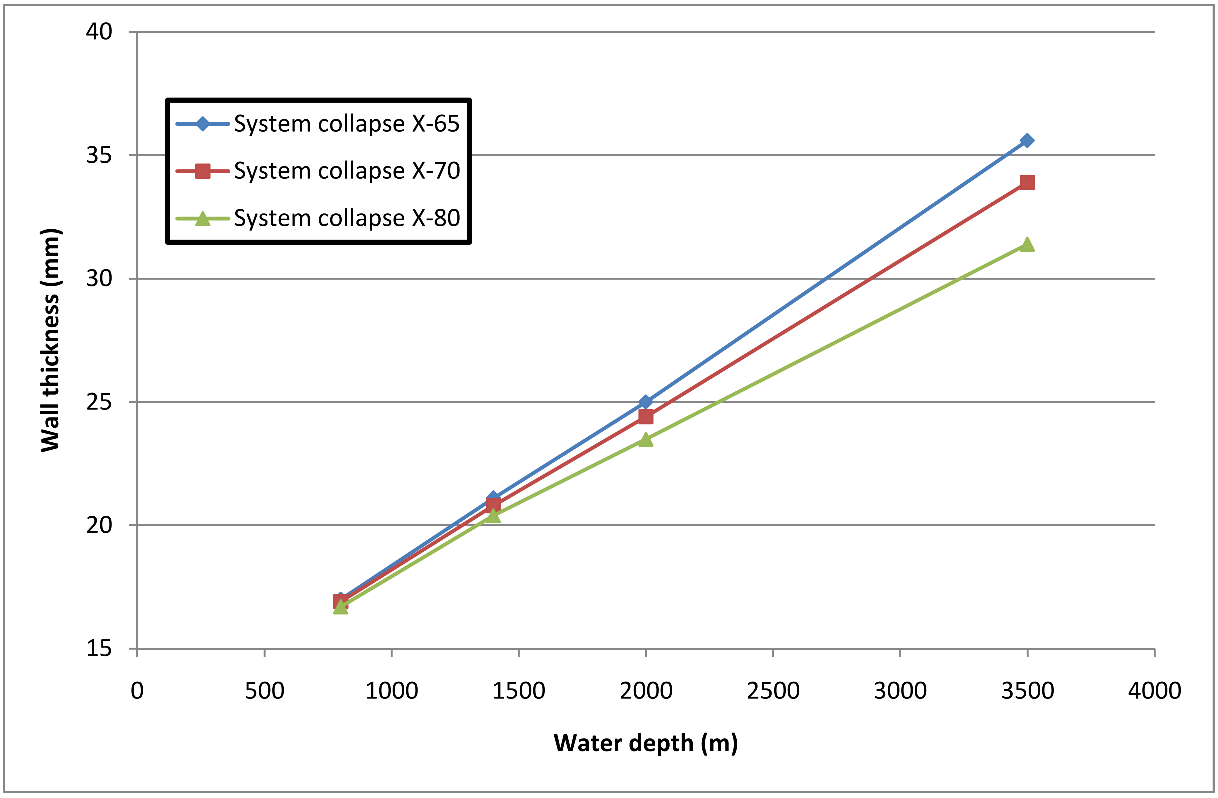


Figure 5-14 20" Pipe: Wall Thickness vs. Steel Grades

28 inch pipeline

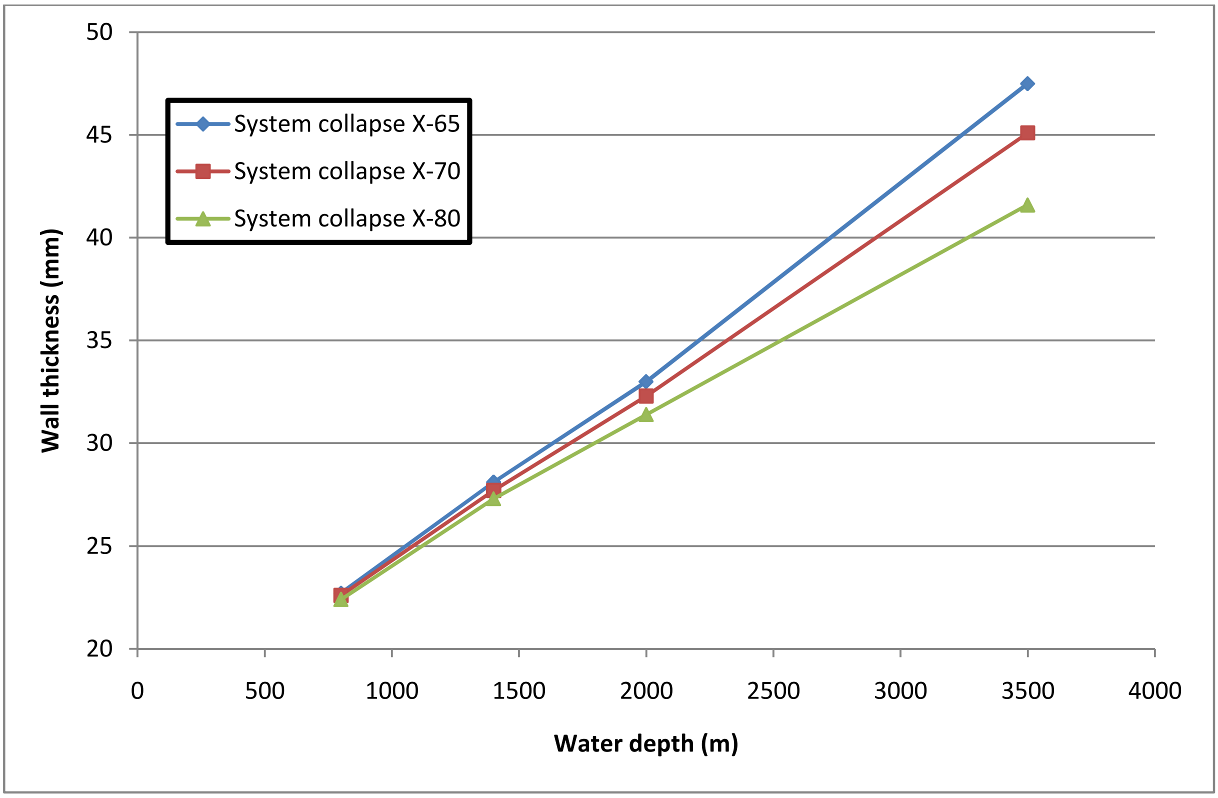


Figure 5-15 28” Pipe: Wall Thickness vs. Steel Grades

5.6.3 Effect from Change in Pipe Ovality

Pipe wall thicknesses are also affected by the requirements to pipe ovalities. An ovality of 1,5% is given for the 14 inch and 20 inch, while 1,0% ovality is given for the 28 inch pipe, set as the out-of-roundness tolerance (pipe body) for the respective diameters, according to DNV (2007 a, table 7-17).

During pipeline installation at deep waters, the pipe will be subject to both bending and external pressure. From DNV (2007 a) it is given that flattening due to bending and out-of-tolerance from fabrication shall not exceed 3% (except for special cases). The collapse pressure p_c (eq. 4.6), which is the external pressure required to buckle a pipe due to external pressure and ovality, is highly dependent on the diameter to thickness (*D/t*) ratio. Low *D/t* ratios will allow for higher external pressure before collapsing (Kyriakides and Corona, 2007).

For deep waters where combined external pressure and bending during installation is likely to cause large pipe ovalities, the wall thicknesses must be sufficiently thick to avoid collapse. This indicates the importance of thoroughly calculations of the wall thicknesses in deep- and ultra-deep waters.

This analysis provides results on the effect of changing pipe ovality in the range between 0,5% and 3,0%, which are the respective minimum and maximum values for ovality according to DNV (2007 a). Variations in wall thicknesses are given in table 5-11, table 5-12 and table 5-13 for the 14 inch, 20 inch and 28 inch respectively. Figure 5-16, figure 5-17 and figure 5-18 show the effects on wall thicknesses (local buckling criteria) based on change in ovality requirements for the 14 inch, 20 inch and 28 inch pipeline, respectively.

Results indicate that the wall thickness is reduced by approximately 15% when changing the ovality requirements from 3,0% to 0,5%.

14 inch X65 Wall thickness (mm)				
Ovality (%)	Water depth (m)			
	800	1400	2000	3500
0,5	11,6	14,0	16,1	23,1
1,0	11,9	14,6	17,0	24,3
1,5	**12,2**	**15,1**	**17,8**	**25,3**
2,0	12,5	15,6	18,5	26,1
2,5	12,8	16,1	19,1	27,0
3,0	13,1	16,6	19,7	27,7

Table 5-11 14” Pipe: Wall Thickness vs. Ovality

20 inch X65 Wall thickness (mm)				
Ovality (%)	Water depth (m)			
	800	1400	2000	3500
0,5	16,1	19,5	22,6	32,6
1,0	16,5	20,3	23,9	34,2
1,5	**17,0**	**21,1**	**25,0**	**35,6**
2,0	17,5	21,9	25,9	36,9
2,5	17,9	22,5	26,9	38,1
3,0	18,3	23,2	27,7	39,2

Table 5-12 20” Pipe: Wall Thickness vs. Ovality

28 inch X65 Wall thickness (mm)				
Ovality (%)	Water depth (m)			
	800	1400	2000	3500
0,5	22,1	26,9	31,2	45,2
1,0	**22,7**	**28,1**	**33,0**	**47,5**
1,5	23,4	29,2	34,5	49,5
2,0	24,0	30,2	35,9	51,2
2,5	24,6	31,1	37,2	52,9
3,0	25,2	32,1	38,4	54,5

Table 5-13 28" Pipe: Wall Thickness vs. Ovalitiy

In 800 meter depth the required wall thickness will decrease by:

- 1,5 mm or 11,5% for a 14 inch pipeline
- 2,2 mm or 12,0% for a 20 inch pipeline
- 3,1 mm or 12,3% for a 28 inch pipeline

as the ovality decreases from 3,0% to 0,5%.

In 1400 meter depth the required wall thickness will decrease by:

- 2,6 mm or 15,7% for a 14 inch pipeline
- 3,7 mm or 15,9% for a 20 inch pipeline
- 5,2 mm or 16,2% for a 28 inch pipeline

as the ovality decreases from 3,0% to 0,5%.

In 2000 meter depth the required wall thickness will decrease by:

- 3,6 mm or 18,3% for a 14 inch pipeline
- 5,1 mm or 18,4% for a 20 inch pipeline
- 7,2 mm or 18,8% for a 28 inch pipeline

as the ovality decreases from 3,0% to 0,5%.

In 3500 meter depth the required wall thickness will decrease by:

- 4,6 mm or 16,6% for a 14 inch pipeline
- 6,6 mm or 16,8% for a 20 inch pipeline
- 9,3 mm or 17,1% for a 28 inch pipeline

as the ovality decreases from 3,0% to 0,5%.

14 inch pipeline

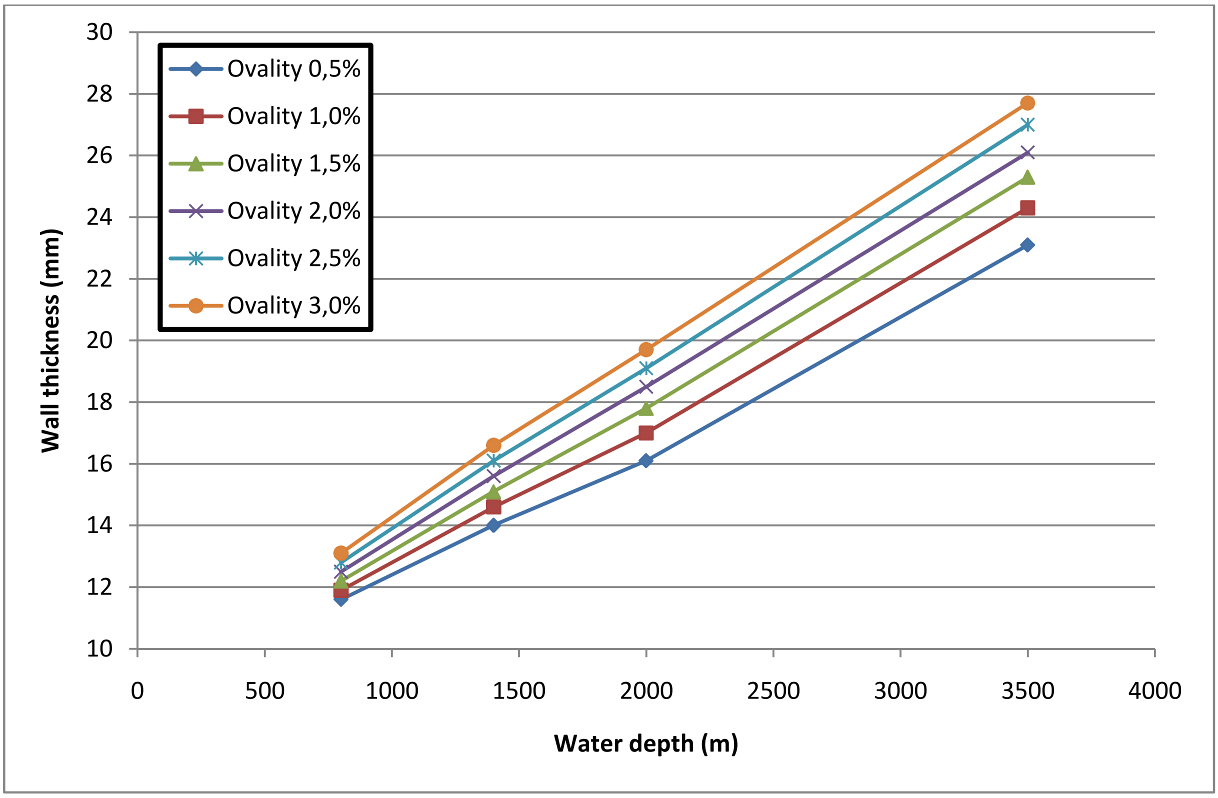


Figure 5-16 14" Pipe: Wall thickness vs. Ovality

20 inch pipeline

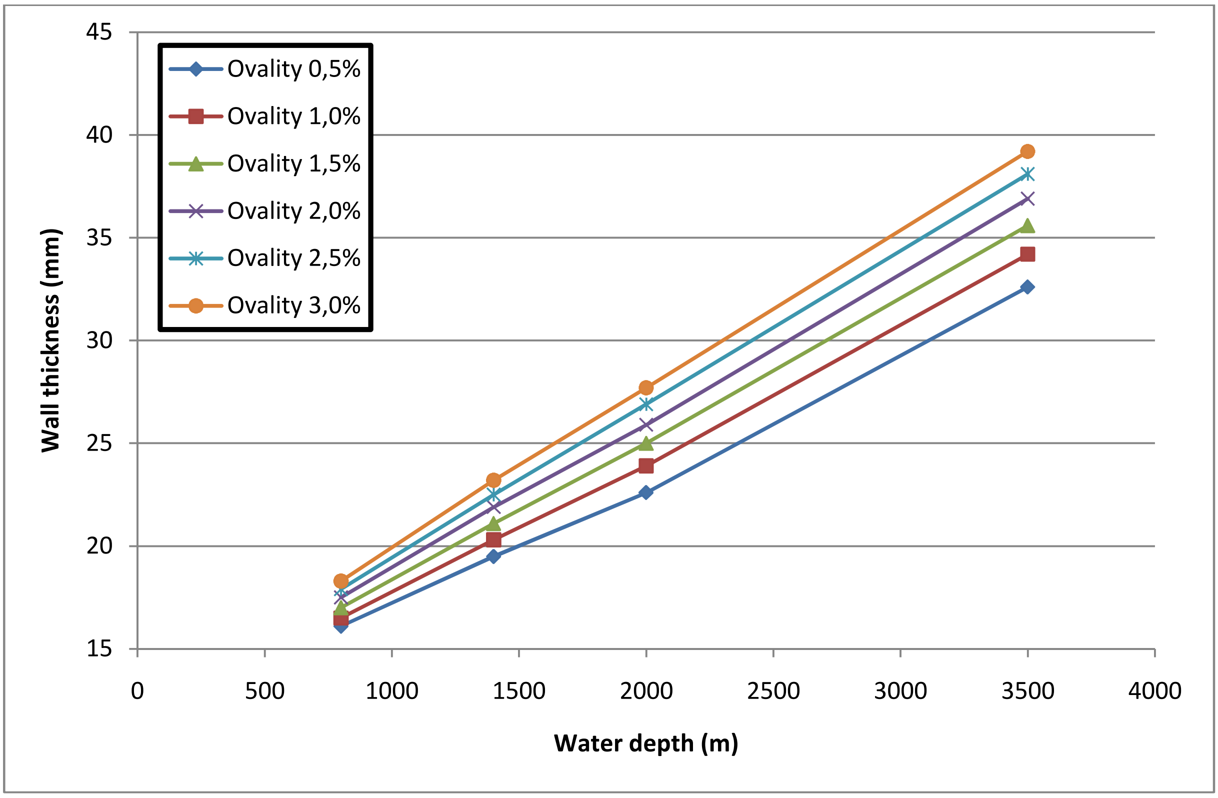


Figure 5-17 20" Pipe: Wall Thickness vs. Ovality

28 inch pipeline

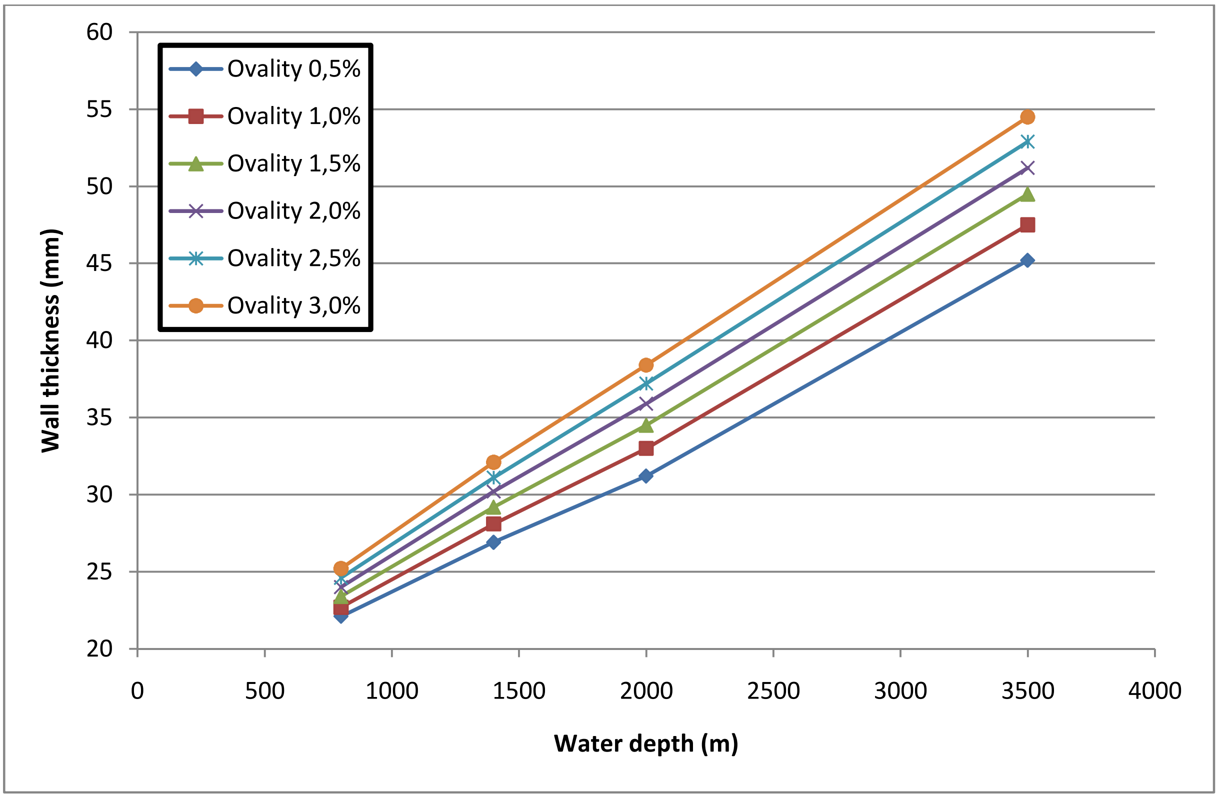


Figure 5-18 28" Pipe: Wall Thickness vs. Ovality

5.6.4 Discussions and Conclusions

Following discussions and conclusions can be made from the parameter study:

- An increase in steel grades has a higher effect on wall thickness requirements for deeper waters than for more shallow waters. As the weight decreases proportional, the layability will hence be more affected for installation in deeper waters, as the total length of the pipeline segment extending from the vessel to the seabed is increased.

- Wall thickness reductions as a result of increased steel grades are independent of pipe diameters when using pipe collapse requirements. The percentage reductions in wall thickness requirements are similar for the 14 inch, 20 inch and 28 inch at all water depths.

- Wall thicknesses are strongly dependent on the pipe ovality. Decreasing the allowable ovality from 3,0% to 0,5% will reduce the wall thicknesses in the range of 15%.

- The ovalities effect on wall thicknesses is increased as the pipes diameter gets larger. This increase is, however, small.

- Wall thickness requirements based on ovality are little influenced of water depth. Results indicate that the wall thickness requirements are reduced similar for deep- and ultra-deep waters, even though the numerical values (mm) are higher as the water depth increase.

5.7 Stability Design

Deep water pipelines are designed to be stable on the seabed when exposed to waves and currents, along with internal and external loads. Stability design shall satisfy requirements to both vertical and lateral movements affecting the pipeline during its design life.

While performing a stability design, the most unfavorable combination of vertical and horizontal forces affecting the pipeline shall be made as a basis. This includes forces from waves and currents. If the joint probability of waves and currents are unknown, the combination of a 100-year wave and 10-year current or a 10-year wave and 100-year current are considered for operations exceeding 12 months, according to DNV (2007 b).

Pipeline weight shall be based on the nominal thickness of the steel wall and coatings, and include weight reduction due to potential corrosion.

Design shall be done in order to ensure vertical and lateral stability of the pipeline (DNV, 2007 b):

Vertical stability

Vertical stability requires the pipeline to have a satisfactory design against sinking (water filled pipes) and floatation (air filled pipes).

For the 14 inch, 20 inch and 28 inch pipelines in a water depth of 800m the wall thickness based on system collapse were not sufficient to avoid pipeline floatation. The required wall thicknesses, to secure vertical stability, are 13,3mm, 19,0mm and 26,6mm for the respective pipe diameters (table 5-14). This is equivalent to a pipe diameter to thickness ratio of $\frac{D}{t} \geq 26{,}73$

Pipelines	Wall Thickness (mm)	Calculated Specific Weight
14 inch pipeline at 800m	13,3	1,10
20 inch pipeline at 800m	19,0	1,10
28 inch pipeline at 800m	26,6	1,10

Table 5-14 Pipeline Specific Weight at 800m water depth

Note: Pipeline coatings have not been included in the calculation of specific weight. For this specific case the coating would increase the submerged weight of the pipeline and hence reduce the required wall thickness necessary to satisfy the specific weight ratio of 1,10. However, as the coating vary for different projects, the wall thickness parameter studies and installation analyses have been done without considering the effect by the coating.

According to DNV (2007 b) lateral pipeline stability can be based on three design methods:

- Dynamic lateral stability method
- Generalized lateral stability method
- Absolute lateral static stability method

Dynamic lateral stability

On-bottom stability design based on dynamic lateral stability may follow one of the approaches:

1. Absolute stability – The hydrodynamic loads shall be less than the soil resistance under an extreme oscillatory cycle in the sea state the design is based on.
2. No break-out – Small displacements are allowed when subject to the largest waves in a sea state. These displacements will be limited to about one half the diameter which ensure the pipe to move out of its cavity.
3. Allowing accumulated displacement - A larger allowable displacement is given for the sea state used in the design, which will cause the pipe to break out of its cavity several times during the sea state.

Allowing small specified lateral displacements for the pipe will reduce the needed wall thickness or concrete weight coating (CWC) that is required to satisfy stability design. By applying the absolute stability method for stability design, no pipe motion is allowed, and hence requirements' to pipe weight and concrete weight coating make this approach highly conservative.

Absolute lateral static stability method

The pipeline shall be resistant against lateral movements under maximum hydrostatic loads during a sea state. This is satisfied when:

$$\gamma_{sc}\frac{F^*{}_Y+\mu F^*{}_Z}{\mu w_s+F_R} \leq 1{,}0 \tag{5.1}$$

and

$$\gamma_{sc}\frac{F^*{}_Z}{w_s} \leq 1{,}0 \tag{5.2}$$

Where:

$$F^*{}_Y = r_{tot,y}\frac{1}{2}\rho_w D C^*{}_Y(U^*+V^*)^2$$

$$F^*{}_Z = r_{tot,z}\frac{1}{2}\rho_w D C^*{}_Z(U^*+V^*)^2$$

F^*_Y	Peak horizontal hydrodynamic load
F^*_Z	Peak vertical hydrodynamic load
γ_{sc}	Safety class resistance factor
μ	Friction coefficient
r_{tot}	Load reduction factor
C^*_Y	Peak horizontal load coefficient; Table 3-9 in DNV (2007 b)
C^*_Z	Peak vertical load coefficient; Table 3-10 in DNV (2007 b)
U^*	Oscillatory velocity amplitude for single design oscillation, perpendicular to pipeline
V^*	Steady current velocity associated with design oscillation, perpendicular to pipeline

Factors affecting the stability design and on-bottom stability are:

- Water depth
- Wave characteristics
- Current characteristics
- Seabed conditions
- Soil properties

In cases where stability requirements are not fulfilled, several mitigating measures can be applied:

- Trenching
- Burial
- Rock dumping
- Structural anchors
- Mattresses
- CWC: Shall provide negative buoyancy and mechanical protection during installation and operation. Requirements to CWC can be found in DNV (2007 a) section 9 C202.

5.8 Cathodic Protection System Design

Cathodic protection (CP) systems are applied to pipelines for external corrosion prevention. According to DNV (2007 a) all submerged pipelines must be equipped with a CP system to secure necessary corrosion protection against defects occurring from coating application, and for possible coating damages in regards with pipeline installation and operation. As the coating deteriorates during the pipe life, increased CP current are required to prevent corrosion.

Two main methods of CP are present:

- Impressed current system: Electrical current supplied by a generator.
- Galvanic (sacrificial) anode system: Anodes connected to the pipeline to form a primary battery.

According to Palmer and King (2008) only the latter method is used for submarine pipelines. This method may include the most common system with bracelet anodes to provide a self-sustaining CP system. The bracelet anodes are mounted on the pipeline with a maximum distance of 300 m (DNV, 2007 a). Anodes are typically made of metals with lower natural potential (zinc and aluminum) than the pipeline steel, and hereby causing these metals to be corroded instead of the pipe itself.

Anodes should be designed to (Braestrup, et al., 2005):

- Provide required protection during the pipeline design lifetime by sufficient anode mass.
- Deliver the required protective current at any time during the pipeline design life from the anode surface area.

To design cathodic protection for deepwater pipelines, the following parameters must be known (Guo, Song, Chacko and Ghalambor, 2005):

- Service/ design life
- Coating breakdown
- Current density for protection buried or unburied
- Seawater resistivity
- Soil resistivity
- Pipeline protective potential
- Anode output
- Anode potential
- Anode utilization factor
- Seawater temperature
- Pipeline temperature
- Depth of pipeline burial

According to Palmer and King (2008) also the expected area of bare pipe shall be estimated, and how this is changing over the pipe lifetime.

CP is provided by aluminum anodes for the pipelines in this study. These are bracelet anodes connected to the pipe joint at the coating yard (normal for S- and J-lay installation). To secure the minimum requirements for CP the single anodes are installed with a maximum distance of 300m (DNV, 2007 a).

A typical anode installed on the pipelines can be seen in figure 5-19. Anode assemblies can also be installed on the seabed, but for deep water pipelines pre-installed bracelet anodes is a better alternative.

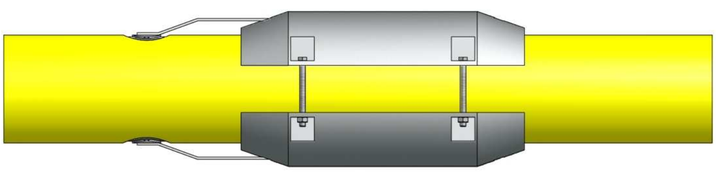


Figure 5-19 Bracelet Pipeline Anode [IKM, In-house document]

5.9 Free Span Analysis and Design

Free spanning pipelines can experience overstresses and fatigue due to pipe weight, waves and currents, and hooking from fishing equipment. Deep water pipelines will normally have limitations to free span lengths based on currents and unsupported pipe weights. To secure a safe and optimal installation and operation at areas subject to significant spans, pipeline free span analysis and design are required to ensure adequate safety against fatigue, excessive yielding, buckling and ovalization within the design life.

Limitations to pipeline routing are normally set to avoid free spans that exceed the critical length where in-line oscillations occur, or span supporters are installed. Measures to reduce or avoid fatigue due to free spans can be done by rock-dumping, mattresses, trenching, sandbags and anchoring. Clamp-on supports with telescoping legs or auger screw legs may be a more optimal approach if the span height is above 1m, according to Lee (2002). For deep waters these mitigating measures may however be both expensive and unpractical to implement and can be too costly to justify for a pipeline installation.

Analysis:
Vortex shedding induced oscillations due to currents are often the governing factor for deep water pipeline span lengths, and several steps should be made to find the allowable span length (Guo, Song, Chacko and Ghalambor, 2005):

1. Determine design current
2. Calculate the effective unit mass of the pipeline
3. Calculate Reynolds Number
4. Calculate stability parameter
5. Determine reduced velocity for in-line motion
6. Determine reduced velocity for cross-flow motion
7. Determine type of free span end conditions and calculate end condition constant
8. Calculate critical span length for in-line and cross-flow motion
9. Allowable span length calculated for cross-flow can be selected instead of the in-line motion critical span if it is economically feasible
10. Calculate and evaluate fatigue life of the free span when in-line motion is permitted

Reduced velocity

$$V_R = \frac{U_C}{f_n D} \tag{5.3}$$

Where:

V_R	Velocity where vortex shedding induced oscillations can occur
U_c	Mean current velocity normal to the pipe
f_n	Natural frequency for a given vibration mode
D	Outer diameter of the pipe

Design:
Free spanning pipeline design shall be done in accordance with DNV (2007 a) and DNV (2006), as figure 5-20 indicates. Screening fatigue criteria (DNV (2006) sec. 2.3), fatigue criterion (DNV (2006) Sec. 2.4) and ULS criterion (DNV (2006) Sec. 2.5 and DNV (2007 a)) shall be satisfied to secure adequate design. Reference is made to DNV (2006) and DNV (2007 a) for further information on this matter.

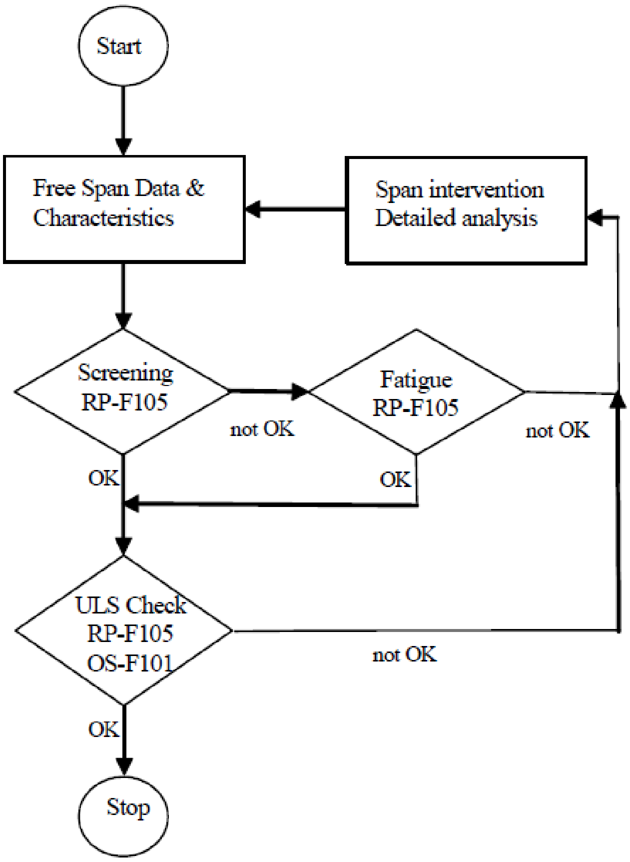


Figure 5-20 Free Span Design Checks [DNV, 2006]

Design of deep water pipelines should be made with the highest level of survey information available, in order to minimize rectification requirements to seabed and free spans.

5.10 Summary

Selection of pipeline concept and design is a complex task in any oil and gas field development. For deep waters this task is normally even more complex, as environmental and installation issues have a larger impact on design.

Optimal route selection is critical to achieve the most cost beneficial and safe pipeline route. This is particularly important for deep water pipelines, as the costs and technical requirements of performing repair and seabed interventions are both more expensive and demanding. Detailed desktop studies and geohazard analyses prior to route selection can provide significant contributions to obtaining the optimal route.

Pipe-in-Pipe (PIP) solutions are popular due to the insulation capacity, where the heat loss per unit length is lower than for any available external coating for single pipes. The PIP is a reliable, thermally efficient and proven technology, particularly beneficial with HP/HT conditions. Good characteristics in free spans, seabed stability and maintenance, are other advantages with the PIP solutions. Sandwich pipes (SP) have been found to give significantly higher bending capacity for equal external pressure, similar steel and lower submerged weight, compared to single steel pipes. Carbon steel pipes have benefits in aspects such as cost and installation, and the experience with use of these pipelines are exceeding the two other concepts by far. Given that costs and safety may be the two most important factors for pipeline developments; single steel pipes are still the preferred concept, particularly in ultra-deep waters where several single steel pipes have been installed successfully (the Medgaz project, Na Kika Export pipelines, etc.). Limited experience on SP and the high weight of PIP, especially for large diameter pipelines, also contribute to single pipes being preferred.

Insulation coatings with good thermal conductivity are necessary to secure a satisfactory pipeline flow assurance. For pipelines operating in deep waters, use of insulation materials with low thermal conductivity is beneficial due to the reductions in pipe size and -weight. This was showed in the parameter study where an insulation thickness reduction of approximately 77% (27mm) was given by materials with thermal conductivity of 0,04W/mK rather than 0,16W/mK. Syntactic PE, -PP and –foam, using plastic or glass matrix, have the potential of low thermal conductivity, low density and good compressive strength, all advantages for deep water pipelines.

Use of higher graded steels is beneficial in form of weight reductions due to the decrease in required wall thicknesses. The reduction in wall thicknesses is increased with water depths. Pipe weight reductions will be particularly important in ultra-deep waters as lay vessels have limits to tension capacity. Selecting steel grades of X80 instead of X65 may be justified in form of cost savings, where a wall thickness reduction by 12% for a 28 inch pipeline at 3500m may be the difference for the pipeline being layable or not.

Required wall thicknesses, to avoid system collapse, are strongly dependent on the pipe ovality. Decreasing the allowable ovality from 3,0% to 0,5% will reduce the pipe wall thicknesses in the range of 15%. The ovality will, however, increase during the installation when the pipe is subject to bending and external pressure. To allow for ovalities exceeding 3%, special considerations should be done (DNV, 2007 a) and the impact made by bending must be known to avoid pipeline failure during installation.

CHAPTER 6 OFFSHORE PIPELAYING

Offshore installation of pipelines is usually done with one of the following technologies:

- S-lay
- J-lay
- Reeled lay
- Towed lay

Installation method applied for various projects is based upon factors such as water depth, pipeline-length, -weight, -diameter and -design, available vessels and seabed topography.

This chapter will go deeper into the methods of S- and J-lay for pipeline installation, which are both dependent on pipe assembly by welding onboard their respective vessels, and the reeled lay method where the pipe string is spooled onto a reel onshore before laying.

6.1 S-Lay

S-lay is the most applied method for offshore pipeline installations, especially for relatively large diameter pipelines (d > 16”). This lay method is applicable for pipe installation in both shallow and deep water areas. The installation technique is characteristic with the s-curve of the pipeline during laying, and is a result of the stinger and tensioners on the vessel. Maximum depth in which a pipeline can be laid is dependent on the stinger length, -curvature, tensioning capacity, tip slope and longitudinal trim of the vessel.

After passing through a number of welding stations, inspection phases and tensioners, the pipeline will lift off from the stinger located typically at the end of the vessel. The stinger will set the curvature for the upper end of the pipeline, the so-called overbend (figure 2-2). Rollers secure the pipeline support during the offloading into sea, from where the pipeline continues as an unsupported span until interacting with the seabed. Here, at the lower part, the pipeline gets a curvature directed opposite of the overbend. Pipe curvature in the sagbend is a result of the tensioners and weight of the pipeline, and can be controlled by the tension applied to the pipe from the vessels tensioning system.

6.1.1 Steep S-Lay

Steep S-lay is a variant of conventional S-lay, making it more applicable for deep water pipeline installations by modifying the stinger and increasing the structural utilization of the pipe (figure 6-1). According to Perinet and Frazer (2007) the method includes setting the stinger in such a way that the liftoff point of the pipeline will be as close to vertical as possible, which reduces the tension in the pipe compared to the traditional S-lay method. The steep liftoff angle implies that the curvature has to be increased, in order to keep the stinger to a reasonable size. As a result of the increased stinger curvature the strains in the overbend will increase.

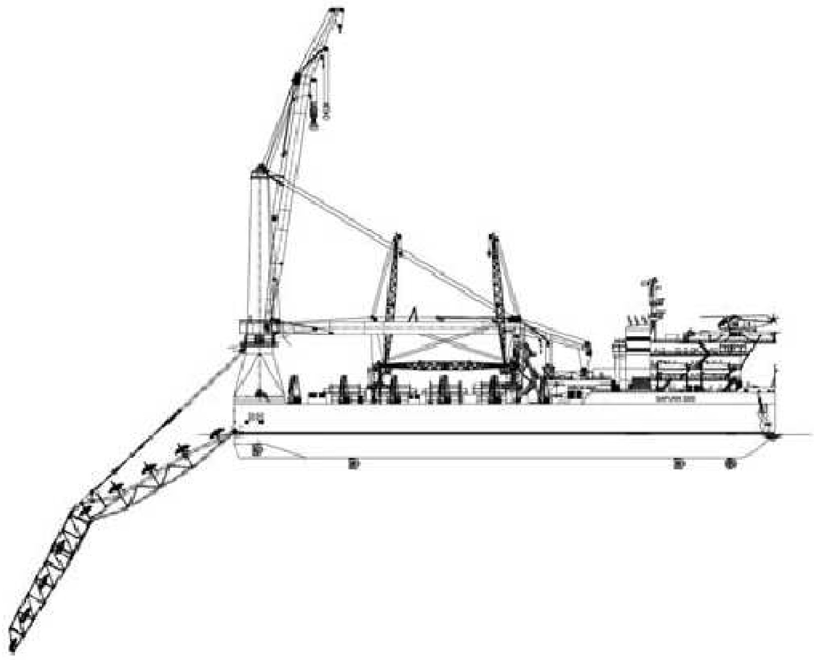


Figure 6-1 Steep S-Lay Configuration [Perinet and Frazer, 2007]

Advantages

- No limitations to pipeline diameter and -length. The vessels can install varying pipeline diameters in different projects, making them feasible for many S-lay installation projects.
- Requires minimal on-shore support ones the installation has started.
- Numerous pipeline tasks can be performed at the same time, including welding, inspections and field joint applications, due to the horizontal transportation across the vessel.
- Several contractors with S-lay experience, which gives advantages due to technical and economical competition.
- Laying speed is quite high, even for large diameter pipelines, and is typically between 2 and 6 km/day (Iorio, Bruschi and Donati, 2000). This is dependent on seabed topography and water depth, among other factors.

Disadvantages

- Limited installation depth. Tension capacities at the vessels are likely to be exceeded at ultra-deep waters for large diameter thick walled pipelines.
- Long stingers are vulnerable to wave and current forces, which is typical for S-lay vessels in deep waters.
- High tension is undesirable as the tensioners can damage the pipeline coating, as well as having to be balanced by the mooring or dynamic positioning system of the vessel.
- High strains in the overbend are common for deep water installations, with a high probability of exceeding the given strain criteria.

6.1.2 S-Lay Main Installation Equipment

The pipeline installation procedure for S-lay vessels is done by the following main equipment:

Tensioners

Tensioners are normally located near the stern of the ramp. Typically rubber pads put a pressure at the top and bottom of the pipe surface. These apply a tension to the pipe, controlling the curvature during installation. Their function is to give sufficient tension in order to secure the integrity of the pipe. The required tension depends on factors such as water depth, length of stinger, stinger radius, pipe diameter and -weight. For deep waters the required tension is higher than for more shallow waters, as the total pipeline segment has a higher weight. The S-lay vessel Solitaire (Allseas Group) has a total tension capacity of 1050t, allowing pipeline installation down to approximately 3000m.

In deep waters the tension capacity of the vessel is usually the limiting factor for how deep a pipeline can be laid. According to Perinet and Frazer (2007) the transfer of tension between tensioner device and pipe is the most critical factor. Tension can be applied to the pipe by:

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

Tension is transferred to the pipe by friction between the pipeline and the tensioning machine. To avoid damage to the pipe coating the area exposed to friction must be large enough. This supports the use of large tensioners with low squeeze.

One way of increasing possible pipe installation depth is by applying tension after the overbend section with use of submerged tensioners. Advantages would be present by not combining the tension force and bending effect, as lower strains would arise in the overbend section, according to Perinet and Frazer (2007).

Stinger

The stinger is an open frame structure with rollers to support the pipeline during installation, and gives the pipe its curvature in the overbend region. It will often be constructed by several hinged sections, giving the possibility to adjust the stinger curvature and shape. Stinger lengths are depending on the lay vessel, but normally the lengths are above 100m for vessels installing pipelines in deep waters. Solitaire has a stinger length of 140m which makes it able to perform deep water installations.

To keep the strain levels in the overbend within the given criteria, long stingers are required for deep water laying. Short stingers will be problematic, as the bending strains would exceed the allowable strain criteria at the end of the stinger, potentially resulting in buckling (figure 6-2).

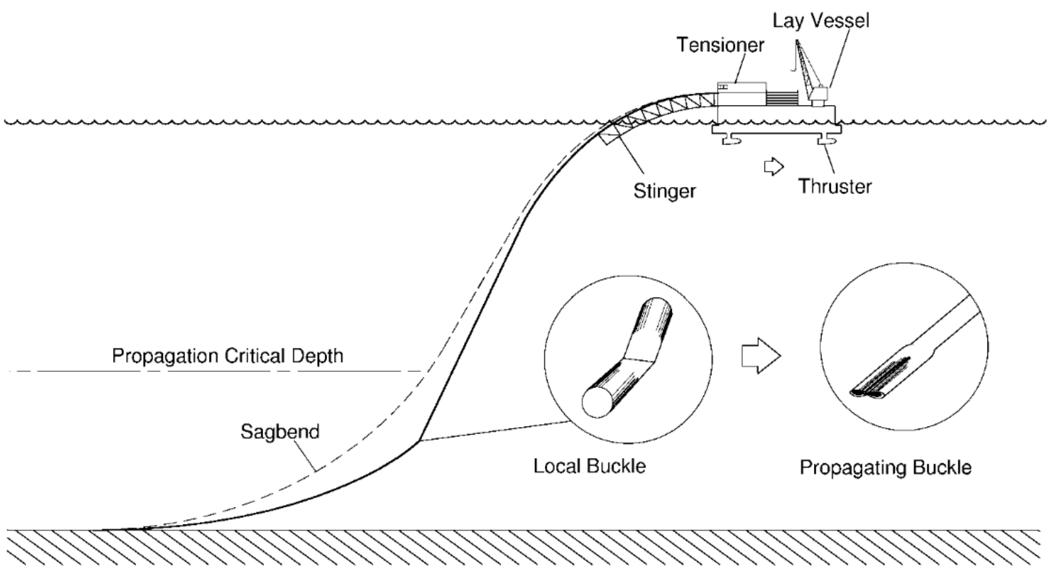


Figure 6-2 Buckling during S-Lay [Kyriakides and Corona, 2007]

Stingers in themselves have to withstand several forces acting on them during operation:

- Waves and current forces
- Contact forces between the pipe and the stinger
- Forces caused by the weight of the stinger
- Forces acting on the stinger due to vessel movements

In order to increase the applicable water depth of pipeline installation, the liftoff angle at the stinger tip should be close to 90°. This can be done by reducing the stinger radius, which will also increase the strains in the overbend region. To make S-lay practical for deep waters this would be preferable, in addition to having a stinger rigidly connected to the lay vessel (Perinet and Frazer, 2007). Stinger configurations applied today normally include:

- Rigid stingers, fixed to the laybarge
- Articulated stingers, flexible or rigid segments joined by hinges

Modern stingers, such as the one on Solitaire, are articulated. This gives possibilities of controlling the curvature of the stinger by setting different angles for the segments, whereas rigid stingers are limited to their given configuration. Installing pipelines in deep waters will require longer stingers to avoid excessive bending at the stinger. There are limitations to how long the stinger length can be due to the increased environmental loads acting on it.

6.2 J-lay

J-lay is a much applied method for pipeline installation at deep water locations, usually limited to pipe diameters up to 32 inches. The J-like shape of the pipeline segment during installation has been found to have advantages for laying in deep waters, as there is no overbend and less tension is required than for the S-lay (section 6.7).

During J-lay installations the pipeline leaves the vessel in a near vertical direction, through a tower located on the vessel. As a result there is no overbend, and only the sagbend curvature at the lower part, close to the seabed, is affecting the required tension from the tensioners. Due to the near vertical installation, only one (or maximum two) stations for welding and inspection is typical for these vessels, making limitations to pipelaying speed (figure 2-3).

Stalks of pipes, from double-joints to 5-6 joints welded together, are lifted on top of the tower and welded together with the existing pipe segment. By welding more joints together before lifting on to the tower the laying speed increases. However, this is still relatively slow compared to the method of S-laying.

Advantages

- As the pipe leaves the vessel in a close to vertical position, the tensioners are only set to limit bending in the sagbend. This will give reductions to the required tension.
- No stinger. No overbend.
- Shorter freespans, due to lower lay tensions, is resulting in reduced bottom tension in the pipe.
- Pipeline laying is more accurate than for S-lay, due to a touchdown point closer to the vessel. This is also a function of the reduced tension.
- Reduced area of interaction from the waves. As the pipelines are installed close to vertical, only a small part of the pipeline segment is affected by the waves. Hence this method will be less susceptible to the weather conditions than the S-lay.
- Fast and relatively safe abandonment and recovery turn around.

Disadvantages

- Limited installation speed. As there is only one combined welding and inspection station, or one welding- and one inspection station, the pipelines will be laid with a speed lower than what is typical for S-lay operations.
- Stability issues. The tower and added weight high up on the vessels are affecting their stability.
- Limitations to shallow water pipe installations. In shallow water the bend close to the seafloor may cause pipeline damages, as this tends to be too sharp.

6.2.1 J-Lay Main Installation Equipment

Installations of pipelines are done through a J-lay tower, which is the core part of any J-lay system.

Towers

Towers are vertical or close to vertical structures that support the pipeline during operation and consist of tensioners and work stations. During installation these will normally vary between 0˚and 15˚ from the vertical position.

Towers can be placed close to the middle of the vessel, as for the DB 50 (McDermott's) or at the stern, which is the case for S-7000 (Saipem), as shown in figure 6-3.

Tensioners

As for S-lay, the tensioners shall provide sufficient tension to avoid potential buckling during pipelaying. The interaction between the submerged weight of the pipes and the given tension controls their curvature in the sagbend region. An insufficient tension can result in excessive curvature at the sagbend.

S-7000 uses friction claps to maintain a possible tension of 525t. Another system can be used, where a collar is welded at the upper end of the pipe and clamps hold it at the end of the tower. This is the system applied at Balder, which has a possible 1050t tension capacity.

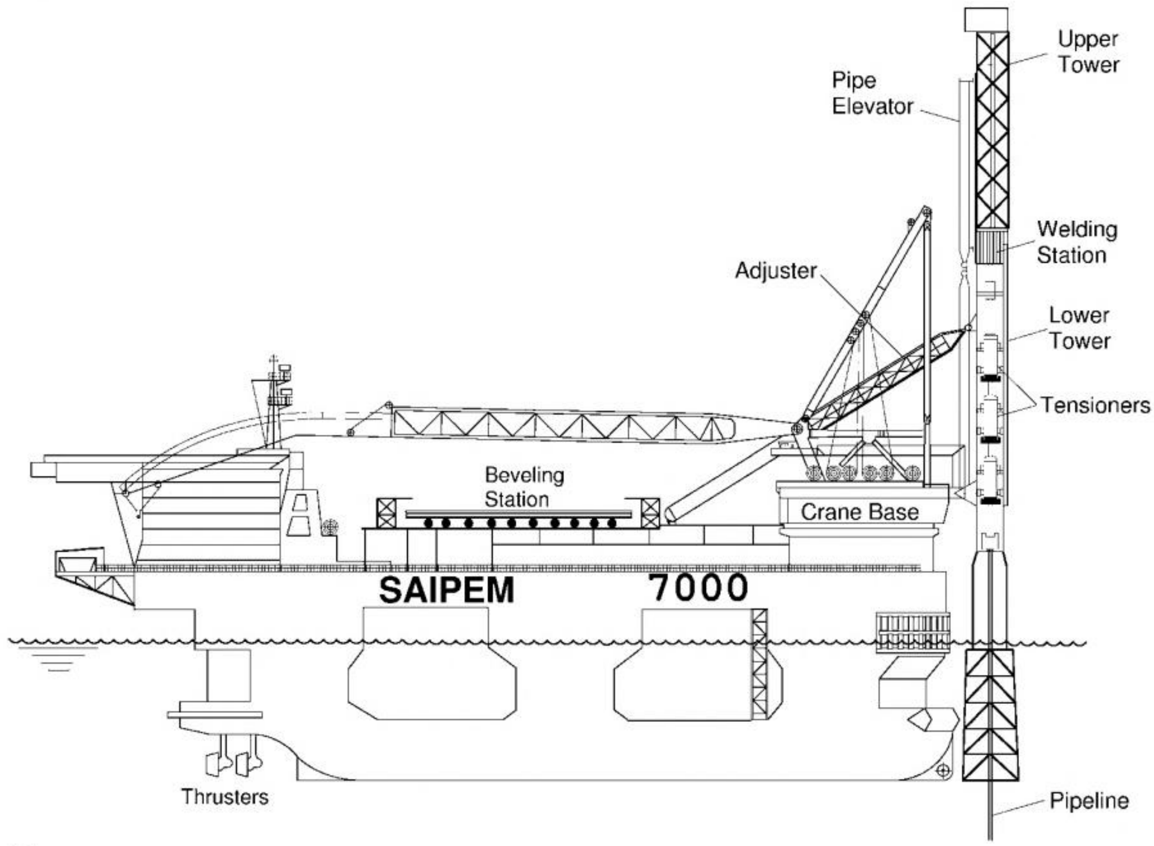


Figure 6-3 Installation Equipment on S-7000 [Kyriakides and Corona, 2007]

6.3 Combined S- and J-Lay

A combination of S-lay fabrication and J-lay ramp configuration has been found to have advantages concerning pipe installation in deep waters. Increase in lay accuracy, and possibly an increase and reduction in transit speed and mobilization time respectively, are potential benefits compared to S-lay. This is due to the horizontal fabrication of the pipelines and installation with use of a ramp, by moving the pipe around a deck radius controller before going into the ramp radius controller, straightener and tensioner (figure 6-4). Plastic deformations occur in these two bends to maintain an optimal operating area. According to Perinet and Frazer (2007) this combined laying method can be especially advantageous for operations requiring accurate pipe placement in combination with long areas of installation. The pipe diameter size is however limited for this system due to the bending radius.

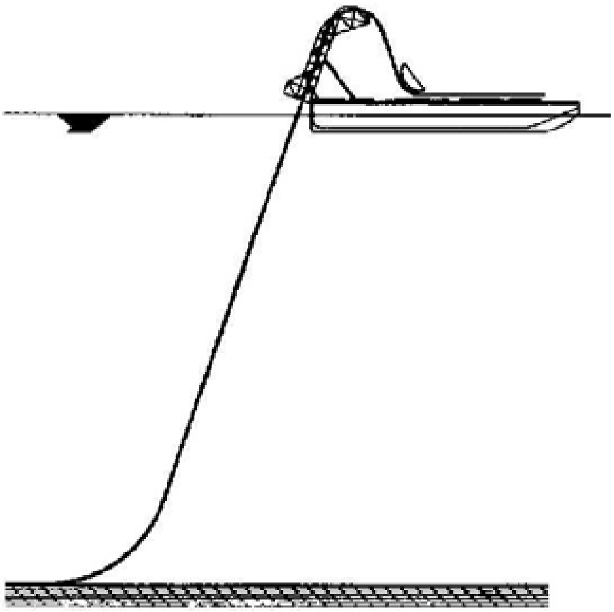


Figure 6-4 Combined S- and J-Lay Pipe Configuration [Perinet and Frazer, 2007]

6.4 Reeled Lay

Reeled lay (figure 6-5) is an efficient pipelaying method for relatively small diameter pipelines (up to 16 inches), where the pipe is installed by unreeling it from the vessel onto the seabed. First the pipeline is spooled onto the reel onshore, where the manufacturing is done. Then the reel is installed on a lay vessel to be taken offshore for installation. Reeled lay can be done both by the S- and J-lay method, depending on water depth and design of the vessel. Horizontal reel vessels apply a stinger and S-lay method for pipe installation in shallow to intermediate water depths, while vertical reel vessels use a tower for the J-lay installation method in deeper waters. The pipe will typically lift off in a relatively steep angle causing minimal or no overbend at the top, and the sagbend (stresses) will be controlled by the tension from the reel itself. High strains are inflicted on the pipeline during spooling onto the reel (depending on reel diameter). By coming into plastic strain both ductility and strength of the pipeline can be affected. Straightening is required to secure a straight pipe in the laying phase. Depending on the pipe- and reel diameter, this method is fast (up to 10 times faster than conventional pipelaying (Guo, Song, Chacko and Ghalambor, 2005)) as it can install pipe lengths up to 10-15km before a pipeline pickup onshore is required.

Advantages

- Faster pipeline installation than for conventional lay methods
- Applicable for deep waters
- Manufacturing and reeling are done in controlled environments onshore
- Cost-effective
- Less weather dependency than for the S- and J-lay methods
- Lower operation costs than S- and J-lay

Disadvantages

- Possible loss of yield strength due to plastic deformation and straightening
- Pipelines cannot be reeled with concrete coating
- Time consuming to re-reel pipelines to remove buckles
- Need of spool base close to the installation site to make the process effective

Figure 6-5 Spooling and Lay Phase [Denniel, 2009]

6.5 Selection of Installation Method

By considering advantages and disadvantages of the mentioned installation methods; S- and J-lay have been selected for the pipeline installation processes in the given study. This is mainly due to reasons such as:

- Pipeline diameter sizes; intermediate to large diameters (14-28 inch pipelines)
- Relatively thick walled pipelines
- Need of high tension capacity at the vessels

6.6 Pipelay Tension

Pipelay tension is the most significant parameter to control in order to make a successful pipe installation i.e. guarantee the pipes structural integrity. Tension will affect the curvature in the sagbend, distance to the touchdown point and the residual tension left in the pipeline at the seabed. Too low tension may cause buckling due to excessive bending, and too much tension may plasticize the pipe at the overbend (Jensen, 2010).

Increasing the tension will reduce the curvature of the pipe in the sagbend, causing a touchdown point further away from the vessel and resulting in a liftoff point higher on the stinger. If the tension becomes too low, the bending moments can exceed the allowable limit, leading to a local collapse which may result in propagating buckling (figure 6-2). As the pipe may interfere with the stinger tip, due to lower tension, the forces acting on it might damage the pipe and stinger.

Figure 6-6 illustrates the loads acting on the pipeline during a typical deep water S-lay installation. At the stinger the pipe will be subject to bending moment M, contact force T_K, and tension T. In the sagbend the pipeline will in addition be affected by external pressure P.

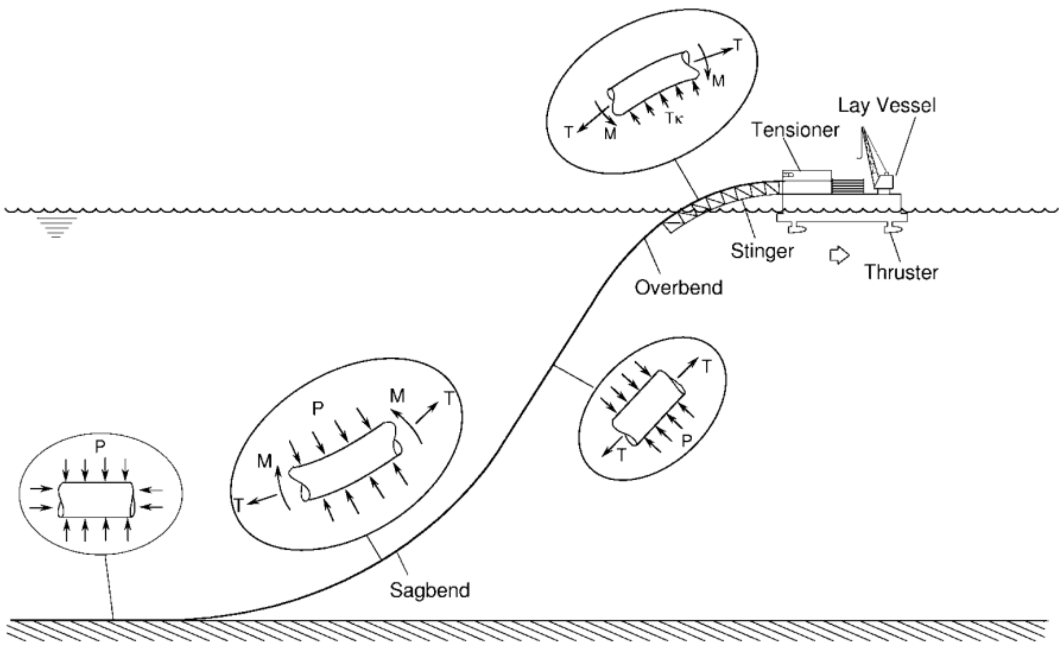


Figure 6-6 Loadings on the Pipeline during S-Lay [Kyriakides and Corona, 2007]

6.7 Comparison of S- and J-Lay

While S-lay vessels include a large stinger during installation, J-lay vessels consists of a tower to perform the installation process. These installation methods cause different pipeline configurations during pipelaying that will affect both the critical areas and required tension.

A comparison of pipeline installations by S- and J-lay has been executed by Perinet and Frazer (2007) to find the required vessel tension for the two methods. To make the study realistic, identical pipeline properties and liftoff angles (θ) were used. As figure 6-7 indicates, results show that the tension required during installation for two similar pipelines are higher for S-lay compared to J-lay. This is due to the S-lay vessel being affected by both a bottom tension (T_0) at the seabed and a horizontal component (R_h) of the stinger reaction force (R). The required tension (T_s) is the sum of R_h and T_0 which must be counterbalanced by the positioning system of the vessel. For the J-lay vessel however, the direction of the applied tension (T_j) with a horizontal component (T_0), is equal to the bottom tension (T_0) which has to be counterbalanced by the vessels positioning system.

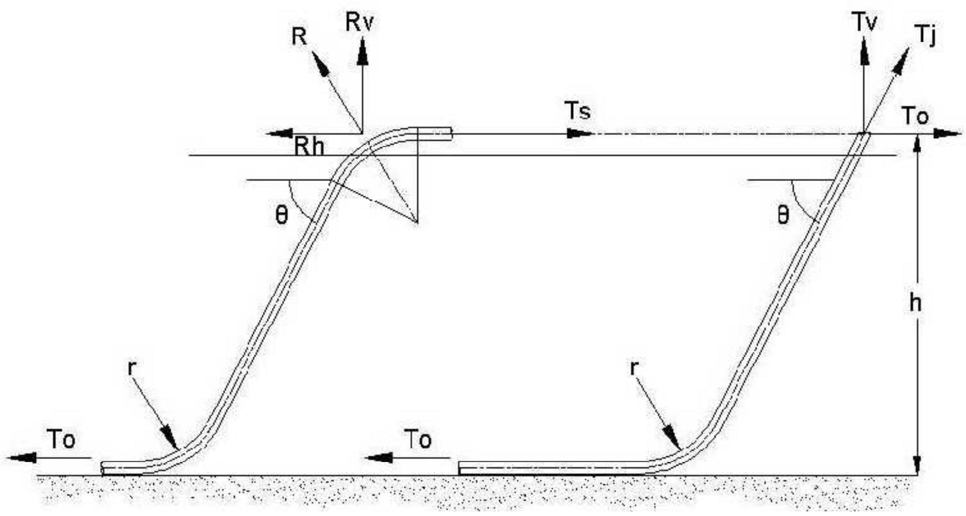


Figure 6-7 Tension for Equal Cases of S- and J-Lay [Perinet and Frazer, 2007]

6.8 Dynamic Positioning

During pipeline installation processes, the control of lay vessels motions and positioning are essential to avoid damages to both pipes and vessels. Positioning of the lay vessels is done either by mooring to anchors or by dynamic positioning (DP) systems with use of thrusters. These systems shall keep the vessel from drifting sideways or yaw away from the pipeline, as this may cause buckling or kinking of the pipe at the end of the stinger (Palmer and King, 2008).

The force by the positioning system has to be adequate in order to ensure a sufficient tension and hereby curvature of the pipe. This tension will react on the lay vessel, resulting in a force that the vessel has to be held in position against. Vessel size and dynamic factors, such as waves, currents and wind affect the force required to hold it in position.

Positioning by anchors has been the common system for lay vessels constructed up until the later years. Anchors controlled by anchor handling tugs are spread around the barges, and winches control the movement. Benefits such as no need for complex computer systems controlling propellers and thrusters, and independency of power supply are advantages for this type of systems. Still, several disadvantages are present. Difficulties of placing anchors without interfering with existing subsea structures and pipelines, is a problem. Continuous relocation of anchors is both time consuming and sensitive to sea conditions and weather. One of the main issues is the limitation for use in deep waters. The water depth is limited to approximately 800m for use of mooring-anchor systems, depending on the pipeline diameter (Palmer and King, 2008).

DP systems using thrusters to position the lay vessels give several advantages for pipelaying operations. Their precision in positioning are maintained by use of thrusters, GPS (Global Positioning System) or acoustic positioning systems, and sensors which measure vessel heading, - motion, wind direction and –speed. A control system also controls the configuration of the pipeline relative to the vessel. Only surge, sway and yaw can be controlled by the DP system, and a specific heading must be held, even though this might not be the optimal position regarding interaction of environmental loads.

Figure 6-8 below shows the forces and motions acting on the vessel which the DP system has to withstand during operation.

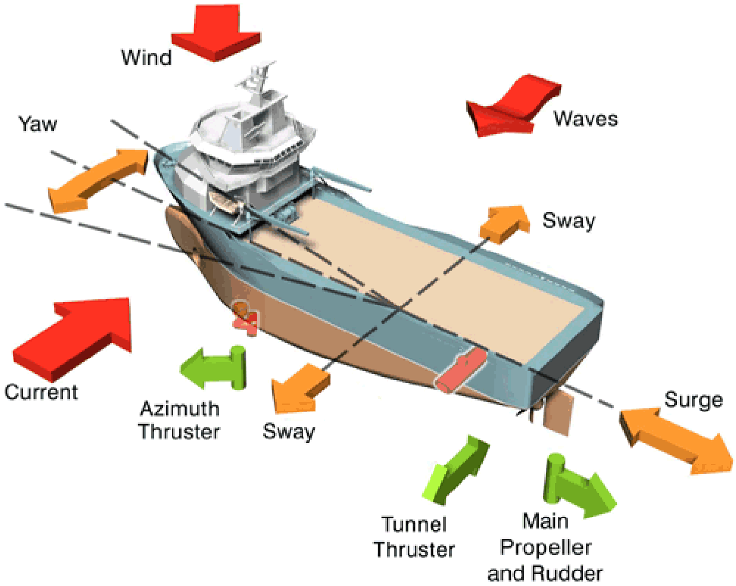


Figure 6-8 DP Vessel Affected by Forces and Motions [Kongsberg Maritime, 2011]

Advantages of using DP systems include faster abandonment and recovery of pipelines, quicker start-up, independency to water depth, no interference with subsea structures such as pipelines, faster pipeline lay-rate, and higher maneuverability and flexibility for use in bad weather conditions. For water depths beyond approximately 800m vessels controlled by DP system is the only realistic option for pipeline installations.

Two of the negative factors by using DP systems are system reliability and power required to balance the applied tension from the pipe. The first factor can result in barge damage and buckling of the pipe, while the second factor require powerful thrusters which results in high fuel costs. DP systems normally include full redundancy in all components, to cope with the reliability issues, according to Jensen (2010). Other disadvantages by the DP systems are vulnerability to thrusters, -electronics and -power supply, and higher day-rates and fuel consumptions than for the anchored vessels.

6.9 Steep S-Lay Evaluations

Future oil and gas projects will at a higher rate be developed in deep- and ultra-deep water areas. Installations performed by the J-lay method have a higher potential of reaching a water depth of 3500m than conventional S-lay, due to lower tension required to justify the installation of large diameter pipelines. For the S-lay method however, installation of large diameter pipelines will be limited due to overbend strains exceeding the criteria given in table 4-1. The existing lay vessels tensioning capacities may also be exceeded at ultra-deep waters. Due to the pipelaying speed of S-lay installations compared to J-lay, the benefits of making this method applicable at water depths exceeding today's potentials are major.

Perinet and Frazer (2008) discuss the potential of increasing the allowable overbend strain criteria applied for S-lay, and how this may affect the lay process at deep waters. First, as ultimate strain levels of steel can be in the region of 20% and around 2,0% strain is allowed during reeling, the strain levels are not considered a limiting factor. However, an increase in strain levels was found to be a potentially limiting factor during installation due to the residual curvature and -strain in the pipe during the process. This has to do with the fact that no straightening process can be executed after the pipe has left the stinger, which will leave the pipe with a residual curvature that can cause effects to (Perinet and Frazer, 2008):

- Sagbend configuration
- Pipeline behavior during operation (upheaval and lateral buckling)
- Liftoff point from the stinger
- Pipeline lay-down on the seabed

The study (Perinet and Frazer, 2008) showed that increasing the allowable strain level in the overbend to the region of 0,35% would be possible without the pipeline serviceability being affected. Residual strains would still be inside the allowable limits considered for reeling operations. A total overbend strain of 0,50% are expected to be applicable without causing any damages to the pipelines. Effects on the pipeline ovalization, weld defects and fatigue crack growth were found to be small or negligible for a higher allowable strain.

To allow S-lay in deeper waters an increase in stinger curvature are considered to have the highest influence on layability compared to an increase in stinger length and -bottom tension, both from a cost and safety point of view. This is showed by Perinet and Frazer (2008) where an increase from 0,20% to 0,35% in allowable overbend strain results in an stinger radius reduction in the range of 40% (minimum stinger radius decreasing from 112m to 64m) for a 18 inch pipeline.

Increasing the allowable overbend strain limits from today's criteria will have several benefits when it comes to pipeline layability in deep waters (Perinet and Frazer, 2008):

- Reduce required stinger radius
- Reduce required stinger length
- Reduce the lay vessel sizes required
- Reduce the total costs of the installation operation
- Increase the potential water depth where existing lay vessels are able to perform pipe installations

Cost reductions for the installation processes may be significant, as smaller vessels can be applied and existing vessels can perform pipe installations at deeper waters (as long as the tensioning capacity is not a limiting factor). Shorter stingers would also be beneficial as these would be less affected by bad weather conditions during laying operations.

6.10 Summary

S-lay is for given reasons the most applied and qualified method of pipelaying in shallow waters. For deep- and ultra-deep waters however, the J-lay method has technical benefits during installation, such as no overbends, less fatigue damage to pipelines and increased accuracy of placement on the seabed. Steep S-lay and combined S- and J-lay are two methods developed to increase the laying- and fabrication speed, which is limited in the J-lay method. Steep S-lay can provide increased lay rate and installation of larger pipeline diameters compared to J-lay, but higher strains in the overbend will come as a result of keeping the stinger length limited. Combined S- and J-lay has benefits concerning laying speed compared to J-lay and lay accuracy compared to S-lay, even though limitations are set to pipeline diameters compatible with the bending radius in the system.

Steep S-lay (Perinet and Frazer, 2007) should be considered for installation of pipelines in deep waters. By setting the stinger liftoff angle close to vertical and increasing the stinger curvature to allow for smaller stingers, the required tension is reduced (and could be inside the tension capacities of existing vessels). This will however result in higher overbend strains. Allowing higher overbend strains should be considered to make pipeline installations possible for S-lay vessels down to a water depth of 3500m and beyond. Steep S-lay will have benefits from both a technical and cost perspective compared to conventional S-lay.

CHAPTER 7 PIPELINE LAYING STUDY

The main purpose of the installation process is to lay the pipeline within the specified route without exceeding the pipeline integrity. For this to be achieved the pipeline must be installed with a tension and curvature that keep the overbend strains and sagbend bending moments within the criteria given in DNV (2007 a) (section 4.2.2).

This chapter gives the parameters, inputs, assumptions and results of the static layability studies performed by OFFPIPE in order to evaluate the potential of installing different diameter pipelines in water depths down to 3500m.

Lay analyses have been performed with use of OFFPIPE to obtain results on:

1. Pipeline layability for the given water depths with S- and J-lay.

2. Effects on the installation process by increased allowable overbend strain criteria (up to 0,35%).

7.1 Pipelay Parameters

Parameters that have a high influence on the pipe laying sequence (Bai and Bai, 2005):

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

These parameters will affect the pipeline installation by changing the:

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

In the pipelay parameter study the following parameters are analyzed on their influence on the laying process (section 7.5):

1. Stinger radius (S-lay)
2. Pipelay tension

7.2 Pipelay Study Input

7.2.1 Pipeline Data

For the pipelaying study, the given data and requirements are selected:

- Water depths: 800m, 1400m, 2000m and 3500m.
- Pipe diameters: 14 inch, 20 inch and 28 inch
- Material grade: X65 (14”) and X70 (20” and 28”)
- Sagbend: Moment criterion is in accordance with DNV (2007 a), assuming Load Controlled condition.
- The pipeline part on the stinger is assumed to be displacement controlled, with maximum allowable strains of 0,25% (X65) and 0,27% (X70) at the overbend. Criteria of maximum allowable overbend strains of 0,35% is set for the parameter study, in addition to the previous requirements.

The following pipeline wall thicknesses and weights will provide the input for the laying study (table 7-1):

Water depth (m)	14 inch		20 inch		28 inch	
	Wall thickness (mm)	Submerged weight (kg/m)	Wall thickness (mm)	Submerged weight (kg/m)	Wall thickness (mm)	Submerged weight (kg/m)
800	13,3	10,5	19,0	21,4	26,6	41,9
1400	15,1	25,0	20,8	42,2	27,7	59,7
2000	17,8	46,5	24,4	83,3	32,3	133,6
3500	25,3	104,3	33,9	188,6	45,1	333,7

Table 7-1 Pipeline Submerged Weight Data for Installation

7.2.2 Lay Vessel Data

In order to make the lay parameter input for the study as realistic as possible, typical lay vessels have been identified. Both S- and J-lay vessels able to install pipelines in deep- and ultra-deep waters are considered.

S-Lay Vessels

Key data for existing S-lay vessels identified are presented in table 7-2:

Lay Vessel	Stinger radius	Tension capacity	Stinger length	Ramp height	Ramp angle
Solitaire	140-300	1050t	140m	10,5m	0˚
Lorelay	-	135t	118m	12,0m	0˚
Castorone	-	750t	120m	-	-

Table 7-2 S-lay Vessel Data

Solitaire is a dynamic positioned (DP) vessel. DP is preferred for vessels in deep waters as there are no limitations to operable water depths, as opposed to the anchored vessels (section 6.8).

Some S-lay vessels with high tension capacities (e.g. Castoro 7), making them able to do pipeline installations in deep waters have had to be excluded due to limited operable water depths for anchored vessels (limited to about 800 meters, depending on the pipe diameter).

J-Lay Vessels

Key data for existing J-lay vessels identified are presented in table 7-3:

Lay Vessel	Tension capacity	Lay angle
Balder	1050t	50˚- 90˚
Saipem 7000	525t	90˚-110˚
Deep Blue	770t	58˚- 90˚

Table 7-3 J-lay Vessel Data

Deep Blue has the highest tension capacity of the three lay vessels. A high tension capacity is preferred at deep waters, as the pipe string extending from the barge to the seabed increase in weight for deeper waters.

7.2.3 Lay Study Assumptions

As this is a general study with no specific locations in mind, only static analyses will be provided for the pipelaying process. Dynamic analyses influenced by wind, waves and currents should be carried out in addition for particular projects, especially for static analyses giving results that are close to vessel- or pipe limits.

The pipelaying system applied in OFFPIPE is assumed to have a flat, continuous, elastic seabed. In actual projects the seabed is however uneven, with varying topography and possibly different soil types and rocks.

In the pipelaying study the pipelines are assumed to be without coating. This is done to get a more general picture of the results, as the influence by coating varies for different locations and water depths. In reality some form of coating would be present, depending on the environment and pipeline design requirements. Coating affects the weight of the pipelines and hence reduces the layability.

Both S- and J-lay installations are considered to be executed with one of the existing lay vessels (note that Castorone is set to finish in the near future). This is done rather than using a single predefined vessel, as this would be unrealistic for laying analyses covering such a spread in water depths (800m-3500m). The stinger radius and length will vary depending on the water depths, but as far as possible these values are set so that the installation process is not dependent on one single vessel. Top tension is in addition considered to be fully utilized, which could be problematic in case of wet buckling (water floods the pipeline and exceed the tension capacities of the vessels).

Main assumptions used in the static pipeline installation analyses consist of the following:

S-Lay

- Departure angle typically between 45˚ to 70˚
- Stinger radius between 110m and 200m
- Maximum top tension of 1050t
- Minimum separation at the last stinger roller above 300mm (based on engineering judgment to allow for dynamic effects).
- During S-lay the strains in the overbend and tension capacity of the lay vessel is normally the limiting factors for pipeline installation

J-Lay

- Departure angle typically between 70˚ to 90˚
- Maximum top tension of 1050t
- Bending moment in the sagbend is together with vessel tension capacity normally the limiting factors for J-lay installations

7.3 Laying Analysis

After the pipeline design is decided, based upon requirements for operation, a static pipeline installation analysis will be performed. This is done in order to control the capabilities of the installation vessels equipment. Based on the analysis; an optimal configuration of the stinger radius, departure angle and lay vessel tension are found. The analysis shall also secure the strains and stresses at the overbend and sagbend to be inside the criteria given in DNV (2007 a).

Pipeline laying analyses will be executed by the program OFFPIPE. OFFPIPE is a finite element based computer program capable of performing modeling and structural analysis of nonlinear problems in pipeline installation processes. Some of the OFFPIPE features include:

- Static pipelaying analyses for S- and J-lay vessels
- Calculation of static pipe strains, -stresses and span lengths

The pipelaying analyses will provide results concerning strains in the overbend and sagbend, including moments and axial tension along the pipe, and pipeline liftoff angle at the stinger tip and vessel stern.

Tension, which is the most significant parameter to control in order to make a successful installation i.e. guarantee the pipes structural integrity, is kept to a minimum.

7.3.1 Pipelay Modeling

OFFPIPE pipelaying system is modeled by finite elements as shown in figure 7-1. The pipeline extending from the line-up station on the barge to a point of apparent fixity on the seabed is constructed by beam-like pipe elements. Tensioners and pipe supports are modeled by specialized elements to act as the structural model for the stinger, while the seabed is set as a continuous elastic foundation model provided by bilinear, elastic-frictional soil elements in the pipelaying system (Malahy, 1996).

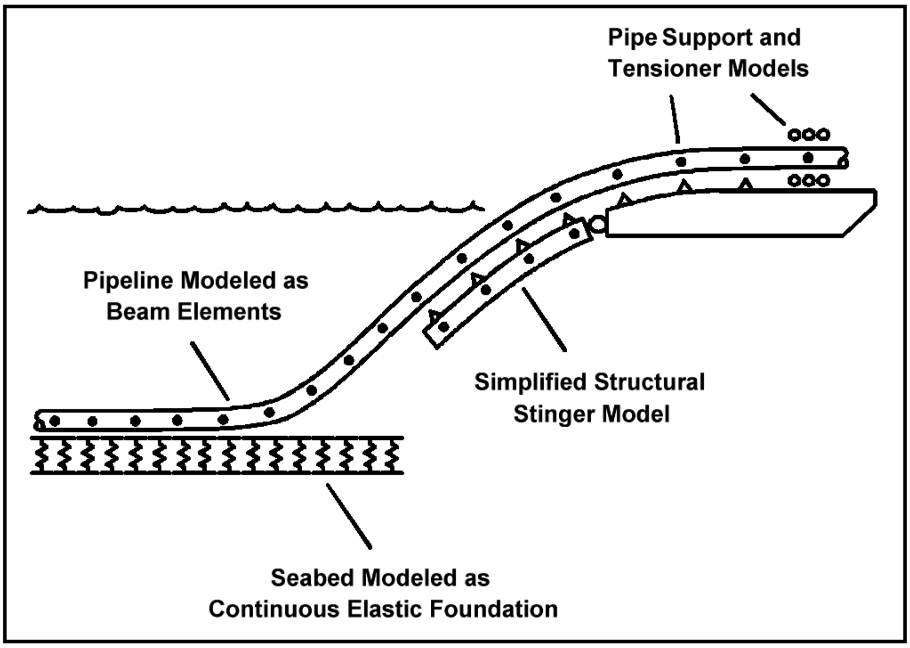


Figure 7-1 Finite Element Model of the Pipeline System [Malahy, 1996]

Laybarge modeling gives the vessel a rigid body, with no independent degrees of freedom associated with it. The pipeline on the laybarge is modeled as a continuous pipe string, extending from the line-up station or first tensioners, to the stern. Here the pipe is controlled by a number of tensioners and support elements, as shown in figure 7-2.

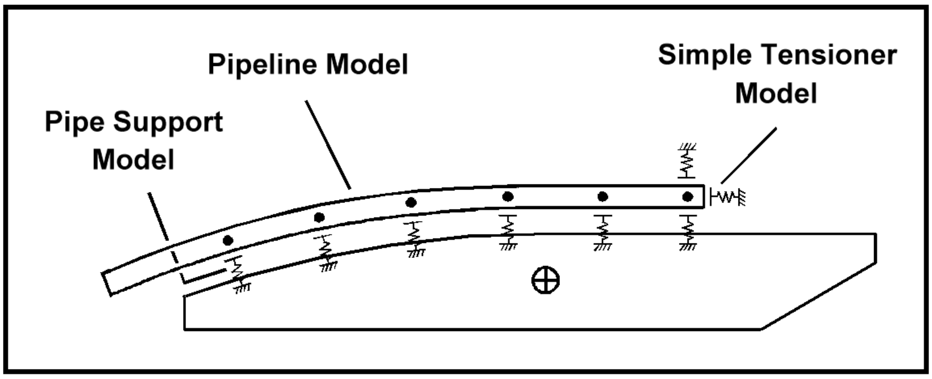


Figure 7-2 Laybarge Model [Malahy, 1996]

The pipeline extending from the barge stern to the stinger tip is modeled as strings of pipe elements (figure 7-3). A series of support elements, as on the lay barge, provide support for the pipeline laying on the stinger.

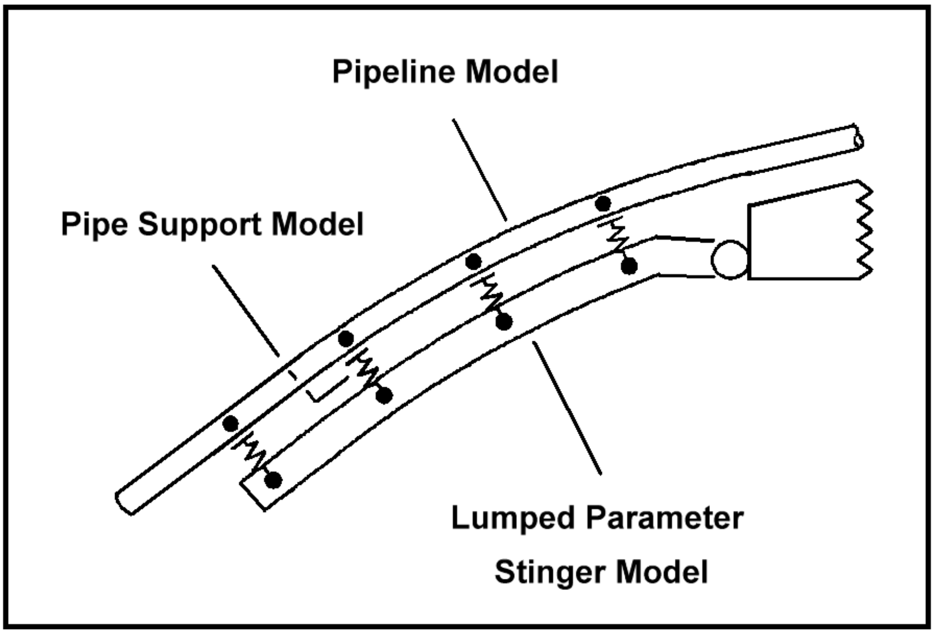


Figure 7-3 Stinger Model [Malahy, 1996]

Pipe supports used at the laybarge and stinger are modeled as frictionless point supports. These supports each consist of two pairs of support rollers, as shown in figure 7-4. The first roller support pair is close to horizontal, and mainly applies weight support for the pipelines. While the second pair, almost vertical positioned, acts as a restrain for lateral movements of the pipes. Each pair of rollers is normally configured into a “V” shape by mounting them in angles as given in figure 7-4.

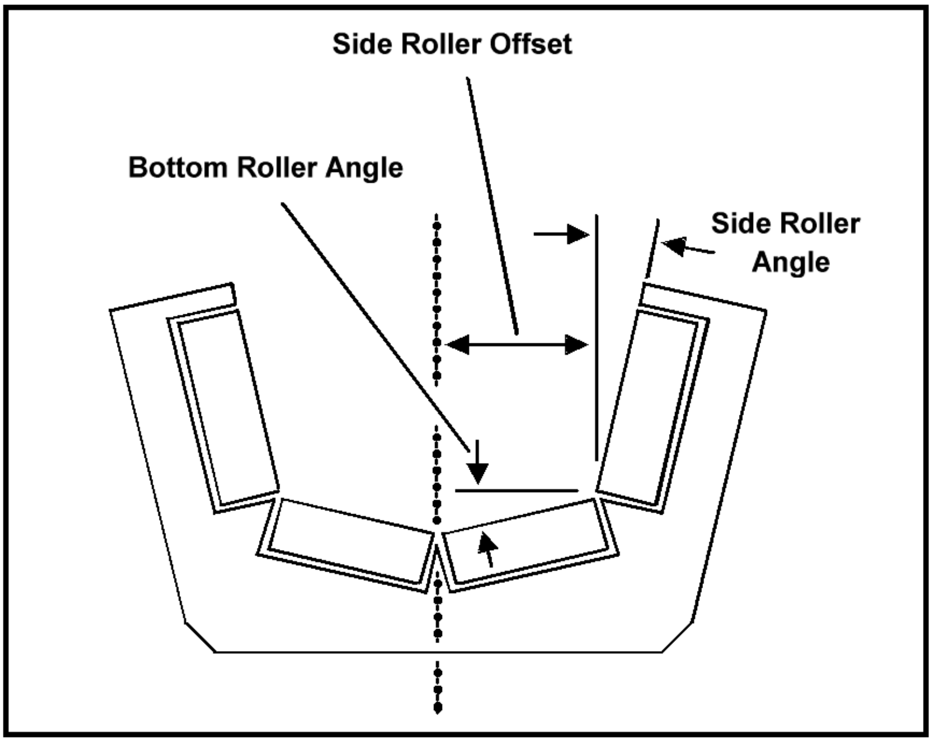


Figure 7-4 Pipe Support Element [Malahy, 1996]

Stress-strain relationship for uniaxial stress is determined based on the Ramberg-Osgood relationship. OFFPIPE uses a material model given by Ramberg-Osgood to find the non-linear moment curvature relationship:

$$\frac{\kappa}{K_y} = \frac{M}{M_y} + A\left(\frac{M}{M_y}\right)^B \tag{7.1}$$

Where:

A	Ramberg-Osgood equation coefficient
B	Ramberg-Osgood equation exponent
κ	Pipe curvature
K_y	Pipe curvature at the nominal yield stress; $K_y = 2\sigma_y / (ED)$
M	Pipe bending moment
M_y	Pipe bending moment at the nominal yield stress; $M_y = 2\sigma_y I_c / D$
E	Modulus of elasticity of the pipe steel
D	Outer diameter of the pipe
I_c	Cross sectional moment of inertia of the steel pipe
σ_y	Nominal yield stress of the pipe steel

Coefficient *A* and exponent *B* can be found by three different methods in OFFPIPE. In this thesis *A* and *B* are determined based on steel grades and cross sections of the pipes (see example in APPENDIX D).

S-Lay Modeling

Lay vessel used for S-lay is specified with a constant radius of curvature and the horizontal X coordinate, elevation (Y coordinate) and angle of the pipeline at the laybarge tangent point (geometry number 2) (Malahy, 1996). The tangent point is where the ramp starts to decline. Coordinates are set to X=15m and Y=0,5m and pipe radius of curvature is 380m. Barge deck is 15m above the water line.

Stinger configuration is set as a rigid stinger, fixed to the lay vessel. The geometry is given by a fixed tangent point, variable curvature and stinger length. Stinger length and curvature is varying based on water depth, pipeline size and -weight (given in each specific case). Pipe support elements divide the stinger into elements, with one (1) support element for each 10m.

J-Lay Modeling

Configuration of the J-lay vessel applied for the installation studies in OFFPIPE is set by geometry number 6 (Malahy, 1996). Here the geometry will be given by an inclined ramp and tangent point. This geometry is intended for use with J-lay analysis where the pipe ramp is steeply inclined with respect to the barge deck. Deck height above the water is set to 15m. One (1) pipe tensioner and four (4) pipe supports are defined with their horizontal X- coordinates relative to the inclined ramp, rather than to the barge deck. The coordinates of the tensioner and pipe supports are rotated around a pivot point specified to 89˚.

7.4 Lay Analyses Results

The static analyses, done with the pipelay program OFFPIPE, provide results on the layability of the given pipelines. Results presented in the following are provided to prove layability of the given pipelines with existing lay vessels.

Load Controlled Condition Evaluation

Pipelines are subject to bending moments, effective axial force and external overpressure during the laying processes, which require the load controlled (LC) condition criteria to be satisfied (section 4.2.2).

The LC condition evaluation are carried out for 14 inch, 20 inch and 28 inch pipelines based on the parameters given in table 7-4, table 7-7 and table 7-10, respectively. Bending moments in the sagbend are provided from the OFFPIPE analyses and summarized in table 7-5 and table 7-6, table 7-8 and table 7-9, table 7-11 and table 7-12, for the 14 inch, 20 inch and 28 inch pipelines, respectively.

Complete results of the pipeline lay analyses are presented in APPENDIX C.

7.4.1 14" Pipeline Results

Figure 7-5 shows the results of minimum vessel top tension requirements alongside water depth. Top tension is increasing close to linear with water depth before reaching 1400m. This is due to the small variations in pipe wall thicknesses between these water depths, as specific weight ratio must be satisfied (table 5-14). When exceeding 1400m the wall thickness increases more rapidly to satisfy the local buckling criteria (section 4.2.1). As a result of heavier pipes and increased water depths; the top tension required during laying increases in a similar manner. Beyond 2000m the vessels tension requirements have an even steeper increase, as the wall thicknesses and water depth increase.

Factors relevant for the LC condition evaluation is given in table 7-4:

Factor	Value				Unit
	800m	***1400m***	**2000m**	**3500m**	
p_i	0	0	0	0	kN/m^2
p_e	8044	14080	20110	35190	kN/m^2
p_c	9676	16930	24190	42330	kN/m^2
f_y	430080	430080	430080	430080	kN/m^2
f_u	508800	508800	508800	508800	kN/m^2
β	0,370	0,405	0,445	0,500	kNm
α_c	1,0677	1,0741	1,0814	1,0915	kN
D/t_2	26,7368	23,5497	19,9775	14,0553	
$M_p(t_2)$	670,1584	752,9401	873,5516	1187,0989	kNm
$S_p(t_2)$	6151,1690	6946,9342	8124,1656	11290,8910	kN

Table 7-4 14" Pipe: LC Condition Parameters

Pipeline utilization factors given in table 7-5 and table 7-6 show that the LC condition criteria is satisfied at all water depths, for both S- and J-lay installations, as the utilization factors are lower or equal to 1. The utilization factors are however significantly higher for the J-lay installations compared to the S-lay installations. This indicates the fact that during J-lay the sagbend is normally the area of most concern.

S-Lay Installation Analyses

The following conclusions were achieved (table 7-5):

- Top tension required for pipeline installations were found to be within the tension capacities of existing vessels at all water depths (figure 7-5).
- Overbend strains were inside the criteria of 0,25% at 800m, 1400m and 2000m water depth.
- Overbend strain criteria of 0,25% was exceeded at approximately 2500m (achieved by linear interpolation).
- Sagbend bending moments were inside the allowable bending moments at all water depths.
- Departure angles were between 50˚- 70˚
- Separation at last stinger roller was above the minimum criteria of 300mm for all runs.

14" S-lay Water Depth (m)	Top tension (kN)	Strain overbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable bending moment (kNm)	Pipeline Utilization	Gap last supp. (mm)	Dep. angle (deg)
800	**194**	**0,181**	**46**	**384**	**0,1198**	**327**	**54**
1400	**692**	**0,199**	**36**	**321**	**0,1121**	**309**	**59**
2000	**1746**	**0,234**	**27**	**277**	**0,0975**	**333**	**59**
3500	**5869**	**0,310**	**25**	**122**	**0,2049**	**308**	**63**

Table 7-5 14" Pipe: S-Lay Results

Note: Strain criteria as 0,25%

J-Lay Installation Analyses

The following conclusions were achieved (table 7-6):

- Top tension required for pipeline installations were found to be within the tension capacities of existing vessels at all water depths (figure 7-5).
- Sagbend bending moments were inside the allowable bending moments at all water depths.
- Departure angles are between 85˚- 90˚

14" J-lay Water Depth (m)	Top tension (kN)	Strain in sagbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable bending moment (kNm)	Pipeline Utilization	Dep. angle (deg)
800	**111**	**0,150**	**348**	**384**	**0,90625**	**88**
1400	**396**	**0,136**	**319**	**323**	**0,9876**	**86**
2000	**949**	**0,127**	**286**	**291**	**0,9828**	**86**
3500	**3585**	**0,122**	**211**	**211**	**1,0000**	**85**

Table 7-6 14" Pipe: J-Lay Results

14" Pipeline: Top Tension for S- and J-lay

Top tensions required for the S- and J-lay are given in figure 7-5:

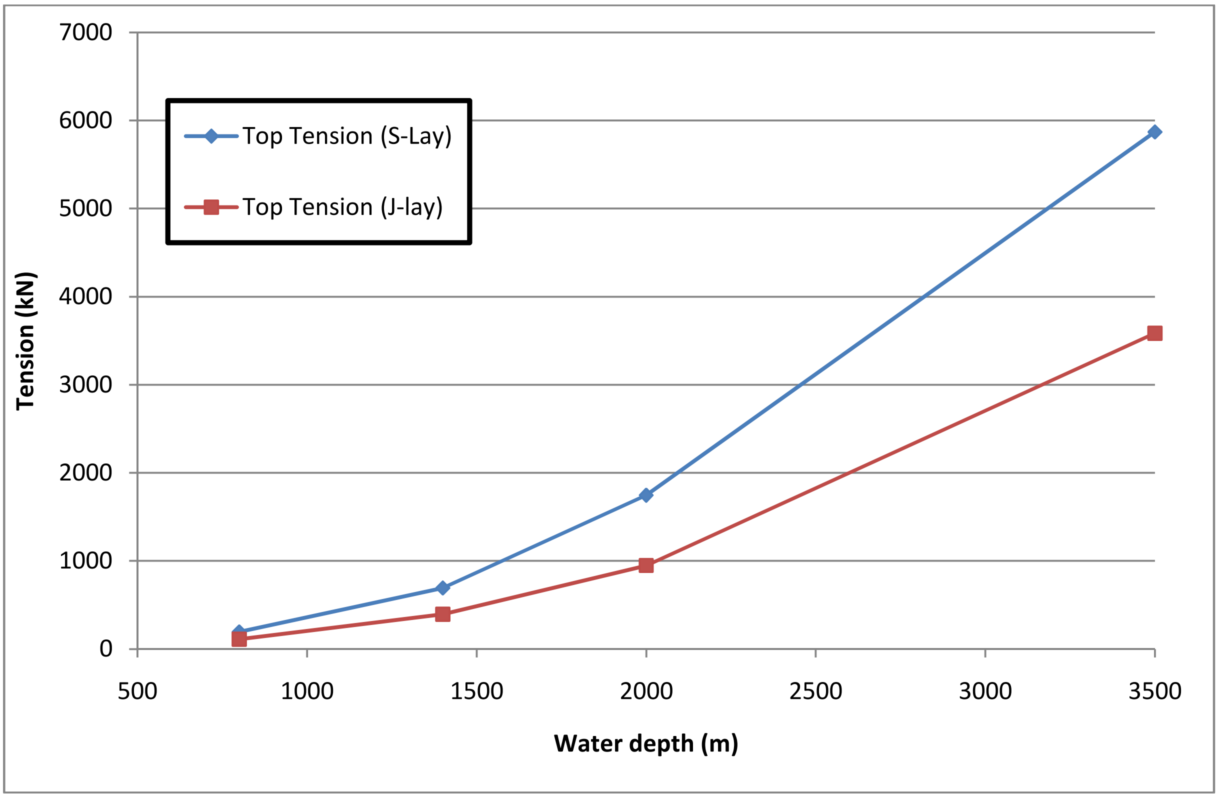


Figure 7-5 14" Pipe: Top Tension vs. Water Depth

7.4.2 20" Pipeline Results

Results on minimum top tension vs. water depth are plotted in figure 7-6. As the figure indicate; required top tension is increasing almost linearly from 800m to 1400m, as the variations in wall thicknesses are limited due to the requirements to specific weight ratio (1,1). From 1400m to 2000m the necessary top tension is increasing more rapidly as the wall thicknesses increase to satisfy the local buckling criteria (section 4.2.1). The required top tension graph is getting even steeper from 2000m to 3500m, as a result of increased water depths and wall thickness requirements causing a much heavier pipeline. Top tension capacity of the S-lay vessels are exceeded at a water depth of approximately 3200m, where the overbend strain is also far above the criteria (0,27%).

Factors relevant for the LC condition evaluation is given in table 7-7:

Factor	**Value**				**Unit**
	800m	***1400m***	**2000m**	**3500m**	
p_i	0	0	0	0	kN/m^2
p_e	8044	14080	20110	35190	kN/m^2
p_c	9676	16930	24190	42330	kN/m^2
f_y	462700	462700	462700	462700	kN/m^2
f_u	542400	542400	542400	542400	kN/m^2
β	0,370	0,395	0,435	0,500	kNm
α_c	1,0637	1,0681	1,0749	1,0861	kN
D/t_2	26,7368	24,4230	20,8197	14,9853	
$M_p(t_2)$	2102,1844	2284,4276	2640,3525	3525,6493	kNm
$S_p(t_2)$	13505,5362	14730,5847	17152,4235	23362,4845	kN

Table 7-7 20" Pipe: LC Condition Parameters

Pipeline utilization factors given in table 7-8 and 7-9 show that the LC condition criteria are satisfied at all water depths for both S- and J-lay installations, as the utilization factors are lower or equal to 1. The utilization factors are however significantly higher for the J-lay installations compared to the S-lay installations. This indicates the fact that during J-lay the sagbend is normally the area of most concern.

S-Lay Installation Analyses

The following conclusions were achieved (table 7-8):

- Top tension required at water depths of 800m, 1400m and 2000m were found to be within the tension capacities of existing vessels (figure 7-6).
- Top tension is exceeding the capacity of Solitaire, with a tension capacity of 1050t (~10300kN), at approximately 3200m. At 3500m water depth a top tension of 1176t (~11530kN) would be required.
- Overbend strains were inside the criteria of 0,27% at 800m, 1400m and 2000m water depth.
- Overbend strain criteria of 0,27% was exceeded at approximately 2000m (achieved by linear interpolation).
- Sagbend bending moments are inside the allowable bending moments at all water depths.
- Departure angles were between 50˚- 70˚
- Separation at last stinger roller was above the minimum criteria of 300mm for all runs.

20" S-lay Water Depth (m)	Top tension (kN)	Strain overbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable bending moment (kNm)	Pipeline Utilization	Gap last supp. (mm)	Dep. angle (deg)
800	363	0,249	-444	1222	0,3633	333	54
1400	1205	0,269	162	978	0,1656	306	59
2000	3426	0,269	105	919	0,1143	381	58
3500	11528	0,363	109	808	0,1349	302	64

Table 7-8 20" Pipe: S-Lay Results

Note: Strain criteria as 0,27%

J-Lay Installation Analyses

The following conclusions were achieved (table 7-9):

- Top tension required for pipeline installations were found to be within the tension capacities of existing vessels all water depths (figure 7-6).
- Sagbend bending moments are inside the allowable bending moments at all water depths.
- Departure angles were between 85˚- 90˚

20" J-lay Water Depth (m)	Top tension (kN)	Strain in sagbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable bending moment (kNm)	Pipeline Utilization	Dep. angle (deg)
800	233	0,149	1010	1223	0,8258	86
1400	743	0,144	974	982	0,9919	85
2000	1853	0,139	954	957	0,9969	85
3500	7050	0,140	1010	1028	0,9825	86

Table 7-9 20" Pipe: J-Lay Results

20" Pipeline: Top Tension for S- and J-lay

Top tensions required for the S- and J-lay are given in figure 7-6:

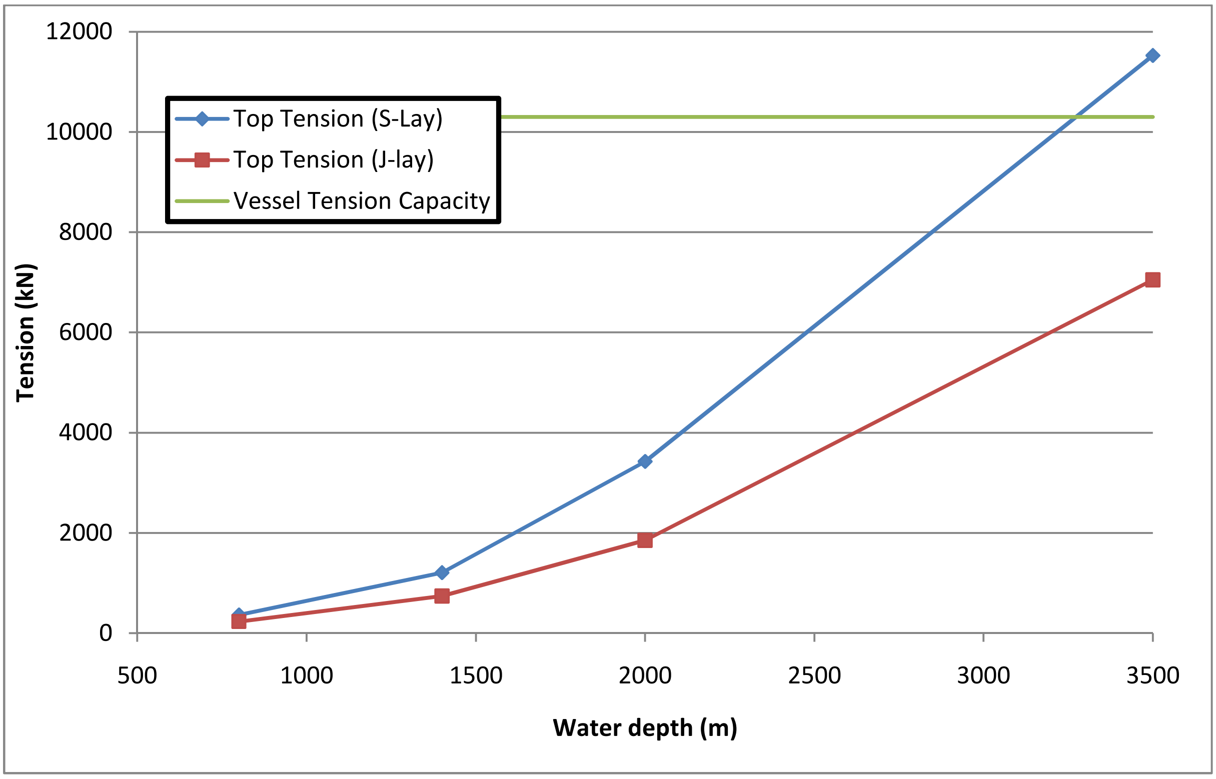


Figure 7-6 20" Pipe: Top Tension vs. Water Depth

7.4.3 28" Pipeline Results

Figure 7-7 shows the results on minimum vessel top tension requirements alongside water depth. As for the 20 inch pipeline, the 28 inch pipeline top tension requirement is increasing approximately linear from 800m to 1400m, due to small variation in wall thickness from satisfying specific weight ratio (1,1). Top tension required for the S-lay is increasing more rapid than for the previous cases, as the stinger radius has been increased from 150m to 170m to satisfy the overbend strain criteria (see APPENDIX C). From 1400m to a water depth of 2000m the top tension graph from S-lay is getting so steep that it will turn towards infinity for deeper waters. The Solitaire's top tension capacity of 1050t (~10300kN) is exceeded at approximately 1800m for S-lay (figure 7-7). For the pipeline installations with J-lay, the required tension is increasing more rapidly between 1400m and 2000m and even more between 2000m and 3500m, as the water depths and required wall thicknesses increase. The top tension of 1050t (~10300kN) at Balder, is exceeded at approximately 3000m for J-lay (figure 7-7).

Factors relevant for the LC condition evaluation is given in table 7-10:

Factor	Value				Unit
	800m	***1400m***	**2000m**	**3500m**	
p_i	0	0	0	0	kN/m^2
p_e	8044	14080	20110	35190	kN/m^2
p_c	9676	16930	24190	42330	kN/m^2
f_y	462700	462700	462700	462700	kN/m^2
f_u	542400	542400	542400	542400	kN/m^2
β	0,367	0,381	0,422	0,491	kNm
α_c	1,0632	1,0657	1,0727	1,0846	kN
D/t_2	26,7368	25,6750	22,0186	15,7694	
$M_p(t_2)$	5768,3941	5987,6486	6888,3252	9258,8044	kNm
$S_p(t_2)$	26470,8510	27521,2186	31875,5512	43668,2057	kN

Table 7-10 28” Pipe: LC Condition Parameters

Pipeline utilization factors given in table 7-11 and table 7-12 show that the LC condition criteria are satisfied at all water depths for both S- and J-lay installation, as the utilization factors are lower or equal to 1. The utilization factors are however significantly higher for the J-lay installation compared to the S-lay installation. This indicates the fact that during J-lay the sagbend is normally the area of most concern.

S-Lay Installation Analyses

The following conclusions were achieved (table 7-11):

- Top tension required for the pipeline installations at water depths of 800m and 1400m were found to be within the tension capacities of existing vessels (figure 7-7).
- Top tension was exceeding the capacity of Solitaire, with a tension capacity of 1050t (~10300kN), at approximately 1800m.
- Overbend strains were inside the criteria of 0,27% at 800m and 1400m water depth.
- Overbend strain criteria of 0,27% was exceeded at approximately 1500m (achieved by linear interpolation).
- Sagbend bending moments are inside the allowable bending moments at all water depths.
- Departure angles were between 35˚- 45˚
- Separation at last stinger roller was above the minimum criteria of 300mm for all runs.

28" S-lay Water Depth (m)	Top tension (kN)	Strain overbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable bending moment (kNm)	Pipeline Utilization	Gap last supp. (mm)	Dep. angle (deg)
800	**1047**	**0,263**	**-1270**	**3484**	**0,3645**	**395**	**43**
1400	**4180**	**0,264**	**147**	**2358**	**0,0623**	**355**	**38**
2000	**12700**	**0,293**	**108**	**1419**	**0,0761**	**333**	**37**
3500	**Not layable**						

Table 7-11 28" Pipe: S-Lay Results

Note: Strain criteria as 0,27%

J-Lay Installation Analyses

The following conclusions were achieved (table 7-12):

- Top tension required for pipeline installations at water depths of 800m, 1400m and 2000m were found to be within the tension capacity of existing vessels (figure 7-7).
- Top tension capacity of 1050t (~10300kN) at Balder was exceeded at approximately 3000m. A top tension of 1319t (~12940kN) would be required to install the pipe at 3500m water depth.
- Sagbend bending moments are inside the allowable bending moments at all water depths.
- Departure angles were between 80˚- 85˚

28" J-lay Water Depth (m)	Top tension (kN)	Strain in sagbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable bending moment (kNm)	Pipeline Utilization	Dep. angle (deg)
800	**478**	**0,150**	**2798**	**3494**	**0,8008**	**83**
1400	**1150**	**0,141**	**2450**	**2468**	**0,9927**	**83**
2000	**3131**	**0,137**	**2341**	**2356**	**0,9936**	**83**
3500	**12933**	**0,143**	**2515**	**2529**	**0,9945**	**84**

Table 7-12 28" Pipe: J-Lay Results

28" Pipeline: Top Tension for S- and J-lay

Top tensions required for the S- and J-lay are given in figure 7-7:

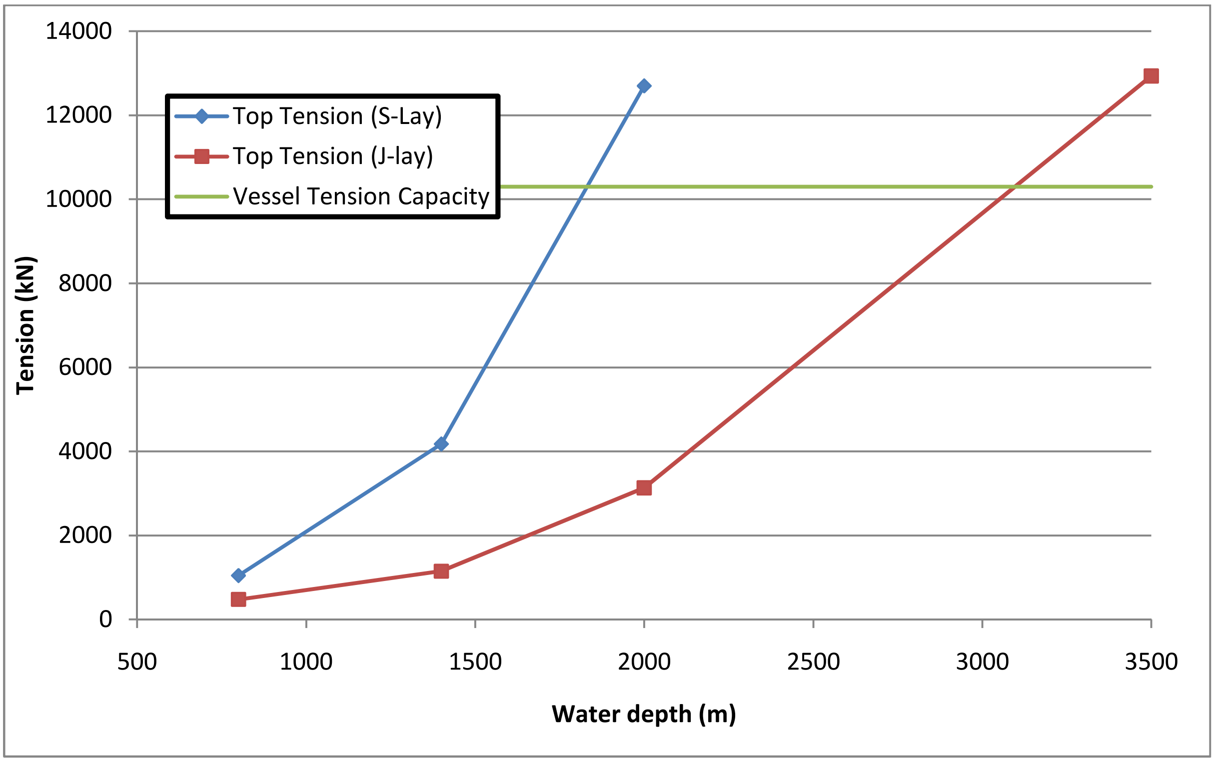


Figure 7-7 28" Pipe: Top Tension vs. Water Depth

7.4.4 Layable Water Depths

Summary of the layable water depths of pipeline installation with S- and J-lay vessels are given in table 7-13.

Pipe Diameter (inch)	S-lay	J-lay
	Water Depth (m)	
14"	2500	3500
20"	2000	3500
28"	1500	3000

Table 7-13 Layable Water Depths of Installation

7.4.5 Discussions on Results

Pipeline installations can be performed by the J-lay method, for 14- and 20 inch pipelines down to a water depth of 3500m. For the 28 inch pipeline the pipelaying was limited to 3000m for J-lay. Due to the high wall thickness and weight of the 28 inch pipe segment at 3500m water depth, the maximum tension capacities of existing vessels are exceeded. By increasing the vessels tension capacity to a minimum of 1319t (25,6% increase) from today's limit of 1050t (Balder); installations could be possible for 28 inch pipelines at 3500m water depth.

Top tension has to be kept within a minimum to avoid bending moments exceeding the allowable bending moments in the sagbend. Loss of tension can result in excessive bending, local buckling and collapse. Hence, buckle arrestors should always be installed on pipelines to reduce the potential of experience severe pipeline damages.

Pipeline installations provided by the S-lay method are not recommended at water depths of 3500m. The required tension to lay the 20- and 28 inch pipelines at this depth exceeded the vessels tension capacities. By increasing the vessels tension capacity to a minimum of 1176t (12% increase) from today's limit of 1050t for Solitaire; installation of the 20 inch pipeline at 3500m water depth would not be limited by the vessels tension capacities.

Overbend strain criteria is the main limiting factor for pipeline installations with S-lay at deep waters. The criteria of allowable strain in the overbend of 0,25% (X65) and 0,27% (X70) are exceeded for all pipe diameters at a water depth of 3500m. This may result in excessive ovalization and buckling as the pipe will experience plasticizing when going outside the elastic regime.

For installation of pipelines to a depth of 3500m, J-lay is providing the best results. Pipeline installation is only limited for the 28 inch pipe (at 3000m) due to the vessels tension capacities for this method. S-lay, on the other hand, is limited by either overbend strain criteria or both strain criteria and vessel tension capacities at this depth. J-lay installations require lower top tension from the vessels, than S-lay, for pipelaying at the same water depths. The differences in required vessel tension capacities are increasing between these two lay methods as the water gets deeper. S-lay is a more efficient installation method when it comes to lay rate than the J-lay method, and would in most cases be the chosen pipelaying method, especially for long pipelines.

7.5 Pipelay Parameter Study

For S-lay pipe installations to be achievable for intermediate and large diameter pipelines at ultra-deep waters, an increase in allowable overbend strains during laying is a potential measure. This parameter study will go into the effects this will have on the installation process.

Effects on the vessels required tension and stinger curvature (including several factors affected directly and indirectly) based on an increase in allowable overbend strains criteria from 0,25% (X65) and 0,27% (X70) to 0,35% are provided in the following.

7.5.1 14" Pipeline Results

Table 7-14 provides results of the lay analyses of the 14 inch pipeline with a 0,25% and 0,35% overbend strain requirement.

14" S-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable Bending moment (kNm)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800[1]	**101**	**2**	**0,268**	**0,157**	**367**	**384**	**71/110**	**1104**	**82**
800[2]	124	25	0,249	0,075	148	384	76/110	2064	72
1400[1]	**386**	**24**	**0,274**	**0,136**	**319**	**323**	**74/120**	**1168**	**84**
1400[2]	399	37	0,250	0,115	248	323	81/120	307	81
2000[1]	**939**	**67**	**0,314**	**0,127**	**285**	**291**	**77/120**	**438**	**84**
2000[2]	1247	375	0,249	0,090	62	288	92/120	312	71
3500[1]	**4709**	**1440**	**0,348**	**0,114**	**46**	**212**	**93/140**	**2973**	**72**
3500[2]	5869	2600	0,310	0,121	25	122	120/140	308	63

Table 7-14 14" Pipe: Effect by Increased Allowable Overbend Strains

Note:
1: Overbend strain criteria as 0,35%
2: Overbend strain criteria as 0,25%

Increasing the overbend strain criteria from 0,25% to 0,35% will have the following effect:

Results from the analyses show that the stinger radius will be reduced by:

- 6,6% at 800m water depth
- 8,6% at 1400m water depth
- 16,3% at 2000m water depth
- 22,5% at 3500m water depth

Results from the analyses show that the required vessel top tension will be reduced by:

- 18,5% at 800m water depth
- 3,3% at 1400m water depth
- 24,7% at 2000m water depth
- 19,8% at 3500m water depth

Overbend strains are inside the allowable criteria for all water depths, with exception of the 0,25% strain criteria at 3500m water depth. Sagbend bending moments and last roller separations are all within their respective allowable values.

It can be seen from table 7-14 that the increase in allowable overbend strains to 0,35% can not be fully utilized for the water depths of 800m to 2000m. This is due to the bending moments in the sagbends, which are limited by the allowable bending moments. Exceeding the allowable sagbend bending moments may cause buckling and collapse of the pipelines.

7.5.2 20" Pipeline Results

Table 7-15 provides results of the lay analyses of the 20 inch pipeline with a 0,27% and 0,35% overbend strain requirement.

20" S-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable Bending moment (kNm)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800[1]	**245**	**42**	**0,346**	**0,101**	**645**	**1223**	**78/110**	**1995**	**71**
800[2]	313	110	0,269	0,079	-533	1222	102/110	351	59
1400[1]	**807**	**142**	**0,349**	**0,100**	**551**	**982**	**84/120**	**720**	**76**
1400[2]	1205	540	0,269	0,076	162	978	110/120	306	59
2000[1]	**1919**	**242**	**0,350**	**0,117**	**681**	**956**	**92/140**	**702**	**81**
2000[2]	3126	1450	0,269	0,093	126	931	125/140	329	61
3500[1]	**11528**	**5000**	**0,363**	**0,122**	**109**	**808**	**120/140**	**302**	**64**
3500[2]	11528	5000	0,363	0,122	109	808	120/140	302	64

Table 7-15 20" Pipe: Effect by Increased Allowable Overbend Strains

Note:
1: Overbend strain criteria as 0,35%
2: Overbend strain criteria as 0,27%

Increasing the overbend strain criteria from 0,27% to 0,35% will have the following effect:

Results from the analyses show that the stinger radius will be reduced by:

- 23,5% at 800 m water depth
- 23,6% at 1400 m water depth
- 26,4% at 2000 m water depth
- 0% at 3500 m water depth, as the overbend strain is exceeding both requirements.

Results from the analyses show that the required vessel top tension will be reduced by:

- 21,7% at 800 m water depth
- 33,0% at 1400 m water depth
- 38,6% at 2000 m water depth
- 0% at 3500 m water depth, as the overbend strain is exceeding both requirements

The results presented in table 7-15 show that the overbend strains are inside the allowable criteria of 0,27% and 0,35% respectively, for all water depths with the exception of 3500m. The overbend strain of 0,36% at this depth is however close to the overbend strain criteria of 0,35%. Sagbend bending moments and separation at the last rollers are all satisfying the criteria necessary for installation.

7.5.3 28" Pipeline Results

Table 7-16 provides results of the lay analyses of the 28 inch pipeline with a 0,27% and 0,35% overbend strain requirement.

28" S-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Sagbend: Bending moment (kNm)	Sagbend: Allowable Bending moment (kNm)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800[1]	**587**	**190**	**0,349**	**0,122**	**-2296**	**3492**	**114/120**	**303**	**58**
800[2]	972	575	0,270	0,082	-1450	3485	147/120	307	44
1400[1]	**2101**	**1120**	**0,350**	**0,079**	**419**	**2455**	**122/120**	**376**	**53**
1400[2]	3730	2750	0,270	0,080	172	2387	162/120	318	40
2000[1]	**5707**	**3005**	**0,350**	**0,099**	**358**	**2272**	**136/140**	**302**	**56**
2000[2]	12700	10000	0,293	0,117	108	1419	200/140	333	37
3500	**Not layable**								
3500									

Table 7-16 28" Pipe: Effect by Increased Allowable Overbend Strains

Note:
1: Overbend strain criteria as 0,35%
2: Overbend strain criteria as 0,27%

Increasing the overbend strain criteria from 0,27% to 0,35% will have the following effect:

Results from the analyses show that the stinger radius will be reduced by:

- 22,4% at 800 m water depth
- 24,7% at 1400 m water depth
- 32% at 2000 m water depth

Results from the analyses show that the required vessel top tension will be reduced by:

- 39,6% at 800 m water depth
- 43,7% at 1400 m water depth
- 55,1% at 2000 m water depth

Pipeline overbend strains are satisfying the criteria given at all water depths, except for the overbend strain criteria of 0,27% at 2000m. Separations from the last roller, as well as sagbend bending moments are all within their respective criteria.

7.5.4 Evaluations of Results

Results from the parameter study presented in table 7-14, table 7-15 and table 7-16 indicate that an increase in allowable overbend strain criteria has the following effects on the S-lay installation process:

Stinger radius

Results and calculations show that the stinger radius can be reduced for increased overbend strain criteria and the reduction in stinger radius is increasing with water depth. Stinger radius is changing directly from the variations in allowable overbend strains. Stinger geometry controls the pipeline strains in this region, and by decreasing the stinger radius a higher bending strain will occur.

Top tension

Vessel top tensions required can be decreased with increased allowable overbend strains, and the reduction is increasing with water depth. The top tension is changing as an indirect effect of the change in allowable overbend strains. The stinger radius is reduced to enhance the layability in deep waters, and will hence reduce the need of tension during the process. This can be compared to the J-lay configuration, where a steep liftoff angle when installing a pipe will require less tension than the S-lay method. Vessel tension capacity is a critical factor during deep water pipeline installations with S-lay, where heavy pipelines are unlayable or dependent on a specific installation vessel. Hence, a lower required tension will be positive for both layability and costs.

Residual tension

Results indicate that residual tensions will be reduced as an indirect effect of higher allowable overbend strains. As lower top tension is required as a function of a reduction in stinger radius, the residual tension remaining in the pipe at the seabed will be reduced. What can be seen is that the residual tension in the pipes will be relatively lower compared to the top tension for installations with larger stinger departure angles. Given that a high bottom tension will result in larger and more frequent free spans, a low residual tension is beneficial as it limits the required interventions to the seabed where free spans occur.

Sagbend bending moment

Bending moments in the sagbend are increased for higher allowable overbend strains. This is an indirect effect from the changes in overbend strains, and a direct reaction from the reduction in tension. Lowering the tension will leave the touchdown point closer to the vessel and hence increase the bending in the sagbend region as the pipe is interaction with the seabed in an angle more perpendicular to the touchdown point. A lower stinger radius which increases the liftoff angle, is also contributing to this effect. This is together with the reduced tension the reasons for increased bending moments where a higher overbend strain is allowed.

Departure angle

Liftoff angles are increased for higher allowable overbend strains, as seen from table 7-14, table 7-15 and table 7-16. Stinger radius reduction, as a function of increased allowable strains, is a factor directly affecting the angle in which the pipe leaves the stinger. The reduction in tension is also contributing to increasing the pipe angle of departure from the stinger. Steep liftoff angles give the pipe a configuration closer to J-lay.

7.5.5 Summary

The following is based on the parameter study:

Overbend strain is highly dependent on stinger curvature. When the stinger radius is decreased, the pipeline will experience a higher bending strain in this region.

Required tension during installation is dependent on stinger curvature. The required vessel tension is decreasing as a function of reduction in stinger radius. This can be explained by a lower stinger reaction force when the stinger radius is reduced (see section 6.7).

Increasing the allowed overbend strains has a higher effect on stinger radius reduction, and hence tension required during pipeline installations, for deeper waters.

Vessels installing large diameter pipelines are more affected by changes in overbend strain criteria, in terms of reduction in stinger radius and required tension, than vessels installing smaller diameter pipelines.

Pipeline liftoff angle from the stinger is increased due to reduced stinger radius and tension.

Sagbend bending moments are increasing due to reduction in tension, which is an effect of a decrease in stinger radius.

Residual tension in the pipeline decrease at a higher rate for larger liftoff angles from the stinger. As residual tension should be kept low, a large liftoff angle is beneficial as a higher percentage of the top tension will be removed during the installation phase.

CHAPTER 8 CONCLUSIONS AND FURTHER STUDIES

8.1 Conclusions

- Several challenges for deeper waters, which are more critical than for shallower waters, affect the design and installation of deep water pipelines. In particular the high external pressures are posing severe threats of local and propagating buckling of the pipelines. Vessels able to install ultra-deep water pipelines are limited, and buckling due to excessive overbend strains and sagbend moments during S- and J-lay, respectively, are potential problems.

- Single steel pipelines are the most beneficial pipeline concept for large diameter pipes to be installed in ultra-deep waters, here limited to 3500m. Compared to Pipe-in-Pipe solutions and Sandwich pipe systems, the single steel pipes have advantages with respect to costs and weight, in addition to being a structurally simple and a well known concept for deep water projects.

- Applying external insulation coatings with low thermal conductivity will have a significant reduction in required insulation coating thickness for deep water pipelines. To satisfy a U-value of $5W/m^2K$, the decrease in insulation coating thicknesses is between 75% and 80% by changing the thermal conductivity from 0,16W/mK to 0,04W/mK. The lower the thermal conductivity of the insulation coating is, the higher the percentage reduction in insulation coating thickness will be. Applying coatings with low thermal conductivity has a relatively higher effect for smaller diameter pipelines than for larger pipelines.

- Use of higher steel grades than X65, such as X70 and X80, has a significant effect on the required wall thicknesses to avoid collapse for deep water pipelines. The effect on wall thickness reductions is higher with increasing depths. This is shown by a wall thickness reduction of approximately 12% for pipelines at 3500m, compared to approximately 1,5% reduction at 800m water depth, when changing the steel grade from X65 to X80.

- By decreasing the allowable pipeline ovality from 3,0% to 0,5% the pipe wall thicknesses can be reduced in the range of 17% at 3500m water depth. This is however problematic due to the high external pressure and bending during installation in deep waters. As the lay process would result in further ovalitization of the pipe due to bending, this could cause collapse of the pipelines.

- Pipeline installation with J-lay requires a significantly lower tension than S-lay to successfully install pipes at deep- and ultra-deep waters. The difference in required tension is higher with increased water depths and -pipeline diameters.

- Pipelines with diameters of 14- and 20 inches are installable with existing J-lay vessels in water depths of 3500m. A 28 inch pipeline is layable in 3000m water depth, and 3500m would be applicable with vessel tension capacities of approximately 1320t.

- Pipeline installations with S-lay is limited to 2500m, 2000m and 1500m for 14 inch, 20 inch and 28 inch pipes, respectively, either due to exceedance of the overbend strain criteria or as a combination with exceeding the vessel tension capacity.

- Increased allowable overbend strains will allow for deeper pipeline installations with S-lay. This is due to reduction in stinger radius and tension, which is increasing with water depths.

- The overbend strain is highly dependent on the stinger curvature. When the stinger radius is decreased, the pipeline will experience a higher bending strain in this region. Reduction in stinger radius will increase the pipe liftoff angle, hence resulting in a steeper lay which require less tension from the vessels.

- Sagbend bending moments are increasing as a function of a reduction in tension. This effect is enhanced with a reduction in stinger radius and hence larger liftoff angels.

- An indicated radius reduction of approximately 20%-30% is achieved by increasing the allowable overbend strain criteria from 0,25% (X65) and 0,27% (X70) to 0,35% for water depths from 800m to 2000m. The reductions in stinger radius are higher for deeper waters and increased pipe diameters. Vessel tensions required during pipelay are reduced with approximately 20%-55% for the same water depths, and the effects are increasing with higher water depths and larger pipe diameters.

- The residual tension left in the pipeline at the seabed is a smaller fraction of the top tension, added at the vessel, when pipeline departure angles from the stinger increases.

8.2 Further Studies

- The effect on wall thickness requirements by use of higher steel grades should be studied for the cases of combined loading i.e. combination of bending and external pressure, as this may limit the reductions in wall thicknesses for deeper waters. For this thesis the wall thickness calculations are based on external pressure only, while checks have been made of the bending moments during the laying operation (load controlled condition criteria).

- In order to increase the confidence on the layability of the pipelines studied, dynamic analyses should be performed in addition to static analyses for the installation processes. As a required minimum distance of 300mm between the pipe and last stinger roller are assumed in this thesis, it is recommended to study if this is sufficient to avoid critical contact in normal laying conditions.

- As this thesis indicate beneficial effects with respect to the acceptable installation depth by allowing increased overbend strain criteria, further studies should be made on the effects plastic strains in the overbend will have on the pipeline properties and installation process. Particularly the effect on pipe rotation during installation would require investigations.

- Investigations should be done on ultra-deep water pipe layability for vessels with Steep S-lay configurations to study the effect this will have on the possible water depths of pipe installation and on the installation process itself. This study should also include the possibilities of stinger length reduction.

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APPENDIX A INSULATION COATING DESIGN CALCULATIONS

Pipeline: 14" @ 800m

Calculation of Insulation Coating Requirements based on U=5 W/(m^2/K)

Calculation Input

Outer Diameter of Steel Pipeline (mm)	$D_s := 355.6$
Pipe Wall Thickness (mm)	$t_s := 13.3$
Ext. Coat (FBE) Thickness (mm)	$t_e := 0.3$
Adhesive + solid PP (mm)	$t_a := 2.7$
Insulation Coat Thickness (mm)	$t_i := 34$
Shield Coat Thickness (mm)	$t_c := 3$
Burial Depth to TOP (m)	$bu\_dth := 0$
Steel Thermal Conductivity (W/mK)	$k_s := 45$
External Coat Thermal Conductivity (W/mK)	$k_e := 0.301$
Adhesive + Solid PP Thermal Conductivity (W/mK)	$k_a := 0.221$
Insulation Coat Thermal Conductivity (W/mK)	$k_i := 0.148$
Shield Thermal Conductivity (W/mK)	$k_c := 0.206$
Soil Thermal Conductivity (W/mK)	$k_{soil} := 2.2$

Options

Pipeline Type:-

1 - Exposed
2 - Buried

$pipeline\_type := 1$

Calculation

$$D_i := \frac{D_s - 2\cdot t_s - 2t_e - 2t_a - 2t_i - 2t_c}{1000}$$ Pipe Internal Diameter (m) $D_i = 0.249$

$$D_1 := \frac{D_s - 2t_e - 2t_a - 2t_i - 2t_c}{1000}$$ Steel External Diameter (m) $D_1 = 0.276$

$$D_2 := D_i + \frac{2t_s + 2\cdot t_e}{1000}$$ Pipe Coating External Diameter (m) $D_2 = 0.2762$

$$D_3 := D_i + \frac{2t_s + 2\cdot t_e + 2\cdot t_a}{1000}$$ Adhesive /Solid External Diameter (m) $D_3 = 0.2816$

$$D_4 := D_i + \frac{2t_s + 2\cdot t_e + 2\cdot t_a + 2\cdot t_i}{1000}$$ Insulation External Diameter (m) $D_4 = 0.3496$

$$D_o := D_i + \frac{2t_s + 2\cdot t_e + 2\cdot t_a + 2\cdot t_i + 2\cdot t_c}{1000}$$ Overall Pipe External Diameter (m) $D_o = 0.3556$

$$b\_dth := bu\_dth + \frac{D_i}{2} + \frac{2\cdot t_s + 2\cdot t_e + 2\cdot t_i + 2\cdot t_c}{2\cdot 1000}$$ Burial Depth to Pipe Centre (m) $b\_dth = 0.175$

$$buried := \frac{D_o\cdot \ln\left[\frac{2\cdot b\_dth}{D_o} + \sqrt{\left(\frac{2\cdot b\_dth}{D_o}\right)^2 - 1}\right]}{2\cdot k_{soil}}$$

$$\mu := \left(\frac{D_o\cdot \ln\left(\frac{D_1}{D_i}\right)}{2\cdot k_s} + \frac{D_o\cdot \ln\left(\frac{D_2}{D_1}\right)}{2\cdot k_e} + \frac{D_o\cdot \ln\left(\frac{D_3}{D_2}\right)}{2\cdot k_a} + \frac{D_o\cdot \ln\left(\frac{D_4}{D_3}\right)}{2\cdot k_i} + \frac{D_o\cdot \ln\left(\frac{D_o}{D_4}\right)}{2\cdot k_c} + \mathrm{if}(pipeline\_type = 2, buried, 0)\right)^{-1}$$

Overall Heat Transfer Coefficient (based on OD of coating) $\mu = 3.4269$

Overall Heat Transfer Coefficient (based on ID of pipe) $U := \mu\cdot\frac{D_o}{D_i}\cdot 1$

$U = 4.894$

Total Coating Thickness (mm) $t := t_e + t_a + t_i + t_c$ $t = 40$

APPENDIX B WALL THICKNESS CALCULATIONS

Wall thickness calculations are done in Mathcad. These examples are given for the 14 inch outer diameter pipeline at 3500m, based on system collapse check and propagation buckling check respectively, from DNV-OS-F101 (2007).

System collapse check:

Steel quality	X65	
Outer diameter	$D := 355.6\ \text{mm}$	
Wall thickness	t	
Fabrication allowance	$t_{fab} := 1\text{mm}$	
Characteristic w.t.	$t_1 = t - t_{fab}$ $t_2 = t$	
Elasticity modulus	$E := 207000\ \text{MPa}$	
Yield stress	$SMYS := 448\text{MPa}$	
Material strength factor	$\alpha_u := 0.96$	
Fabrication factor	$\alpha_{fab} := 0.85$	
Derating on yield stress	f_{ytemp}	$f_{ytemp} := 0\text{Pa}$
Characteristic material strength	$f_y := \left(SMYS - f_{ytemp}\right)\cdot\alpha_u$	$f_y = 4.301\times 10^8\ \text{Pa}$
Poisson ratio	$\upsilon := 0.3$	
Gravity constant	$g := 9.81\dfrac{m}{s^2}$	
Water density	$\rho_w := 1025\dfrac{kg}{m^3}$	
Water depth	$h := 3500\text{m}$	
External pressure	$p_e := \rho_w\cdot g\cdot h$	$p_e = 3.519\times 10^7\ \text{Pa}$
Min. internal pressure	$p_{min} := 0\text{MPa}$	
Out – of – roundness	$f_o := 0.015$	
Material resistance factor	$\gamma_m := 1.15$	
Safety class resistance factor	$\gamma_{sc} := 1.046$	
Design factor (functional load effect factor- system check)	$\gamma_F := 1.2$	

Local buckling: Collapse due to external pressure

Elastic collapse pressure $$p_{el}(D,t) := 2 \cdot E \cdot \left(\frac{t - t_{fab}}{D}\right)^3$$

Plastic collapse pressure $$p_p(fy, \alpha_{fab}, D, t) := fy \cdot \alpha_{fab} \cdot \frac{2(t - t_{fab})}{D}$$

Characteristic resistance $$(p_c - p_{el}) \cdot \left(p_c^{\ 2} - p_p^{\ 2}\right) = p_c \cdot p_{el} \cdot p_p \cdot f_0 \cdot \frac{D}{t - t_{fab}}$$

Characteristic collapse pressure $$p_c := (p_e - p_{min}) \cdot (\gamma_m \cdot \gamma_{sc})$$

$$p_c = 4.233 \times 10^7 \text{ Pa}$$

System collapse check $$pe - pmin \le \frac{pc(t - t_{fab})}{\gamma m \cdot \gamma sc}$$

$$p_e - p_{min} = 3.519 \times 10^7 \text{ Pa}$$

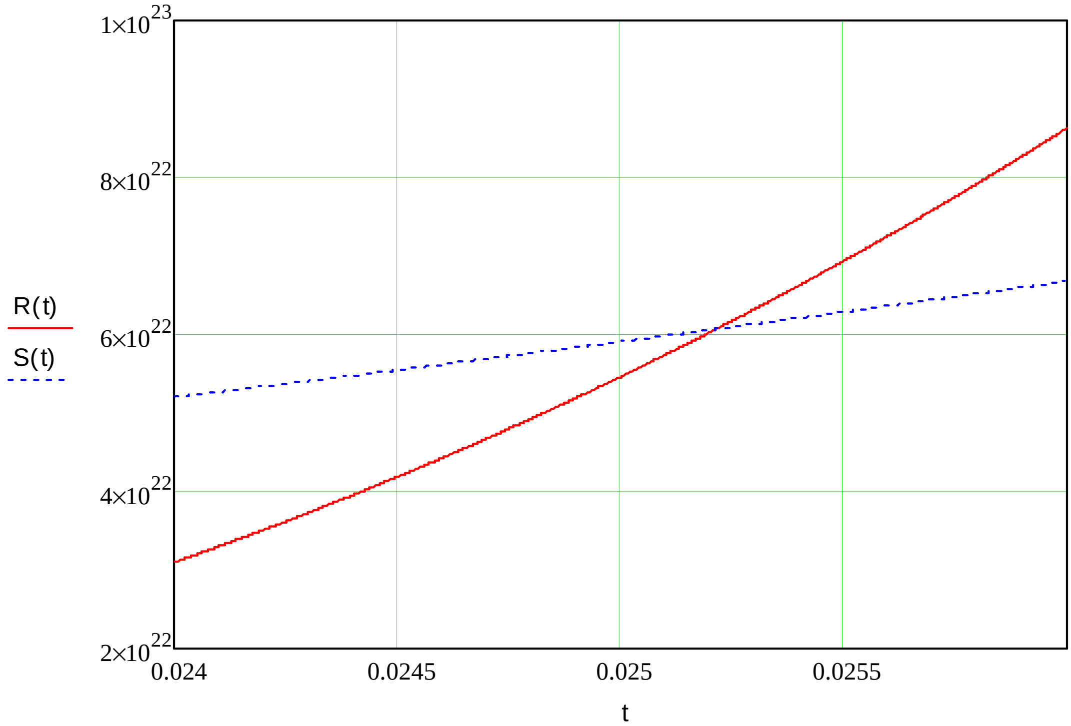
$$\frac{p_c}{\gamma_m \cdot \gamma_{sc}} = 3.519 \times 10^7 \text{ Pa}$$

Utility ratio $$U := \frac{p_e - p_{min}}{\left(\frac{p_c}{\gamma_m \cdot \gamma_{sc}}\right)}$$

$$U = 1$$

$$R(t) := (p_c - p_{el}(D,t)) \cdot \left(p_c^{\ 2} - p_p(f_y, \alpha_{fab}, D, t)^2\right)$$

$$S(t) := p_c \cdot p_{el}(D,t) \cdot p_p(f_y, \alpha_{fab}, D, t) \cdot f_o \cdot \frac{D}{t - t_{fab}}$$



Wall thickness $t = 0.02522\,\mathrm{m} = 25.3\,\mathrm{mm}$

Propagation buckling check:

Steel quality	X65	
Outer diameter	$D := 355.6mm$	
Wall thickness	t	
Fabrication allowance	$t_{fab} := 1mm$	
Characteristic w.t.	$t_1(t) := t - t_{fab}$ $t_2(t) := t$	
Elasticity modulus	$E := 207000MPa$	
Yield stress	$SMYS := 448MPa$	
Material strength factor	$\alpha_u := 0.96$	
Fabrication factor	$\alpha_{fab} := 0.85$	
Derating on yield stress	f_{ytemp}	$f_{ytemp} := 0Pa$
Characteristic material strength	$f_y := (SMYS - f_{ytemp}) \cdot \alpha_u$	$f_y = 4.301 \times 10^8 Pa$
Poisson ratio	$\upsilon := 0.3$	
Gravity constant	$g := 9.81 \frac{m}{s^2}$	
Water density	$\rho_w := 1025 \frac{kg}{m^3}$	
Water depth	$h := 3500\ m$	
External pressure	$p_e := \rho_w \cdot g \cdot h$	$p_e = 3.519 \times 10^7 Pa$
Min. internal pressure	$p_{min} := 0MPa$	
$Out - of - roundness$	$f_o := 0.015$	
Material resistance factor	$\gamma_m := 1.15$	
Safety class resistance factor	$\gamma_{sc} := 1.046$	
Design factor (functional load effect factor- system check)	$\gamma_F := 1.2$	

Propagating pressure

$$p_{pr}(t) := 35 \cdot f_y \cdot \alpha_{fab} \cdot \left(\frac{t_2(t)}{D}\right)^{2.5}$$

$$p_{pr} := p_e \cdot (\gamma_m \cdot \gamma_{sc})$$

$$p_{pr} = 4.233 \times 10^7\ \text{Pa}$$

Diameter - wall thickness -ratio

$$\frac{D}{t} < 45$$

Propagation buckle check

$$pe < \frac{p_{pr}}{\gamma_m \cdot \gamma_{sc}}$$

$$p_e = 3.519 \times 10^7\ \text{Pa}$$

$$\frac{p_{pr}}{\gamma_m \cdot \gamma_{sc}} = 3.519 \times 10^7\ \text{Pa}$$

Utility ratio

$$U := \frac{p_e}{\left(\frac{p_{pr}}{\gamma_m \cdot \gamma_{sc}}\right)}$$

$$U = 1$$

Wall thickness:

$$t := \left[\sqrt[5]{\left(\frac{p_{pr}}{35 \cdot f_y \cdot \alpha_{fab}}\right)}\right]^2 \cdot D$$

$$t = 0.0362\text{m}$$

APPENDIX C STATIC PIPELAY ANALYSES RESULTS

OFFPIPE Results for the Layability Study

Pipelay analyses results for 14 inch pipeline:

14” S-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800	194	95	0,181	0,049	110/110	327	54
1400	692	330	0,199	0,072	110/120	309	59
2000	1746	875	0,234	0,091	110/120	333	59
3500	5869	2600	0,310	0,121	120/140	308	63

Table C-1 14” Pipe: OFFPIPE Layability Results for S-Lay

14” J-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800	111	3	-	0,150	-	-	88
1400	396	24	-	0,136	-	-	86
2000	949	67	-	0,127	-	-	86
3500	3585	300	-	0,122	-	-	85

Table C-2 14” Pipe: OFFPIPE Layability Results for J-Lay

Pipelay analyses results for 20 inch pipeline:

20” S-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800	363	160	0,249	0,068	110/110	333	54
1400	1205	540	0,269	0,076	110/120	306	59
2000	3426	1750	0,269	0,093	130/140	381	58
3500	11528	5000	0,363	0,122	120/140	302	64

Table C-3 20” Pipe: OFFPIPE Layability Results for S-Lay

20” J-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800	233	14	-	0,149	-	-	86
1400	743	60	-	0,144	-	-	85
2000	1853	155	-	0,139	-	-	85
3500	7050	490	-	0,140	-	-	86

Table C-4 20” Pipe: OFFPIPE Layability Results for J-Lay

Pipelay analyses results for 28 inch pipeline:

28" S-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800	1047	650	0,263	0,073	150/120	395	43
1400	4180	3200	0,264	0,081	170/120	355	38
2000	12700	10000	0,293	0,117	200/140	333	37
3500	Not layable						

Table C-5 28" Pipe: OFFPIPE Layability Results for S-Lay

28" J-lay Water Depth (m)	Top tension (kN)	Residual tension (kN)	Strain overbend (%)	Strain in sagbend (%)	Stinger Radius/ Length	Gap last supp. (mm)	Dep. angle (deg)
800	478	48	-	0,150	-	-	83
1400	1150	135	-	0,141	-	-	83
2000	3131	390	-	0,137	-	-	83
3500	12933	1320	-	0,143	-	-	84

Table C-6 28" Pipe: OFFPIPE Layability Results for J-Lay

APPENDIX D MOMENT CURVATURE

Material and pipe properties are used to obtain Ramberg- Osgood coefficient *A* and -exponent *B*, and moment-curvature.

A Ramberg-Osgood equation coefficient

B Ramberg-Osgood equation exponent

This example is given for the 20 inch outer diameter pipeline at 2000m water depth (figure D-1).

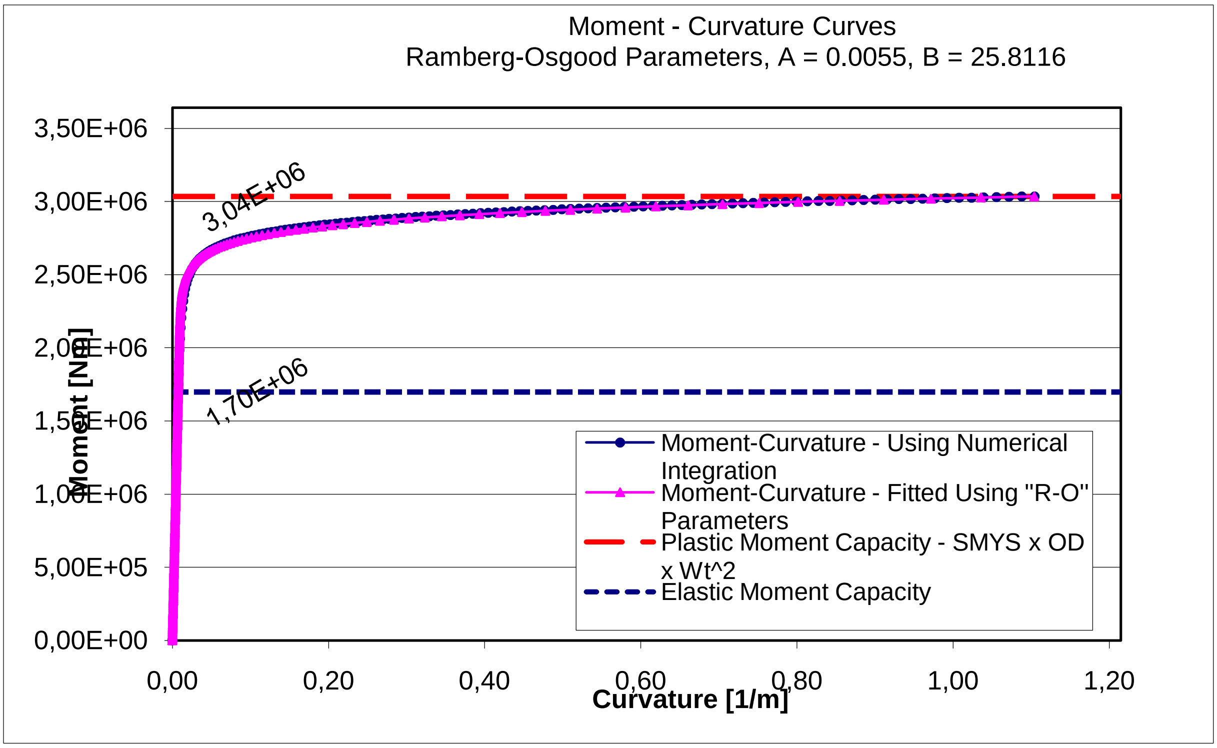


Figure D-1 Moment Curvature for 20” Pipe at 2000m

APPENDIX E OFFPIPE PROGRAM FILES

Static analysis results provided by OFFPIPE are presented in the following.

This example is given for the 20 inch outer diameter pipeline at 2000m water depth installed by S-lay:

```
     MMMMMMM        MMMMMMMMMMMM    MMMMMMMMMMMM    MMMMMMMMMM      MMMMMMMMM    MMMMMMMMMM       MMMMMMMMMMMM
   MMMMMMMMMMM      MMMMMMMMMMMM    MMMMMMMMMMMM    MMMMMMMMMMMM    MMMMMMMMM    MMMMMMMMMMMM     MMMMMMMMMMMM
  MMM       MMM     MMM             MMM             MMM      MMMM      MMM       MMM      MMMM    MMM
 MMM         MMM    MMM             MMM             MMM       MMM      MMM       MMM       MMM    MMM
 MMM         MMM    MMM             MMM             MMM      MMMM      MMM       MMM      MMMM    MMM
 MMM         MMM    MMMMMMMMMM      MMMMMMMMMM      MMMMMMMMMMMM       MMM       MMMMMMMMMMMM     MMMMMMMMMM
 MMM         MMM    MMMMMMMMMM      MMMMMMMMMM      MMMMMMMMMM         MMM       MMMMMMMMMM       MMMMMMMMMM
 MMM         MMM    MMM             MMM             MMM                MMM       MMM              MMM
 MMM         MMM    MMM             MMM             MMM                MMM       MMM              MMM
  MMM       MMM     MMM             MMM             MMM                MMM       MMM              MMM
   MMMMMMMMMMM      MMM             MMM             MMM             MMMMMMMMM    MMM              MMMMMMMMMMMM
     MMMMMMM        MMM             MMM             MMM             MMMMMMMMM    MMM              MMMMMMMMMMMM
```



```
                       I N P U T   D A T A   E C H O


PIPE PROPERTIES
===============
   PROPERTY TABLE ROW INDEX ..........         1
   PIPE STRING LENGTH ................      .000 M
   STEEL MODULUS OF ELASTICITY .......   207000. MPA
   STEEL CROSS SECTIONAL AREA ........      .000 CM**2
   COATED PIPE AVG MOMENT OF INERTIA .       .00 CM**4
   WEIGHT PER-UNIT-LENGTH IN AIR .....       .00 N/M
   WEIGHT PER-UNIT-LENGTH SUBMERGED ..    816.34 N/M
   MAXIMUM ALLOWABLE PIPE STRAIN .....   .270000 PCT

   STEEL OUTSIDE DIAMETER ............   50.8000 CM
   STEEL WALL THICKNESS ..............    2.4400 CM
   YIELD STRESS ......................    482.00 MPA
   STRESS/STRAIN INTENSE FACTOR ......     .0000
   HYDRODYNAMIC OUTSIDE DIAMETER .....      .000 CM
   DRAG COEFFICIENT ..................     .0000
   HYDRODYNAMIC TOTAL AREA ...........      .000 CM**2
   ADDED MASS COEFFICIENT ............     .0000
   POISSON'S RATIO ...................     .3000
   COEFFICIENT OF THERMAL EXPANSION .. .00000000 1/DEG C

PIPE COATING PROPERTIES
=======================
   PIPE PROPERTY TABLE INDEX .........         1
```

```
   CORROSION COATING THICKNESS .......      .000 CM
   CONCRETE COATING THICKNESS ........      .000 CM
   STEEL WEIGHT DENSITY .............         0. N/M**3
   CORROSION COATING WEIGHT DENSITY ..        0. N/M**3
   CONCRETE COATING WEIGHT DENSITY ...        0. N/M**3
   DESIRED PIPE SPECIFIC GRAVITY .....     .0000

   AVERAGE PIPE JOINT LENGTH .........      .000 M
   FIELD JOINT LENGTH ...............       .000 M
   JOINT FILL WEIGHT DENSITY .........        0. N/M**3
   DENSITY OF PIPE CONTENTS ..........        0. N/M**3

MOMENT-CURVATURE COEFFICIENTS
=============================
   PIPE PROPERTY TABLE INDEX .........         1
   FORM OF EQUATION USED ............SPECIFIED COEFFICIENT AND EXPONENT
   RAMBERG-OSGOOD COEFFICIENT ........ .00550000
   RAMBERG-OSGOOD EXPONENT ...........    25.812
   PIPE YIELD STRENGTH RATIO .........      .000
   DIMENSIONLESS CURVATURE AT POINT 1      .0000
   DIMENSIONLESS MOMENT AT POINT 1 ...     .0000
   DIMENSIONLESS CURVATURE AT POINT 2      .0000
   DIMENSIONLESS MOMENT AT POINT 2 ...     .0000
```



```
                       I N P U T   D A T A   E C H O


PIPE TENSION
============
   STATIC PIPE TENSION ON LAYBARGE ...      .000 KN
   MINIMUM DYNAMIC PIPE TENSION ......      .000 KN
   MAXIMUM DYNAMIC PIPE TENSION ......      .000 KN
   STATIC HORIZONTAL BOTTOM TENSION ..  1750.000 KN

LAYBARGE DESCRIPTION
====================
   NUMBER OF PIPE NODES .............        10
   BARGE GEOMETRY SPECIFIED BY .......        2 RADIUS AND TANGENT POINT
   OVERBEND PIPE SUPPORT RADIUS ......   380.000 M
   TANGENT POINT X-COORDINATE ........    15.000 M
   TANGENT POINT Y-COORDINATE ........      .500 M
   PIPE ANGLE RELATIVE TO DECK .......     .0000 DEG
   HEIGHT OF DECK ABOVE WATER ........    15.000 M
   LAYBARGE FORWARD (X) OFFSET .......      .000 M
   BARGE TRIM ANGLE ................       .0000 DEG

   STERN SHOE X COORDINATE ..........       .000 M
   STERN SHOE Y COORDINATE ...........      .000 M
   ROTATION CENTER X COORDINATE ......      .000 M
   ROTATION CENTER Y COORDINATE ......      .000 M
   ROTATION CENTER Z COORDINATE ......      .000 M
   BARGE HEADING ....................      .0000 DEG
   BARGE OFFSET FROM RIGHT-OF-WAY ....      .000 M
   PIPE RAMP PIVOT X COORDINATE ......      .000 M
   PIPE RAMP PIVOT Y COORDINATE ......      .000 M
   PIPE RAMP PIVOT ROTATION ANGLE ....      .000 DEG

    NODE X     NODE Y          SUPPORT          DAVIT
     COORD      COORD            TYPE          SPACING
    (M   )     (M   )                           (M   )
   ========   ========   ====================   =======
     89.350       .000     1  SIMPLE SUPPORT       .000
     76.777       .000     1  SIMPLE SUPPORT       .000
     70.650       .000     2  PIPE TENSIONER       .000
     63.000       .000     1  SIMPLE SUPPORT       .000
     51.055       .000     1  SIMPLE SUPPORT       .000
     40.888       .000     1  SIMPLE SUPPORT       .000
     31.252       .000     1  SIMPLE SUPPORT       .000
     25.727       .000     2  PIPE TENSIONER       .000
     16.377       .000     2  PIPE TENSIONER       .000
      3.300       .000     1  SIMPLE SUPPORT       .000
```



```
                       I N P U T   D A T A   E C H O


STINGER DESCRIPTION
===================
   NUMBER OF PIPE/STINGER NODES ......        14
```

```
   STINGER GEOMETRY SPECIFIED BY .....         3 RADIUS AND TANGENT POINT
   STINGER TYPE .....................          1 FIXED GEOMETRY OR RAMP
   OVERBEND PIPE SUPPORT RADIUS ......    130.00 M
   HITCH X-COORDINATE ...............       .000 M
   HITCH Y-COORDINATE ...............       .000 M

   X COORDINATE OF LOCAL ORIGIN ......      .000 M
   Y COORDINATE OF LOCAL ORIGIN ......      .000 M
   ROTATION ABOUT STINGER HITCH ......      .000 DEG
   TANGENT POINT X-COORDINATE ........      .000 M
   TANGENT POINT Y-COORDINATE ........      .000 M
   TANGENT POINT ANGLE ..............       .000 DEG
```

NODE X COORD (M)	NODE Y COORD (M)	SUPPORT TYPE	ELEMENT TYPE	ELEMENT LENGTH (M)
.000	.000	1 SIMPLE SUPPORT	0 HINGED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000
.000	.000	1 SIMPLE SUPPORT	0 FIXED END	10.000

I N P U T   D A T A   E C H O

```
SUPPORT ELEMENT PROPERTIES
==========================
   SUPPORT PROPERTY TABLE INDEX ......           1
   SUPPORT ELEMENT TYPE .............            1 SIMPLE SUPPORT
   TENSIONER AXIAL STIFFNESS (F/L) ...  0.000E+00 KN/M
   VERTICAL STIFFNESS (F/L) .........   0.000E+00 KN/M
   STATIC VERTICAL DEFLECTION ........      .0000 CM
   LATERAL STIFFNESS (F/L) ..........   0.000E+00 KN/M
   BOTTOM ROLLER ANGLE TO HORIZONTAL .       .000 DEG

   SIDE ROLLER ANGLE TO VERTICAL .....       .000 DEG
   SIDE ROLLER OFFSET FROM C.L. ......       .000 M
   BED ROLLER LENGTH ................       4.000 M
   HEIGHT OF TOP ROLLER ABOVE BED ....       .000 M
   TENSIONER X-AXIS ROTATIONAL STIF. .       .000 KN/DEG
   TENSIONER Y-AXIS ROTATIONAL STIF. .       .000 KN/DEG
   TENSIONER Y-AXIS ROTATIONAL STIF. .       .000 KN/DEG

SUPPORT ELEMENT PROPERTIES
==========================
   SUPPORT PROPERTY TABLE INDEX ......           2
   SUPPORT ELEMENT TYPE .............            2 TENSIONER
   TENSIONER AXIAL STIFFNESS (F/L) ...  0.000E+00 KN/M
   VERTICAL STIFFNESS (F/L) .........   0.000E+00 KN/M
   STATIC VERTICAL DEFLECTION ........      .0000 CM
   LATERAL STIFFNESS (F/L) ..........   0.000E+00 KN/M
   BOTTOM ROLLER ANGLE TO HORIZONTAL .       .000 DEG

   SIDE ROLLER ANGLE TO VERTICAL .....       .000 DEG
   SIDE ROLLER OFFSET FROM C.L. ......       .000 M
   BED ROLLER LENGTH ................       7.000 M
   HEIGHT OF TOP ROLLER ABOVE BED ....       .000 M
   TENSIONER X-AXIS ROTATIONAL STIF. .       .000 KN/DEG
   TENSIONER Y-AXIS ROTATIONAL STIF. .       .000 KN/DEG
   TENSIONER Y-AXIS ROTATIONAL STIF. .       .000 KN/DEG
```


I N P U T   D A T A   E C H O

```
SAGBEND GEOMETRY
================
   SAGBEND PIPE ELEMENT LENGTH .......    10.000 M
   WATER DEPTH ......................   2000.00 M
```

```
   X-COORDINATE AT SPECIFIED DEPTH . .       .00 M
   ESTIMATED SAGBEND X LENGTH ........       .00 M
   ESTIMATED PIPE LENGTH ON SEABED ...       .00 M
   X-COORD OF PIPE FREE END ON SEABED        .00 M
   X-COORD POINT OF FIXITY ON SEABED .       .00 M
   MAXIMUM SLOPE (ANGLE) OF SEABED ...      .000 DEG
   DIRECTION OF MAXIMUM SLOPE ........      .000 DEG

   PIPE/CABLE SPAN END CONDITION .....PIPE/CABLE RESTING ON SEABED
   PIPE/CABLE SPAN LENGTH GIVEN BY ...SPECIFIED PIPE/CABLE TENSION
   ESTIMATED SPAN DEPTH AT FREE END ..       .00 M
   PIPE VERTICAL ANGLE AT FREE END ...      .000 DEG

SOIL ELEMENT PROPERTIES
=======================
   VERTICAL STIFFNESS ................         .00 KN/M**2
   DEFLECTION UNDER REFERENCE LOAD ...       .0000 CM
   LATERAL STIFFNESS .................         .00 KN/M**2
   SOIL COEFFICIENT OF FRICTION ......        .300
   NUMBER 0F INTEGRATION POINTS ......           0

PRINTED OUTPUT SELECTED
=======================
   STATIC PIPE FORCES AND STRESSES ...YES
   STATIC SOLUTION SUMMARY ...........YES
   OVERBEND PIPE SUPPORT GEOMETRY ....YES
   STINGER BALLAST SCHEDULE DATA .....NO
   DYNAMIC PIPE FORCES AND STRESSES ..NO
   DYNAMIC RANGE OF PIPE DATA ........NO
   DYNAMIC TRACKING OF PIPE DATA .....NO
   PLOT DATA FILE SUMMARY TABLES .....YES

   PRINT STINGER ELEMENT FORCES ......NO
   PRINT PIPE STRAINS IN OUTPUT ......YES
   USE DNV STRESS FORMULA ............NO
   USE THICK WALL CYLINDER FORMULA ...NO
   ENABLE/DISABLE WARNING MESSAGES ...ENABLE
```



```
                        I N P U T    D A T A    E C H O


PROFILE PLOT TABLE ENTRIES
==========================
   PLOT TABLE INDEX ..................        1
   PLOT NUMBER .......................        1
   PLOT TYPE OPTION NUMBER ...........        1
   DYNAMIC PROFILE TIME POINT ........      .000
   DYNAMIC PROFILE TIME INCREMENT ....      .000
   ORDINATE PARAMETER CODE NUMBER ....        2
   AXIS LABEL FOR ORDINATE ........... "PIPE ELEVETION OR Y COORDINATE  "
   ABSCISSA PARAMETER CODE NUMBER ....        1
   AXIS LABEL FOR ABSCISSA ........... "PIPE HORIZONTAL X COORDINATE    "

   PLOT TITLE ........................ "PIPELINE ELEVATION PROFILE AND TOTAL PIPE STRAIN        "
   MINIMUM HORIZONTAL AXIS RANGE .....      .000
   MAXIMUM HORIZONTAL AXIS RANGE .....      .000
   MINIMUM VERTICAL AXIS RANGE .......      .000
   MAXIMUM VERTICAL AXIS RANGE .......      .000

PROFILE PLOT TABLE ENTRIES
==========================
   PLOT TABLE INDEX ..................        3
   PLOT NUMBER .......................        2
   PLOT TYPE OPTION NUMBER ...........        1
   DYNAMIC PROFILE TIME POINT ........      .000
   DYNAMIC PROFILE TIME INCREMENT ....      .000
   ORDINATE PARAMETER CODE NUMBER ....       10
   AXIS LABEL FOR ORDINATE ........... "VERTICAL MOMENT                 "
   ABSCISSA PARAMETER CODE NUMBER ....        1
   AXIS LABEL FOR ABSCISSA ........... "PIPE HORIZONTAL X COORDINATE    "

   PLOT TITLE ........................ "VERTICAL BENDING MOMENT AND PERCENT YIELD               "
   MINIMUM HORIZONTAL AXIS RANGE .....      .000
   MAXIMUM HORIZONTAL AXIS RANGE .....      .000
   MINIMUM VERTICAL AXIS RANGE .......      .000
   MAXIMUM VERTICAL AXIS RANGE .......      .000
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                        I N P U T    D A T A    E C H O
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PROFILE PLOT TABLE ENTRIES
=========================
   PLOT TABLE INDEX .................         4
   PLOT NUMBER ......................         2
   PLOT TYPE OPTION NUMBER ...........        1
   DYNAMIC PROFILE TIME POINT ........     .000
   DYNAMIC PROFILE TIME INCREMENT ....     .000
   ORDINATE PARAMETER CODE NUMBER ....       15
   AXIS LABEL FOR ORDINATE ........... "PERCENT YIELD                    "
   ABSCISSA PARAMETER CODE NUMBER ....        1
   AXIS LABEL FOR ABSCISSA ........... "PIPE HORIZONTAL X COORDINATE    "

   PLOT TITLE ....................... "VERTICAL BENDING MOMENT AND PERCENT YIELD              "
   MINIMUM HORIZONTAL AXIS RANGE .....     .000
   MAXIMUM HORIZONTAL AXIS RANGE .....     .000
   MINIMUM VERTICAL AXIS RANGE .......     .000
   MAXIMUM VERTICAL AXIS RANGE .......     .000

PROFILE PLOT TABLE ENTRIES
=========================
   PLOT TABLE INDEX .................         2
   PLOT NUMBER ......................         1
   PLOT TYPE OPTION NUMBER ...........        1
   DYNAMIC PROFILE TIME POINT ........     .000
   DYNAMIC PROFILE TIME INCREMENT ....     .000
   ORDINATE PARAMETER CODE NUMBER ....       14
   AXIS LABEL FOR ORDINATE ........... "TOTAL VON MISES PIPE STRESS     "
   ABSCISSA PARAMETER CODE NUMBER ....        1
   AXIS LABEL FOR ABSCISSA ........... "PIPE HORIZONTAL X COORDINATE    "

   PLOT TITLE ....................... "PIPELINE ELEVATION PROFILE AND TOTAL PIPE STRAIN        "
   MINIMUM HORIZONTAL AXIS RANGE .....     .000
   MAXIMUM HORIZONTAL AXIS RANGE .....     .000
   MINIMUM VERTICAL AXIS RANGE .......     .000
   MAXIMUM VERTICAL AXIS RANGE .......     .000

PLOTTER CONFIGURATION
=====================
   PLOTTER TYPE OPTION NUMBER ........        3
   DATA RANGE OPTION NUMBER ..........        0
   PLOT PAGE WIDTH ( IN ) ...........      .000
   PLOT PAGE HEIGHT ( IN ) ..........      .000

END OF INPUT DATA

STATIC SOLUTION CONVERGED IN (   11 ) ITERATIONS
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S T A T I C   P I P E   C O O R D I N A T E S,   F O R C E S   A N D   S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
1	LAYBARGE	89.34	15.50	.04	.00	14.598	.000	.00	.000	.0000	.0000	.0000	.00
3	LAYBARGE	76.77	15.50	-.02	12.57	36.712	.000	.00	-16.205	.0000	-.0018	.0018	.68
5	TENSIONR	70.65	15.50	.00	18.69	9.049	.000	3426.31	7.181	.0447	.0008	.0455	16.84
7	LAYBARGE	63.00	15.50	.01	26.34	31.332	.000	3426.31	-13.063	.0447	-.0015	.0461	17.08
9	LAYBARGE	51.05	15.50	.00	38.29	32.971	.000	3426.31	-15.301	.0447	-.0017	.0464	17.18
11	LAYBARGE	40.88	15.50	.00	48.45	25.893	.000	3426.31	-6.777	.0447	-.0008	.0454	16.82
13	LAYBARGE	31.25	15.50	.01	58.09	41.709	.000	3426.31	-10.160	.0447	-.0011	.0458	16.96
15	TENSIONR	25.72	15.50	-.03	63.61	-40.078	.000	3426.30	38.888	.0447	.0044	.0490	18.16
17	TENSIONR	16.37	15.50	.19	72.96	82.299	.000	3426.08	-250.784	.0446	-.0283	.0730	27.03
19	LAYBARGE	3.30	15.32	1.66	86.04	162.982	.000	3424.26	-755.336	.0446	-.0853	.1299	48.12
22	STINGER	-10.00	14.61	4.75	99.36	233.330	.000	3418.99	-1360.314	.0446	-.1536	.1982	73.40
24	STINGER	-19.93	13.46	8.73	109.36	367.336	.000	3410.83	-1909.433	.0444	-.2158	.2603	96.40
26	STINGER	-29.75	11.55	13.25	119.36	271.547	.000	3406.72	-1807.078	.0444	-.2041	.2485	92.05
28	STINGER	-39.39	8.89	17.63	129.36	293.133	.000	3398.83	-1831.021	.0443	-.2069	.2511	93.02
30	STINGER	-48.79	5.50	22.05	139.37	287.004	.000	3389.22	-1825.553	.0442	-.2062	.2504	92.74
32	STINGER	-57.91	1.39	26.45	149.37	279.798	.000	3377.55	-1823.893	.0440	-.2060	.2501	92.62
34	STINGER	-66.68	-3.41	30.86	159.37	268.050	.000	3370.91	-1818.761	.0438	-.2055	.2494	92.37
36	STINGER	-75.07	-8.86	35.27	169.37	266.256	.000	3366.46	-1819.226	.0436	-.2055	.2494	92.36
38	STINGER	-83.00	-14.95	39.68	179.38	262.782	.000	3361.54	-1816.073	.0434	-.2052	.2489	92.20
40	STINGER	-90.45	-21.62	44.10	189.38	273.775	.000	3355.94	-1828.422	.0432	-.2066	.2503	92.69
42	STINGER	-97.36	-28.85	48.45	199.38	223.575	.000	3350.71	-1775.398	.0429	-.2005	.2442	90.43
44	STINGER	-103.69	-36.59	53.08	209.38	427.084	.000	3341.48	-1994.117	.0426	-.2258	.2693	99.73
46	STINGER	-109.41	-44.79	56.57	219.39	65.304	.000	3343.88	-844.327	.0424	-.0954	.1389	51.44
48	STINGER	-114.81	-53.21	57.83	229.39	.000	.381	3338.59	-239.209	.0421	-.0270	.0705	26.11
50	SAGBEND	-120.11	-61.70	58.15	239.39	.000	.000	3331.79	-50.500	.0418	-.0057	.0491	18.19
51	SAGBEND	-125.38	-70.19	58.19	249.39	.000	.000	3324.86	5.487	.0415	.0006	.0440	16.28
52	SAGBEND	-130.65	-78.69	58.15	259.39	.000	.000	3317.93	22.179	.0411	.0025	.0458	16.95
53	SAGBEND	-135.93	-87.18	58.09	269.39	.000	.000	3311.00	27.222	.0408	.0031	.0463	17.14

54	SAGBEND	-141.22	-95.67	58.02	279.39	.000	.000	3304.07	28.808	.0405	.0033	.0464	17.18
55	SAGBEND	-146.53	-104.15	57.94	289.39	.000	.000	3297.16	29.368	.0402	.0033	.0464	17.18
56	SAGBEND	-151.84	-112.62	57.87	299.39	.000	.000	3290.24	29.622	.0399	.0033	.0463	17.16
57	SAGBEND	-157.16	-121.08	57.79	309.39	.000	.000	3283.34	29.786	.0396	.0034	.0463	17.15
58	SAGBEND	-162.50	-129.54	57.72	319.39	.000	.000	3276.43	29.923	.0393	.0034	.0463	17.13
59	SAGBEND	-167.85	-137.99	57.64	329.39	.000	.000	3269.54	30.053	.0389	.0034	.0462	17.12
60	SAGBEND	-173.20	-146.43	57.56	339.39	.000	.000	3262.65	30.181	.0386	.0034	.0462	17.11
61	SAGBEND	-178.57	-154.87	57.49	349.39	.000	.000	3255.77	30.309	.0383	.0034	.0462	17.09
62	SAGBEND	-183.95	-163.30	57.41	359.39	.000	.000	3248.89	30.438	.0380	.0034	.0461	17.08
63	SAGBEND	-189.35	-171.72	57.33	369.39	.000	.000	3242.02	30.567	.0377	.0035	.0461	17.07
64	SAGBEND	-194.75	-180.13	57.25	379.39	.000	.000	3235.15	30.697	.0374	.0035	.0461	17.07
65	SAGBEND	-200.16	-188.54	57.17	389.39	.000	.000	3228.29	30.827	.0371	.0035	.0461	17.06
66	SAGBEND	-205.59	-196.94	57.10	399.39	.000	.000	3221.44	30.959	.0368	.0035	.0460	17.05
67	SAGBEND	-211.03	-205.33	57.02	409.39	.000	.000	3214.59	31.091	.0364	.0035	.0460	17.05
68	SAGBEND	-216.48	-213.72	56.94	419.39	.000	.000	3207.75	31.223	.0361	.0035	.0460	17.04

OFFPIPE - OFFSHORE PIPELAY ANALYSIS SYSTEM - VERSION 2.05 X DATE - 6/ 6/2011 TIME - 9:24: 8 PAGE 11
PROJECT - 2000waterdepth JOB NO. 1
USER ID - ML LICENSEE: J. P. KENNY CASE 1

S T A T I C P I P E C O O R D I N A T E S, F O R C E S A N D S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
69	SAGBEND	-221.94	-222.09	56.86	429.39	.000	.000	3200.91	31.357	.0358	.0035	.0460	17.04
70	SAGBEND	-227.41	-230.46	56.78	439.39	.000	.000	3194.08	31.491	.0355	.0036	.0460	17.04
71	SAGBEND	-232.90	-238.83	56.70	449.39	.000	.000	3187.26	31.626	.0352	.0036	.0460	17.04
72	SAGBEND	-238.40	-247.18	56.62	459.39	.000	.000	3180.44	31.762	.0349	.0036	.0460	17.04
73	SAGBEND	-243.90	-255.53	56.54	469.39	.000	.000	3173.63	31.898	.0346	.0036	.0460	17.04
74	SAGBEND	-249.42	-263.86	56.45	479.39	.000	.000	3166.83	32.036	.0343	.0036	.0460	17.05
75	SAGBEND	-254.96	-272.19	56.37	489.39	.000	.000	3160.03	32.174	.0340	.0036	.0460	17.05
76	SAGBEND	-260.50	-280.52	56.29	499.39	.000	.000	3153.24	32.312	.0336	.0036	.0461	17.06
77	SAGBEND	-266.06	-288.83	56.21	509.39	.000	.000	3146.45	32.452	.0333	.0037	.0461	17.06
78	SAGBEND	-271.62	-297.14	56.12	519.39	.000	.000	3139.67	32.592	.0330	.0037	.0461	17.07
79	SAGBEND	-277.20	-305.44	56.04	529.39	.000	.000	3132.90	32.733	.0327	.0037	.0461	17.08
80	SAGBEND	-282.80	-313.73	55.96	539.39	.000	.000	3126.14	32.875	.0324	.0037	.0461	17.09
81	SAGBEND	-288.40	-322.01	55.87	549.39	.000	.000	3119.38	33.018	.0321	.0037	.0462	17.10
82	SAGBEND	-294.02	-330.28	55.79	559.39	.000	.000	3112.63	33.161	.0318	.0037	.0462	17.11
83	SAGBEND	-299.64	-338.55	55.71	569.39	.000	.000	3105.88	33.305	.0315	.0038	.0462	17.13
84	SAGBEND	-305.28	-346.81	55.62	579.39	.000	.000	3099.14	33.450	.0312	.0038	.0463	17.14
85	SAGBEND	-310.94	-355.05	55.53	589.39	.000	.000	3092.41	33.596	.0309	.0038	.0463	17.16
86	SAGBEND	-316.60	-363.30	55.45	599.39	.000	.000	3085.69	33.743	.0306	.0038	.0464	17.17
87	SAGBEND	-322.28	-371.53	55.36	609.39	.000	.000	3078.97	33.890	.0303	.0038	.0464	17.19
88	SAGBEND	-327.97	-379.75	55.28	619.39	.000	.000	3072.26	34.038	.0300	.0038	.0465	17.21
89	SAGBEND	-333.67	-387.97	55.19	629.39	.000	.000	3065.56	34.187	.0297	.0039	.0465	17.23
90	SAGBEND	-339.39	-396.17	55.10	639.39	.000	.000	3058.86	34.337	.0293	.0039	.0466	17.25
91	SAGBEND	-345.11	-404.37	55.01	649.39	.000	.000	3052.17	34.488	.0290	.0039	.0466	17.28
92	SAGBEND	-350.85	-412.56	54.93	659.39	.000	.000	3045.49	34.639	.0287	.0039	.0467	17.30
93	SAGBEND	-356.61	-420.74	54.84	669.39	.000	.000	3038.82	34.792	.0284	.0039	.0468	17.32
94	SAGBEND	-362.37	-428.91	54.75	679.39	.000	.000	3032.15	34.945	.0281	.0039	.0468	17.35
95	SAGBEND	-368.15	-437.07	54.66	689.39	.000	.000	3025.49	35.099	.0278	.0040	.0469	17.37
96	SAGBEND	-373.94	-445.22	54.57	699.39	.000	.000	3018.83	35.254	.0275	.0040	.0470	17.40
97	SAGBEND	-379.74	-453.37	54.48	709.39	.000	.000	3012.19	35.410	.0272	.0040	.0471	17.43
98	SAGBEND	-385.56	-461.50	54.39	719.39	.000	.000	3005.55	35.566	.0269	.0040	.0471	17.46
99	SAGBEND	-391.39	-469.63	54.30	729.39	.000	.000	2998.92	35.724	.0266	.0040	.0472	17.49
100	SAGBEND	-397.23	-477.74	54.21	739.39	.000	.000	2992.30	35.882	.0263	.0041	.0473	17.52
101	SAGBEND	-403.09	-485.85	54.12	749.39	.000	.000	2985.68	36.041	.0260	.0041	.0474	17.55
102	SAGBEND	-408.95	-493.95	54.02	759.39	.000	.000	2979.07	36.201	.0257	.0041	.0475	17.59
103	SAGBEND	-414.84	-502.04	53.93	769.39	.000	.000	2972.47	36.362	.0254	.0041	.0476	17.62
104	SAGBEND	-420.73	-510.11	53.84	779.39	.000	.000	2965.88	36.524	.0251	.0041	.0477	17.66
105	SAGBEND	-426.64	-518.18	53.75	789.39	.000	.000	2959.30	36.687	.0248	.0041	.0478	17.69
106	SAGBEND	-432.56	-526.24	53.65	799.39	.000	.000	2952.72	36.850	.0245	.0042	.0479	17.73
107	SAGBEND	-438.49	-534.29	53.56	809.39	.000	.000	2946.15	37.015	.0242	.0042	.0480	17.77
108	SAGBEND	-444.44	-542.33	53.46	819.39	.000	.000	2939.59	37.180	.0239	.0042	.0481	17.81
109	SAGBEND	-450.40	-550.36	53.37	829.39	.000	.000	2933.04	37.347	.0236	.0042	.0482	17.85
110	SAGBEND	-456.37	-558.38	53.27	839.39	.000	.000	2926.49	37.514	.0233	.0042	.0483	17.89
111	SAGBEND	-462.36	-566.39	53.18	849.39	.000	.000	2919.96	37.682	.0230	.0043	.0484	17.93
112	SAGBEND	-468.36	-574.39	53.08	859.39	.000	.000	2913.43	37.851	.0227	.0043	.0485	17.97
113	SAGBEND	-474.37	-582.38	52.99	869.39	.000	.000	2906.91	38.021	.0224	.0043	.0486	18.02

OFFPIPE - OFFSHORE PIPELAY ANALYSIS SYSTEM - VERSION 2.05 X DATE - 6/ 6/2011 TIME - 9:24: 8 PAGE 12
PROJECT - 2000waterdepth JOB NO. 1
USER ID - ML LICENSEE: J. P. KENNY CASE 1

S T A T I C P I P E C O O R D I N A T E S, F O R C E S A N D S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
114	SAGBEND	-480.40	-590.36	52.89	879.39	.000	.000	2900.40	38.192	.0221	.0043	.0488	18.06
115	SAGBEND	-486.44	-598.33	52.79	889.39	.000	.000	2893.89	38.364	.0218	.0043	.0489	18.11
116	SAGBEND	-492.49	-606.29	52.69	899.39	.000	.000	2887.40	38.537	.0215	.0044	.0490	18.15
117	SAGBEND	-498.56	-614.24	52.59	909.39	.000	.000	2880.91	38.710	.0212	.0044	.0491	18.20

118	SAGBEND	-504.64	-622.18	52.50	919.39	.000	.000	2874.43	38.885	.0209	.0044	.0493	18.25
119	SAGBEND	-510.74	-630.10	52.40	929.39	.000	.000	2867.97	39.061	.0206	.0044	.0494	18.30
120	SAGBEND	-516.84	-638.02	52.30	939.39	.000	.000	2861.50	39.237	.0204	.0044	.0495	18.34
121	SAGBEND	-522.97	-645.93	52.20	949.39	.000	.000	2855.05	39.415	.0201	.0045	.0497	18.39
122	SAGBEND	-529.10	-653.82	52.10	959.39	.000	.000	2848.61	39.593	.0198	.0045	.0498	18.45
123	SAGBEND	-535.25	-661.71	51.99	969.39	.000	.000	2842.17	39.773	.0195	.0045	.0499	18.50
124	SAGBEND	-541.42	-669.58	51.89	979.39	.000	.000	2835.75	39.953	.0192	.0045	.0501	18.55
125	SAGBEND	-547.60	-677.45	51.79	989.39	.000	.000	2829.33	40.135	.0189	.0045	.0502	18.60
126	SAGBEND	-553.79	-685.30	51.69	999.39	.000	.000	2822.92	40.317	.0186	.0046	.0504	18.66
127	SAGBEND	-559.99	-693.14	51.59	1009.39	.000	.000	2816.53	40.500	.0183	.0046	.0505	18.71
128	SAGBEND	-566.22	-700.97	51.48	1019.39	.000	.000	2810.14	40.685	.0180	.0046	.0507	18.77
129	SAGBEND	-572.45	-708.79	51.38	1029.39	.000	.000	2803.76	40.870	.0177	.0046	.0508	18.82
130	SAGBEND	-578.70	-716.60	51.27	1039.39	.000	.000	2797.39	41.057	.0174	.0046	.0510	18.88
131	SAGBEND	-584.96	-724.39	51.17	1049.39	.000	.000	2791.02	41.244	.0171	.0047	.0511	18.94
132	SAGBEND	-591.24	-732.18	51.06	1059.39	.000	.000	2784.67	41.432	.0169	.0047	.0513	18.99
133	SAGBEND	-597.53	-739.95	50.96	1069.39	.000	.000	2778.33	41.622	.0166	.0047	.0514	19.05
134	SAGBEND	-603.84	-747.71	50.85	1079.39	.000	.000	2771.99	41.812	.0163	.0047	.0516	19.11
135	SAGBEND	-610.16	-755.46	50.75	1089.39	.000	.000	2765.67	42.004	.0160	.0047	.0518	19.17
136	SAGBEND	-616.49	-763.20	50.64	1099.39	.000	.000	2759.36	42.196	.0157	.0048	.0519	19.23
137	SAGBEND	-622.84	-770.92	50.53	1109.39	.000	.000	2753.05	42.390	.0154	.0048	.0521	19.29
138	SAGBEND	-629.21	-778.64	50.42	1119.39	.000	.000	2746.76	42.584	.0151	.0048	.0523	19.35
139	SAGBEND	-635.58	-786.34	50.31	1129.39	.000	.000	2740.47	42.780	.0148	.0048	.0524	19.42
140	SAGBEND	-641.98	-794.03	50.20	1139.39	.000	.000	2734.20	42.976	.0146	.0049	.0526	19.48
141	SAGBEND	-648.38	-801.70	50.09	1149.39	.000	.000	2727.93	43.174	.0143	.0049	.0528	19.54
142	SAGBEND	-654.81	-809.37	49.98	1159.39	.000	.000	2721.68	43.373	.0140	.0049	.0529	19.61
143	SAGBEND	-661.24	-817.02	49.87	1169.39	.000	.000	2715.43	43.572	.0137	.0049	.0531	19.67
144	SAGBEND	-667.70	-824.66	49.76	1179.39	.000	.000	2709.20	43.773	.0134	.0049	.0533	19.74
145	SAGBEND	-674.16	-832.29	49.65	1189.39	.000	.000	2702.97	43.975	.0131	.0050	.0535	19.80
146	SAGBEND	-680.65	-839.90	49.54	1199.39	.000	.000	2696.76	44.178	.0128	.0050	.0536	19.87
147	SAGBEND	-687.14	-847.51	49.43	1209.39	.000	.000	2690.56	44.382	.0126	.0050	.0538	19.93
148	SAGBEND	-693.65	-855.10	49.31	1219.39	.000	.000	2684.36	44.587	.0123	.0050	.0540	20.00
149	SAGBEND	-700.18	-862.67	49.20	1229.39	.000	.000	2678.18	44.793	.0120	.0051	.0542	20.07
150	SAGBEND	-706.72	-870.23	49.08	1239.39	.000	.000	2672.01	45.000	.0117	.0051	.0544	20.14
151	SAGBEND	-713.28	-877.78	48.97	1249.39	.000	.000	2665.85	45.208	.0114	.0051	.0546	20.20
152	SAGBEND	-719.85	-885.32	48.85	1259.39	.000	.000	2659.69	45.418	.0112	.0051	.0547	20.27
153	SAGBEND	-726.44	-892.85	48.74	1269.39	.000	.000	2653.56	45.628	.0109	.0052	.0549	20.34
154	SAGBEND	-733.04	-900.36	48.62	1279.39	.000	.000	2647.43	45.840	.0106	.0052	.0551	20.41
155	SAGBEND	-739.66	-907.85	48.50	1289.39	.000	.000	2641.31	46.052	.0103	.0052	.0553	20.48
156	SAGBEND	-746.29	-915.34	48.39	1299.39	.000	.000	2635.20	46.266	.0100	.0052	.0555	20.55
157	SAGBEND	-752.94	-922.81	48.27	1309.39	.000	.000	2629.11	46.481	.0098	.0052	.0557	20.62
158	SAGBEND	-759.61	-930.26	48.15	1319.39	.000	.000	2623.02	46.697	.0095	.0053	.0559	20.70

S T A T I C   P I P E   C O O R D I N A T E S,   F O R C E S   A N D   S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
159	SAGBEND	-766.29	-937.70	48.03	1329.39	.000	.000	2616.95	46.914	.0092	.0053	.0561	20.77
160	SAGBEND	-772.98	-945.13	47.91	1339.39	.000	.000	2610.89	47.132	.0089	.0053	.0563	20.84
161	SAGBEND	-779.69	-952.55	47.79	1349.39	.000	.000	2604.84	47.351	.0087	.0053	.0565	20.91
162	SAGBEND	-786.42	-959.95	47.67	1359.39	.000	.000	2598.80	47.571	.0084	.0054	.0567	20.99
163	SAGBEND	-793.16	-967.33	47.55	1369.39	.000	.000	2592.77	47.793	.0081	.0054	.0569	21.06
164	SAGBEND	-799.92	-974.70	47.43	1379.39	.000	.000	2586.75	48.015	.0078	.0054	.0571	21.13
165	SAGBEND	-806.69	-982.06	47.30	1389.39	.000	.000	2580.75	48.239	.0076	.0054	.0573	21.21
166	SAGBEND	-813.48	-989.40	47.18	1399.39	.000	.000	2574.76	48.464	.0073	.0055	.0575	21.28
167	SAGBEND	-820.28	-996.73	47.06	1409.39	.000	.000	2568.78	48.690	.0070	.0055	.0577	21.36
168	SAGBEND	-827.10	-1004.04	46.93	1419.39	.000	.000	2562.81	48.917	.0067	.0055	.0579	21.43
169	SAGBEND	-833.94	-1011.34	46.81	1429.39	.000	.000	2556.85	49.145	.0065	.0056	.0581	21.51
170	SAGBEND	-840.79	-1018.62	46.68	1439.39	.000	.000	2550.91	49.374	.0062	.0056	.0583	21.58
171	SAGBEND	-847.66	-1025.89	46.56	1449.39	.000	.000	2544.98	49.605	.0059	.0056	.0585	21.66
172	SAGBEND	-854.55	-1033.15	46.43	1459.39	.000	.000	2539.06	49.836	.0057	.0056	.0587	21.73
173	SAGBEND	-861.45	-1040.38	46.30	1469.39	.000	.000	2533.15	50.069	.0054	.0057	.0589	21.81
174	SAGBEND	-868.36	-1047.61	46.18	1479.39	.000	.000	2527.26	50.303	.0051	.0057	.0591	21.89
175	SAGBEND	-875.30	-1054.81	46.05	1489.39	.000	.000	2521.38	50.538	.0049	.0057	.0593	21.96
176	SAGBEND	-882.24	-1062.00	45.92	1499.39	.000	.000	2515.51	50.774	.0046	.0057	.0595	22.04
177	SAGBEND	-889.21	-1069.18	45.79	1509.39	.000	.000	2509.65	51.011	.0043	.0058	.0597	22.12
178	SAGBEND	-896.19	-1076.34	45.66	1519.39	.000	.000	2503.81	51.249	.0041	.0058	.0599	22.20
179	SAGBEND	-903.19	-1083.48	45.53	1529.39	.000	.000	2497.98	51.489	.0038	.0058	.0601	22.27
180	SAGBEND	-910.20	-1090.61	45.40	1539.39	.000	.000	2492.16	51.730	.0035	.0058	.0604	22.35
181	SAGBEND	-917.23	-1097.72	45.26	1549.39	.000	.000	2486.36	51.971	.0033	.0059	.0606	22.43
182	SAGBEND	-924.28	-1104.82	45.13	1559.39	.000	.000	2480.57	52.214	.0030	.0059	.0608	22.51
183	SAGBEND	-931.34	-1111.90	45.00	1569.39	.000	.000	2474.79	52.458	.0027	.0059	.0610	22.59
184	SAGBEND	-938.42	-1118.96	44.86	1579.39	.000	.000	2469.03	52.704	.0025	.0060	.0612	22.67
185	SAGBEND	-945.52	-1126.01	44.73	1589.39	.000	.000	2463.28	52.950	.0022	.0060	.0614	22.75
186	SAGBEND	-952.63	-1133.04	44.59	1599.39	.000	.000	2457.54	53.197	.0019	.0060	.0616	22.83
187	SAGBEND	-959.76	-1140.05	44.46	1609.39	.000	.000	2451.82	53.446	.0017	.0060	.0618	22.91
188	SAGBEND	-966.91	-1147.04	44.32	1619.39	.000	.000	2446.11	53.696	.0014	.0061	.0621	22.98
189	SAGBEND	-974.07	-1154.02	44.18	1629.39	.000	.000	2440.42	53.947	.0012	.0061	.0623	23.06
190	SAGBEND	-981.25	-1160.98	44.05	1639.39	.000	.000	2434.74	54.199	.0009	.0061	.0625	23.14
191	SAGBEND	-988.44	-1167.93	43.91	1649.39	.000	.000	2429.07	54.452	.0007	.0061	.0627	23.22
192	SAGBEND	-995.66	-1174.85	43.77	1659.39	.000	.000	2423.42	54.706	.0004	.0062	.0629	23.30
193	SAGBEND	-1002.89	-1181.76	43.63	1669.39	.000	.000	2417.78	54.962	.0001	.0062	.0631	23.38
194	SAGBEND	-1010.13	-1188.65	43.49	1679.39	.000	.000	2412.15	55.218	-.0001	.0062	.0634	23.47
195	SAGBEND	-1017.40	-1195.53	43.35	1689.39	.000	.000	2406.54	55.476	-.0004	.0063	.0636	23.55

196	SAGBEND	-1024.68	-1202.38	43.21	1699.39	.000	.000	2400.95	55.735	-.0006	.0063	.0638	23.63
197	SAGBEND	-1031.98	-1209.22	43.06	1709.39	.000	.000	2395.37	55.995	-.0009	.0063	.0640	23.71
198	SAGBEND	-1039.29	-1216.04	42.92	1719.39	.000	.000	2389.80	56.256	-.0011	.0064	.0642	23.79
199	SAGBEND	-1046.62	-1222.84	42.78	1729.39	.000	.000	2384.25	56.518	-.0014	.0064	.0644	23.87
200	SAGBEND	-1053.97	-1229.62	42.63	1739.39	.000	.000	2378.72	56.781	-.0016	.0064	.0647	23.95
201	SAGBEND	-1061.34	-1236.38	42.49	1749.39	.000	.000	2373.20	57.046	-.0019	.0064	.0649	24.03
202	SAGBEND	-1068.72	-1243.13	42.34	1759.39	.000	.000	2367.69	57.311	-.0021	.0065	.0651	24.11
203	SAGBEND	-1076.12	-1249.86	42.20	1769.39	.000	.000	2362.21	57.578	-.0024	.0065	.0653	24.19

S T A T I C   P I P E   C O O R D I N A T E S,   F O R C E S   A N D   S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
204	SAGBEND	-1083.53	-1256.56	42.05	1779.39	.000	.000	2356.73	57.846	-.0026	.0065	.0655	24.27
205	SAGBEND	-1090.97	-1263.25	41.90	1789.39	.000	.000	2351.27	58.115	-.0029	.0066	.0658	24.35
206	SAGBEND	-1098.42	-1269.92	41.75	1799.39	.000	.000	2345.83	58.385	-.0031	.0066	.0660	24.44
207	SAGBEND	-1105.89	-1276.57	41.60	1809.39	.000	.000	2340.40	58.656	-.0034	.0066	.0662	24.52
208	SAGBEND	-1113.38	-1283.20	41.46	1819.39	.000	.000	2334.99	58.928	-.0036	.0067	.0664	24.60
209	SAGBEND	-1120.88	-1289.81	41.30	1829.39	.000	.000	2329.60	59.201	-.0039	.0067	.0666	24.68
210	SAGBEND	-1128.40	-1296.40	41.15	1839.39	.000	.000	2324.22	59.476	-.0041	.0067	.0669	24.76
211	SAGBEND	-1135.94	-1302.97	41.00	1849.39	.000	.000	2318.86	59.751	-.0044	.0067	.0671	24.84
212	SAGBEND	-1143.49	-1309.52	40.85	1859.39	.000	.000	2313.51	60.027	-.0046	.0068	.0673	24.92
213	SAGBEND	-1151.07	-1316.05	40.70	1869.39	.000	.000	2308.18	60.305	-.0049	.0068	.0675	25.00
214	SAGBEND	-1158.66	-1322.56	40.54	1879.39	.000	.000	2302.87	60.584	-.0051	.0068	.0677	25.09
215	SAGBEND	-1166.27	-1329.05	40.39	1889.39	.000	.000	2297.57	60.863	-.0053	.0069	.0680	25.17
216	SAGBEND	-1173.89	-1335.52	40.23	1899.39	.000	.000	2292.29	61.144	-.0056	.0069	.0682	25.25
217	SAGBEND	-1181.53	-1341.97	40.08	1909.39	.000	.000	2287.03	61.426	-.0058	.0069	.0684	25.33
218	SAGBEND	-1189.19	-1348.40	39.92	1919.39	.000	.000	2281.78	61.708	-.0061	.0070	.0686	25.41
219	SAGBEND	-1196.87	-1354.81	39.76	1929.39	.000	.000	2276.56	61.992	-.0063	.0070	.0688	25.49
220	SAGBEND	-1204.57	-1361.19	39.60	1939.39	.000	.000	2271.34	62.277	-.0065	.0070	.0690	25.57
221	SAGBEND	-1212.28	-1367.56	39.44	1949.39	.000	.000	2266.15	62.563	-.0068	.0071	.0693	25.65
222	SAGBEND	-1220.01	-1373.90	39.28	1959.39	.000	.000	2260.97	62.849	-.0070	.0071	.0695	25.73
223	SAGBEND	-1227.76	-1380.22	39.12	1969.39	.000	.000	2255.82	63.137	-.0072	.0071	.0697	25.82
224	SAGBEND	-1235.53	-1386.52	38.96	1979.39	.000	.000	2250.67	63.426	-.0075	.0072	.0699	25.90
225	SAGBEND	-1243.31	-1392.80	38.80	1989.39	.000	.000	2245.55	63.716	-.0077	.0072	.0701	25.98
226	SAGBEND	-1251.12	-1399.05	38.64	1999.39	.000	.000	2240.45	64.006	-.0079	.0072	.0704	26.06
227	SAGBEND	-1258.94	-1405.28	38.47	2009.39	.000	.000	2235.36	64.298	-.0082	.0073	.0706	26.14
228	SAGBEND	-1266.77	-1411.49	38.31	2019.39	.000	.000	2230.29	64.591	-.0084	.0073	.0708	26.22
229	SAGBEND	-1274.63	-1417.68	38.15	2029.39	.000	.000	2225.24	64.884	-.0086	.0073	.0710	26.30
230	SAGBEND	-1282.50	-1423.85	37.98	2039.39	.000	.000	2220.21	65.178	-.0089	.0074	.0712	26.38
231	SAGBEND	-1290.39	-1429.99	37.81	2049.39	.000	.000	2215.20	65.474	-.0091	.0074	.0714	26.46
232	SAGBEND	-1298.30	-1436.11	37.65	2059.39	.000	.000	2210.20	65.770	-.0093	.0074	.0717	26.54
233	SAGBEND	-1306.23	-1442.21	37.48	2069.39	.000	.000	2205.23	66.067	-.0095	.0075	.0719	26.62
234	SAGBEND	-1314.18	-1448.28	37.31	2079.39	.000	.000	2200.27	66.365	-.0098	.0075	.0721	26.70
235	SAGBEND	-1322.14	-1454.33	37.14	2089.39	.000	.000	2195.33	66.664	-.0100	.0075	.0723	26.78
236	SAGBEND	-1330.12	-1460.35	36.97	2099.39	.000	.000	2190.42	66.964	-.0102	.0076	.0725	26.86
237	SAGBEND	-1338.12	-1466.36	36.80	2109.39	.000	.000	2185.52	67.264	-.0104	.0076	.0727	26.94
238	SAGBEND	-1346.13	-1472.33	36.63	2119.39	.000	.000	2180.64	67.565	-.0107	.0076	.0729	27.02
239	SAGBEND	-1354.17	-1478.29	36.46	2129.39	.000	.000	2175.78	67.868	-.0109	.0077	.0732	27.09
240	SAGBEND	-1362.22	-1484.22	36.28	2139.39	.000	.000	2170.94	68.170	-.0111	.0077	.0734	27.17
241	SAGBEND	-1370.29	-1490.12	36.11	2149.39	.000	.000	2166.12	68.474	-.0113	.0077	.0736	27.25
242	SAGBEND	-1378.38	-1496.01	35.93	2159.39	.000	.000	2161.32	68.779	-.0115	.0078	.0738	27.33
243	SAGBEND	-1386.48	-1501.86	35.76	2169.39	.000	.000	2156.54	69.084	-.0118	.0078	.0740	27.41
244	SAGBEND	-1394.61	-1507.69	35.58	2179.39	.000	.000	2151.78	69.390	-.0120	.0078	.0742	27.49
245	SAGBEND	-1402.75	-1513.50	35.40	2189.39	.000	.000	2147.04	69.696	-.0122	.0079	.0744	27.56
246	SAGBEND	-1410.91	-1519.28	35.23	2199.39	.000	.000	2142.33	70.004	-.0124	.0079	.0746	27.64
247	SAGBEND	-1419.09	-1525.03	35.05	2209.39	.000	.000	2137.63	70.312	-.0126	.0079	.0748	27.72
248	SAGBEND	-1427.28	-1530.76	34.87	2219.39	.000	.000	2132.95	70.620	-.0128	.0080	.0751	27.80

S T A T I C   P I P E   C O O R D I N A T E S,   F O R C E S   A N D   S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
249	SAGBEND	-1435.50	-1536.47	34.69	2229.39	.000	.000	2128.30	70.929	-.0131	.0080	.0753	27.87
250	SAGBEND	-1443.73	-1542.15	34.51	2239.39	.000	.000	2123.66	71.239	-.0133	.0080	.0755	27.95
251	SAGBEND	-1451.98	-1547.80	34.33	2249.39	.000	.000	2119.05	71.550	-.0135	.0081	.0757	28.03
252	SAGBEND	-1460.25	-1553.42	34.14	2259.39	.000	.000	2114.46	71.861	-.0137	.0081	.0759	28.10
253	SAGBEND	-1468.53	-1559.02	33.96	2269.39	.000	.000	2109.89	72.172	-.0139	.0082	.0761	28.18
254	SAGBEND	-1476.83	-1564.60	33.77	2279.39	.000	.000	2105.34	72.485	-.0141	.0082	.0763	28.26
255	SAGBEND	-1485.16	-1570.14	33.59	2289.39	.000	.000	2100.81	72.797	-.0143	.0082	.0765	28.33
256	SAGBEND	-1493.49	-1575.66	33.40	2299.39	.000	.000	2096.31	73.110	-.0145	.0083	.0767	28.41
257	SAGBEND	-1501.85	-1581.15	33.22	2309.39	.000	.000	2091.83	73.424	-.0147	.0083	.0769	28.48
258	SAGBEND	-1510.23	-1586.62	33.03	2319.39	.000	.000	2087.37	73.738	-.0149	.0083	.0771	28.56
259	SAGBEND	-1518.62	-1592.06	32.84	2329.39	.000	.000	2082.93	74.053	-.0151	.0084	.0773	28.63

260	SAGBEND	-1527.03	-1597.46	32.65	2339.39	.000	.000	2078.52	74.367	-.0153	.0084	.0775	28.71
261	SAGBEND	-1535.46	-1602.85	32.46	2349.39	.000	.000	2074.12	74.683	-.0155	.0084	.0777	28.78
262	SAGBEND	-1543.91	-1608.20	32.27	2359.39	.000	.000	2069.75	74.998	-.0157	.0085	.0779	28.86
263	SAGBEND	-1552.37	-1613.52	32.08	2369.39	.000	.000	2065.41	75.314	-.0159	.0085	.0781	28.93
264	SAGBEND	-1560.85	-1618.82	31.89	2379.39	.000	.000	2061.09	75.631	-.0161	.0085	.0783	29.00
265	SAGBEND	-1569.35	-1624.09	31.70	2389.39	.000	.000	2056.79	75.947	-.0163	.0086	.0785	29.08
266	SAGBEND	-1577.87	-1629.33	31.50	2399.39	.000	.000	2052.51	76.264	-.0165	.0086	.0787	29.15
267	SAGBEND	-1586.40	-1634.54	31.31	2409.39	.000	.000	2048.26	76.581	-.0167	.0086	.0789	29.22
268	SAGBEND	-1594.96	-1639.72	31.11	2419.39	.000	.000	2044.03	76.898	-.0169	.0087	.0791	29.29
269	SAGBEND	-1603.53	-1644.88	30.92	2429.39	.000	.000	2039.82	77.215	-.0171	.0087	.0793	29.36
270	SAGBEND	-1612.11	-1650.00	30.72	2439.39	.000	.000	2035.64	77.533	-.0173	.0088	.0795	29.44
271	SAGBEND	-1620.72	-1655.09	30.52	2449.39	.000	.000	2031.48	77.850	-.0175	.0088	.0797	29.51
272	SAGBEND	-1629.34	-1660.16	30.32	2459.39	.000	.000	2027.35	78.168	-.0176	.0088	.0799	29.58
273	SAGBEND	-1637.98	-1665.19	30.12	2469.39	.000	.000	2023.24	78.486	-.0178	.0089	.0801	29.65
274	SAGBEND	-1646.64	-1670.19	29.92	2479.39	.000	.000	2019.16	78.804	-.0180	.0089	.0802	29.72
275	SAGBEND	-1655.32	-1675.17	29.72	2489.39	.000	.000	2015.10	79.121	-.0182	.0089	.0804	29.79
276	SAGBEND	-1664.01	-1680.11	29.52	2499.39	.000	.000	2011.07	79.439	-.0184	.0090	.0806	29.86
277	SAGBEND	-1672.72	-1685.02	29.32	2509.39	.000	.000	2007.06	79.757	-.0186	.0090	.0808	29.93
278	SAGBEND	-1681.45	-1689.90	29.11	2519.39	.000	.000	2003.08	80.074	-.0188	.0090	.0810	30.00
279	SAGBEND	-1690.20	-1694.75	28.91	2529.39	.000	.000	1999.12	80.391	-.0189	.0091	.0812	30.07
280	SAGBEND	-1698.96	-1699.57	28.70	2539.39	.000	.000	1995.18	80.709	-.0191	.0091	.0814	30.13
281	SAGBEND	-1707.74	-1704.36	28.50	2549.39	.000	.000	1991.28	81.026	-.0193	.0092	.0815	30.20
282	SAGBEND	-1716.54	-1709.11	28.29	2559.39	.000	.000	1987.40	81.342	-.0195	.0092	.0817	30.27
283	SAGBEND	-1725.35	-1713.83	28.08	2569.39	.000	.000	1983.54	81.659	-.0196	.0092	.0819	30.34
284	SAGBEND	-1734.18	-1718.53	27.87	2579.39	.000	.000	1979.71	81.975	-.0198	.0093	.0821	30.40
285	SAGBEND	-1743.03	-1723.18	27.67	2589.39	.000	.000	1975.91	82.291	-.0200	.0093	.0823	30.47
286	SAGBEND	-1751.89	-1727.81	27.46	2599.39	.000	.000	1972.13	82.606	-.0202	.0093	.0824	30.53
287	SAGBEND	-1760.78	-1732.41	27.24	2609.39	.000	.000	1968.38	82.921	-.0203	.0094	.0826	30.60
288	SAGBEND	-1769.68	-1736.97	27.03	2619.39	.000	.000	1964.66	83.236	-.0205	.0094	.0828	30.66
289	SAGBEND	-1778.59	-1741.50	26.82	2629.39	.000	.000	1960.97	83.550	-.0207	.0094	.0830	30.73
290	SAGBEND	-1787.52	-1745.99	26.61	2639.39	.000	.000	1957.30	83.863	-.0208	.0095	.0831	30.79
291	SAGBEND	-1796.47	-1750.45	26.39	2649.39	.000	.000	1953.65	84.176	-.0210	.0095	.0833	30.86
292	SAGBEND	-1805.44	-1754.88	26.18	2659.39	.000	.000	1950.04	84.488	-.0212	.0095	.0835	30.92
293	SAGBEND	-1814.42	-1759.28	25.96	2669.39	.000	.000	1946.45	84.800	-.0213	.0096	.0837	30.98

S T A T I C   P I P E   C O O R D I N A T E S,   F O R C E S   A N D   S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
294	SAGBEND	-1823.42	-1763.64	25.75	2679.39	.000	.000	1942.89	85.111	-.0215	.0096	.0838	31.05
295	SAGBEND	-1832.44	-1767.96	25.53	2689.39	.000	.000	1939.36	85.421	-.0217	.0096	.0840	31.11
296	SAGBEND	-1841.47	-1772.26	25.31	2699.39	.000	.000	1935.86	85.730	-.0218	.0097	.0842	31.17
297	SAGBEND	-1850.52	-1776.52	25.09	2709.39	.000	.000	1932.38	86.039	-.0220	.0097	.0843	31.23
298	SAGBEND	-1859.58	-1780.74	24.87	2719.40	.000	.000	1928.94	86.347	-.0221	.0098	.0845	31.29
299	SAGBEND	-1868.66	-1784.93	24.65	2729.40	.000	.000	1925.52	86.654	-.0223	.0098	.0847	31.35
300	SAGBEND	-1877.76	-1789.08	24.43	2739.40	.000	.000	1922.13	86.959	-.0224	.0098	.0848	31.41
301	SAGBEND	-1886.87	-1793.20	24.21	2749.40	.000	.000	1918.77	87.264	-.0226	.0099	.0850	31.47
302	SAGBEND	-1896.00	-1797.28	23.99	2759.40	.000	.000	1915.43	87.568	-.0227	.0099	.0851	31.53
303	SAGBEND	-1905.14	-1801.33	23.76	2769.40	.000	.000	1912.13	87.871	-.0229	.0099	.0853	31.59
304	SAGBEND	-1914.30	-1805.34	23.54	2779.40	.000	.000	1908.86	88.173	-.0230	.0100	.0855	31.65
305	SAGBEND	-1923.48	-1809.32	23.31	2789.40	.000	.000	1905.61	88.473	-.0232	.0100	.0856	31.71
306	SAGBEND	-1932.67	-1813.26	23.09	2799.40	.000	.000	1902.40	88.772	-.0233	.0100	.0858	31.76
307	SAGBEND	-1941.88	-1817.16	22.86	2809.40	.000	.000	1899.21	89.070	-.0235	.0101	.0859	31.82
308	SAGBEND	-1951.10	-1821.03	22.64	2819.40	.000	.000	1896.05	89.367	-.0236	.0101	.0861	31.88
309	SAGBEND	-1960.34	-1824.86	22.41	2829.40	.000	.000	1892.93	89.663	-.0238	.0101	.0862	31.93
310	SAGBEND	-1969.59	-1828.65	22.18	2839.40	.000	.000	1889.83	89.956	-.0239	.0102	.0864	31.99
311	SAGBEND	-1978.86	-1832.41	21.95	2849.40	.000	.000	1886.77	90.249	-.0241	.0102	.0865	32.04
312	SAGBEND	-1988.14	-1836.13	21.72	2859.40	.000	.000	1883.73	90.540	-.0242	.0102	.0867	32.10
313	SAGBEND	-1997.44	-1839.81	21.49	2869.40	.000	.000	1880.73	90.830	-.0243	.0103	.0868	32.15
314	SAGBEND	-2006.75	-1843.45	21.26	2879.40	.000	.000	1877.75	91.117	-.0245	.0103	.0870	32.20
315	SAGBEND	-2016.08	-1847.06	21.02	2889.40	.000	.000	1874.81	91.404	-.0246	.0103	.0871	32.26
316	SAGBEND	-2025.42	-1850.63	20.79	2899.40	.000	.000	1871.90	91.688	-.0247	.0104	.0872	32.31
317	SAGBEND	-2034.78	-1854.16	20.56	2909.40	.000	.000	1869.01	91.971	-.0249	.0104	.0874	32.36
318	SAGBEND	-2044.15	-1857.65	20.32	2919.40	.000	.000	1866.16	92.252	-.0250	.0104	.0875	32.41
319	SAGBEND	-2053.53	-1861.10	20.09	2929.40	.000	.000	1863.35	92.532	-.0251	.0105	.0877	32.46
320	SAGBEND	-2062.93	-1864.52	19.85	2939.40	.000	.000	1860.56	92.809	-.0252	.0105	.0878	32.51
321	SAGBEND	-2072.34	-1867.90	19.61	2949.40	.000	.000	1857.80	93.084	-.0254	.0105	.0879	32.56
322	SAGBEND	-2081.77	-1871.23	19.38	2959.40	.000	.000	1855.08	93.358	-.0255	.0105	.0881	32.61
323	SAGBEND	-2091.21	-1874.53	19.14	2969.40	.000	.000	1852.39	93.629	-.0256	.0106	.0882	32.66
324	SAGBEND	-2100.66	-1877.79	18.90	2979.40	.000	.000	1849.73	93.899	-.0257	.0106	.0883	32.71
325	SAGBEND	-2110.13	-1881.01	18.66	2989.40	.000	.000	1847.10	94.166	-.0259	.0106	.0884	32.76
326	SAGBEND	-2119.61	-1884.19	18.42	2999.40	.000	.000	1844.50	94.431	-.0260	.0107	.0886	32.80
327	SAGBEND	-2129.11	-1887.33	18.18	3009.40	.000	.000	1841.94	94.694	-.0261	.0107	.0887	32.85
328	SAGBEND	-2138.61	-1890.43	17.94	3019.40	.000	.000	1839.41	94.955	-.0262	.0107	.0888	32.90
329	SAGBEND	-2148.13	-1893.49	17.69	3029.40	.000	.000	1836.91	95.213	-.0263	.0108	.0889	32.94
330	SAGBEND	-2157.67	-1896.51	17.45	3039.40	.000	.000	1834.45	95.469	-.0264	.0108	.0891	32.99
331	SAGBEND	-2167.21	-1899.49	17.21	3049.40	.000	.000	1832.02	95.722	-.0265	.0108	.0892	33.03
332	SAGBEND	-2176.77	-1902.42	16.96	3059.40	.000	.000	1829.62	95.973	-.0267	.0108	.0893	33.07
333	SAGBEND	-2186.34	-1905.32	16.72	3069.40	.000	.000	1827.26	96.222	-.0268	.0109	.0894	33.12
334	SAGBEND	-2195.93	-1908.18	16.47	3079.40	.000	.000	1824.93	96.468	-.0269	.0109	.0895	33.16
335	SAGBEND	-2205.52	-1910.99	16.23	3089.40	.000	.000	1822.63	96.711	-.0270	.0109	.0896	33.20
336	SAGBEND	-2215.13	-1913.77	15.98	3099.40	.000	.000	1820.36	96.952	-.0271	.0109	.0898	33.24
337	SAGBEND	-2224.75	-1916.50	15.73	3109.40	.000	.000	1818.13	97.190	-.0272	.0110	.0899	33.28

338	SAGBEND	-2234.38	-1919.19	15.49	3119.40	.000	.000	1815.94	97.425	-.0273	.0110	.0900	33.32

S T A T I C P I P E C O O R D I N A T E S, F O R C E S A N D S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
339	SAGBEND	-2244.02	-1921.84	15.24	3129.40	.000	.000	1813.77	97.657	-.0274	.0110	.0901	33.36
340	SAGBEND	-2253.68	-1924.45	14.99	3139.40	.000	.000	1811.65	97.887	-.0275	.0111	.0902	33.40
341	SAGBEND	-2263.34	-1927.01	14.74	3149.40	.000	.000	1809.55	98.113	-.0276	.0111	.0903	33.44
342	SAGBEND	-2273.02	-1929.54	14.49	3159.40	.000	.000	1807.49	98.337	-.0277	.0111	.0904	33.48
343	SAGBEND	-2282.71	-1932.02	14.24	3169.40	.000	.000	1805.47	98.558	-.0278	.0111	.0905	33.51
344	SAGBEND	-2292.41	-1934.45	13.99	3179.40	.000	.000	1803.48	98.775	-.0278	.0112	.0906	33.55
345	SAGBEND	-2302.11	-1936.85	13.74	3189.40	.000	.000	1801.52	98.990	-.0279	.0112	.0907	33.59
346	SAGBEND	-2311.83	-1939.20	13.48	3199.40	.000	.000	1799.60	99.201	-.0280	.0112	.0908	33.62
347	SAGBEND	-2321.56	-1941.51	13.23	3209.40	.000	.000	1797.72	99.409	-.0281	.0112	.0909	33.65
348	SAGBEND	-2331.30	-1943.78	12.98	3219.40	.000	.000	1795.87	99.614	-.0282	.0113	.0910	33.69
349	SAGBEND	-2341.05	-1946.00	12.72	3229.40	.000	.000	1794.05	99.816	-.0283	.0113	.0910	33.72
350	SAGBEND	-2350.81	-1948.18	12.47	3239.40	.000	.000	1792.27	100.014	-.0284	.0113	.0911	33.75
351	SAGBEND	-2360.58	-1950.32	12.21	3249.40	.000	.000	1790.53	100.209	-.0284	.0113	.0912	33.79
352	SAGBEND	-2370.36	-1952.42	11.96	3259.40	.000	.000	1788.82	100.400	-.0285	.0113	.0913	33.82
353	SAGBEND	-2380.15	-1954.47	11.70	3269.40	.000	.000	1787.15	100.588	-.0286	.0114	.0914	33.85
354	SAGBEND	-2389.94	-1956.47	11.45	3279.40	.000	.000	1785.51	100.773	-.0287	.0114	.0915	33.88
355	SAGBEND	-2399.75	-1958.43	11.19	3289.40	.000	.000	1783.91	100.954	-.0287	.0114	.0916	33.91
356	SAGBEND	-2409.56	-1960.35	10.93	3299.40	.000	.000	1782.34	101.131	-.0288	.0114	.0916	33.94
357	SAGBEND	-2419.39	-1962.23	10.67	3309.40	.000	.000	1780.81	101.305	-.0289	.0114	.0917	33.96
358	SAGBEND	-2429.22	-1964.06	10.41	3319.40	.000	.000	1779.32	101.475	-.0289	.0115	.0918	33.99
359	SAGBEND	-2439.06	-1965.84	10.16	3329.40	.000	.000	1777.86	101.641	-.0290	.0115	.0919	34.02
360	SAGBEND	-2448.90	-1967.58	9.90	3339.40	.000	.000	1776.44	101.804	-.0291	.0115	.0919	34.05
361	SAGBEND	-2458.76	-1969.28	9.64	3349.40	.000	.000	1775.05	101.963	-.0291	.0115	.0920	34.07
362	SAGBEND	-2468.62	-1970.93	9.38	3359.40	.000	.000	1773.71	102.118	-.0292	.0115	.0921	34.10
363	SAGBEND	-2478.49	-1972.54	9.12	3369.40	.000	.000	1772.39	102.269	-.0293	.0116	.0921	34.12
364	SAGBEND	-2488.37	-1974.10	8.86	3379.40	.000	.000	1771.12	102.416	-.0293	.0116	.0922	34.14
365	SAGBEND	-2498.25	-1975.62	8.60	3389.40	.000	.000	1769.88	102.560	-.0294	.0116	.0922	34.17
366	SAGBEND	-2508.14	-1977.09	8.33	3399.40	.000	.000	1768.68	102.699	-.0294	.0116	.0923	34.19
367	SAGBEND	-2518.04	-1978.52	8.07	3409.40	.000	.000	1767.52	102.834	-.0295	.0116	.0924	34.21
368	SAGBEND	-2527.95	-1979.90	7.81	3419.40	.000	.000	1766.39	102.966	-.0295	.0116	.0924	34.23
369	SAGBEND	-2537.86	-1981.23	7.55	3429.40	.000	.000	1765.30	103.093	-.0296	.0116	.0925	34.25
370	SAGBEND	-2547.77	-1982.52	7.29	3439.40	.000	.000	1764.24	103.216	-.0296	.0117	.0925	34.27
371	SAGBEND	-2557.69	-1983.77	7.02	3449.40	.000	.000	1763.23	103.335	-.0297	.0117	.0926	34.29
372	SAGBEND	-2567.62	-1984.97	6.76	3459.40	.000	.000	1762.25	103.450	-.0297	.0117	.0926	34.31
373	SAGBEND	-2577.56	-1986.12	6.50	3469.40	.000	.000	1761.31	103.560	-.0298	.0117	.0927	34.32
374	SAGBEND	-2587.49	-1987.23	6.23	3479.40	.000	.000	1760.40	103.667	-.0298	.0117	.0927	34.34
375	SAGBEND	-2597.44	-1988.29	5.97	3489.40	.000	.000	1759.53	103.769	-.0298	.0117	.0928	34.36
376	SAGBEND	-2607.39	-1989.31	5.70	3499.40	.000	.000	1758.70	103.867	-.0299	.0117	.0928	34.37
377	SAGBEND	-2617.34	-1990.28	5.44	3509.40	.000	.000	1757.91	103.960	-.0299	.0117	.0928	34.39
378	SAGBEND	-2627.30	-1991.21	5.17	3519.40	.000	.000	1757.16	104.050	-.0300	.0118	.0929	34.40
379	SAGBEND	-2637.26	-1992.09	4.91	3529.40	.000	.000	1756.44	104.135	-.0300	.0118	.0929	34.41
380	SAGBEND	-2647.22	-1992.92	4.64	3539.40	.000	.000	1755.76	104.215	-.0300	.0118	.0930	34.43
381	SAGBEND	-2657.19	-1993.70	4.38	3549.40	.000	.000	1755.12	104.291	-.0301	.0118	.0930	34.44
382	SAGBEND	-2667.16	-1994.44	4.11	3559.40	.000	.000	1754.52	104.363	-.0301	.0118	.0930	34.45
383	SAGBEND	-2677.14	-1995.14	3.85	3569.40	.000	.000	1753.95	104.431	-.0301	.0118	.0930	34.46

S T A T I C P I P E C O O R D I N A T E S, F O R C E S A N D S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
384	SAGBEND	-2687.12	-1995.79	3.58	3579.40	.000	.000	1753.42	104.493	-.0301	.0118	.0931	34.47
385	SAGBEND	-2697.10	-1996.39	3.31	3589.40	.000	.000	1752.93	104.551	-.0302	.0118	.0931	34.48
386	SAGBEND	-2707.08	-1996.94	3.05	3599.40	.000	.000	1752.48	104.604	-.0302	.0118	.0931	34.49
387	SAGBEND	-2717.07	-1997.45	2.78	3609.40	.000	.000	1752.06	104.651	-.0302	.0118	.0931	34.49
388	SAGBEND	-2727.06	-1997.91	2.51	3619.40	.000	.000	1751.69	104.690	-.0302	.0118	.0932	34.50
389	SAGBEND	-2737.05	-1998.33	2.25	3629.40	.000	.000	1751.35	104.715	-.0302	.0118	.0932	34.51
390	SAGBEND	-2747.05	-1998.69	1.98	3639.40	.000	.000	1751.05	104.714	-.0302	.0118	.0932	34.51
391	SAGBEND	-2757.04	-1999.02	1.71	3649.40	.000	.000	1750.78	104.655	-.0302	.0118	.0932	34.52
392	SAGBEND	-2767.04	-1999.29	1.45	3659.40	.000	.000	1750.56	104.465	-.0303	.0118	.0932	34.52
393	SAGBEND	-2777.03	-1999.52	1.18	3669.40	.000	.000	1750.37	103.963	-.0303	.0117	.0932	34.51
394	SAGBEND	-2787.03	-1999.71	.92	3679.40	.000	.000	1750.22	102.713	-.0303	.0116	.0931	34.50
395	SAGBEND	-2797.03	-1999.84	.66	3689.40	.000	.000	1750.11	99.667	-.0303	.0113	.0930	34.46
396	SAGBEND	-2807.03	-1999.94	.41	3699.40	.000	.000	1750.04	92.288	-.0303	.0104	.0928	34.35
397	SAGBEND	-2817.03	-1999.99	.20	3709.40	.390	.000	1750.00	74.451	-.0303	.0084	.0921	34.12
398	SEABED	-2827.03	-2000.01	.05	3719.40	6.230	.000	1750.00	36.860	-.0303	.0042	.0909	33.66
399	SEABED	-2837.03	-2000.01	.00	3729.40	9.386	.000	1750.00	8.357	-.0303	.0009	.0901	33.36
400	SEABED	-2847.03	-2000.01	-.01	3739.40	8.986	.000	1750.00	-.621	-.0303	-.0001	.0899	33.28

401	SEABED	-2857.03	-2000.01	.00	3749.40	8.398	.000	1750.00	-1.324	-.0303	-.0001	.0899	33.29
402	SEABED	-2867.03	-2000.01	.00	3759.40	8.171	.000	1750.00	-.546	-.0303	-.0001	.0899	33.28
403	SEABED	-2877.03	-2000.01	.00	3769.40	8.137	.000	1750.00	-.093	-.0303	.0000	.0899	33.28
404	SEABED	-2887.03	-2000.01	.00	3779.40	8.149	.000	1750.00	.024	-.0303	.0000	.0899	33.28
405	SEABED	-2897.03	-2000.01	.00	3789.40	8.159	.000	1750.00	.023	-.0303	.0000	.0899	33.28
406	SEABED	-2907.03	-2000.01	.00	3799.40	8.162	.000	1750.00	.008	-.0303	.0000	.0899	33.28
407	SEABED	-2917.03	-2000.01	.00	3809.40	8.162	.000	1750.00	.001	-.0303	.0000	.0899	33.28
408	SEABED	-2927.03	-2000.01	.00	3819.40	8.162	.000	1750.00	-.001	-.0303	.0000	.0899	33.28
409	SEABED	-2937.03	-2000.01	.00	3829.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
410	SEABED	-2947.03	-2000.01	.00	3839.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
411	SEABED	-2957.03	-2000.01	.00	3849.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
412	SEABED	-2967.03	-2000.01	.00	3859.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
413	SEABED	-2977.03	-2000.01	.00	3869.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
414	SEABED	-2987.03	-2000.01	.00	3879.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
415	SEABED	-2997.03	-2000.01	.00	3889.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
416	SEABED	-3007.03	-2000.01	.00	3899.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
417	SEABED	-3017.03	-2000.01	.00	3909.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
418	SEABED	-3027.03	-2000.01	.00	3919.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
419	SEABED	-3037.03	-2000.01	.00	3929.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
420	SEABED	-3047.03	-2000.01	.00	3939.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
421	SEABED	-3057.03	-2000.01	.00	3949.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
422	SEABED	-3067.03	-2000.01	.00	3959.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
423	SEABED	-3077.03	-2000.01	.00	3969.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
424	SEABED	-3087.03	-2000.01	.00	3979.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
425	SEABED	-3097.03	-2000.01	.00	3989.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
426	SEABED	-3107.03	-2000.01	.00	3999.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
427	SEABED	-3117.03	-2000.01	.00	4009.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28

OFFPIPE - OFFSHORE PIPELAY ANALYSIS SYSTEM - VERSION 2.05 X   DATE - 6/ 6/2011   TIME - 9:24: 8   PAGE 19
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S T A T I C   P I P E   C O O R D I N A T E S,   F O R C E S   A N D   S T R A I N S

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	PIPE LENGTH (M)	SUPPORT REACTION (KN)	SEPARA -TION (M)	AXIAL TENSION (KN)	BENDING MOMENT (KN-M)	TENSILE STRAIN (PCT)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PERCNT ALLOW (PCT)
428	SEABED	-3127.03	-2000.01	.00	4019.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
429	SEABED	-3137.03	-2000.01	.00	4029.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
430	SEABED	-3147.03	-2000.01	.00	4039.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
431	SEABED	-3157.03	-2000.01	.00	4049.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
432	SEABED	-3167.03	-2000.01	.00	4059.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
433	SEABED	-3177.03	-2000.01	.00	4069.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
434	SEABED	-3187.03	-2000.01	.00	4079.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
435	SEABED	-3197.03	-2000.01	.00	4089.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
436	SEABED	-3207.03	-2000.01	.00	4099.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
437	SEABED	-3217.03	-2000.01	.00	4109.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
438	SEABED	-3227.03	-2000.01	.00	4119.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
439	SEABED	-3237.03	-2000.01	.00	4129.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
440	SEABED	-3247.03	-2000.01	.00	4139.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
441	SEABED	-3257.03	-2000.01	.00	4149.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
442	SEABED	-3267.03	-2000.01	.00	4159.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
443	SEABED	-3277.03	-2000.01	.00	4169.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
444	SEABED	-3287.03	-2000.01	.00	4179.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
445	SEABED	-3297.03	-2000.01	.00	4189.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
446	SEABED	-3307.03	-2000.01	.00	4199.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
447	SEABED	-3317.03	-2000.01	.00	4209.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
448	SEABED	-3327.03	-2000.01	.00	4219.40	8.162	.000	1750.00	.000	-.0303	.0000	.0899	33.28
449	SEABED	-3337.03	-2000.01	.00	4229.40	.000	.000	1750.00	.000	-.0303	.0000	.0899	33.28

OFFPIPE - OFFSHORE PIPELAY ANALYSIS SYSTEM - VERSION 2.05 X   PAGE 20
2000waterdepth
JOB NO. - 1   LICENSEE: J. P. KENNY
USER ID - ML   DATE - 6/ 6/2011   TIME - 9:24: 8   CASE 1

S T A T I C   S O L U T I O N   S U M M A R Y

PIPE PROPERTIES (1)

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  PIPE SECTION LENGTH ..       .00 M     ELASTIC MODULUS ......   207000. MPA
  OUTSIDE DIAMETER .....    50.800 CM    CROSS SECTIONAL AREA .    370.70 CM2
  WALL THICKNESS .......     2.440 CM    MOMENT OF INERTIA .... 108645.80 CM4
  WEIGHT/LENGTH IN AIR . 2853.300 N/M    YIELD STRESS .........    482.00 MPA
  SUBMERGED WGHT/LENG ..  816.340 N/M    STRESS INTENS FACTOR .     1.000
  SPECIFIC GRAVITY .....     1.401
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BARGE DATA

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  TOTAL PIPE TENSION ...   3426.31 KN    RADIUS OF CURVATURE ..    380.00 M
  NUMBER OF TENSIONERS .         3       BARGE TRIM ANGLE .....      .000 DEG
  NO. OF PIPE SUPPORTS .         7       PIPE ANGLE AT STERN ..     1.665 DEG
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STINGER DATA

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  NO. OF PIPE SUPPORTS .        14       PIPE DEPTH AT STERN ..    -53.21 M
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NO. STINGER SECTIONS . 14 PIPE ANGLE AT STERN .. 57.829 DEG
RADIUS OF CURVATURE .. 130.00 M STINGER STERN DEPTH .. -53.41 M
STINGER LENGTH .... 140.00 M

SAGBEND DATA
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WATER DEPTH .... 2000.00 M TENSION AT TOUCHDOWN . 1750.00 KN
TOUCHDOWN X-COORD. ... -2820.84 M BOTTOM SLOPE ANGLE ... .000 DEG
PROJECTED SPAN LENGTH 2706.03 M PIPE LENGTH GAIN ..... 803.03 M

============================== SOLUTION SUMMARY ==============================

NODE NO.	PIPE SECTION	X COORD (M)	Y COORD (M)	VERT ANGLE (DEG)	REACT -ION (KN)	BENDING MOMENT (KN-M)	BENDING STRAIN (PCT)	TOTAL STRAIN (PCT)	PCT ALL (%)
1	LAYBARGE	89.3	15.5	.0	14.6	.0	.000	.000	0.
3	LAYBARGE	76.8	15.5	.0	36.7	-16.2	-.002	.002	1.
5	TENSIONR	70.6	15.5	.0	9.0	7.2	.001	.045	17.
7	LAYBARGE	63.0	15.5	.0	31.3	-13.1	-.001	.046	17.
9	LAYBARGE	51.1	15.5	.0	33.0	-15.3	-.002	.046	17.
11	LAYBARGE	40.9	15.5	.0	25.9	-6.8	-.001	.045	17.
13	LAYBARGE	31.2	15.5	.0	41.7	-10.2	-.001	.046	17.
15	TENSIONR	25.7	15.5	.0	-40.1	38.9	.004	.049	18.
17	TENSIONR	16.4	15.5	.2	82.3	-250.8	-.028	.073	27.
19	LAYBARGE	3.3	15.3	1.7	163.0	-755.3	-.085	.130	48.
22	STINGER	-10.0	14.6	4.8	233.3	-1360.3	-.154	.198	73.
24	STINGER	-19.9	13.5	8.7	367.3	-1909.4	-.216	.260	96.
26	STINGER	-29.7	11.6	13.2	271.5	-1807.1	-.204	.249	92.
28	STINGER	-39.4	8.9	17.6	293.1	-1831.0	-.207	.251	93.
30	STINGER	-48.8	5.5	22.0	287.0	-1825.6	-.206	.250	93.
32	STINGER	-57.9	1.4	26.4	279.8	-1823.9	-.206	.250	93.

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OFFPIPE - OFFSHORE PIPELAY ANALYSIS SYSTEM - VERSION 2.05 X PAGE 21
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JOB NO. - 1 LICENSEE: J. P. KENNY
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S T A T I C S O L U T I O N S U M M A R Y

34	STINGER	-66.7	-3.4	30.9	268.1	-1818.8	-.205	.249	92.
36	STINGER	-75.1	-8.9	35.3	266.3	-1819.2	-.206	.249	92.
38	STINGER	-83.0	-14.9	39.7	262.8	-1816.1	-.205	.249	92.
40	STINGER	-90.4	-21.6	44.1	273.8	-1828.4	-.207	.250	93.
42	STINGER	-97.4	-28.9	48.5	223.6	-1775.4	-.201	.244	90.
44	STINGER	-103.7	-36.6	53.1	427.1	-1994.1	-.226	.269	100.
46	STINGER	-109.4	-44.8	56.6	65.3	-844.3	-.095	.139	51.
48	STINGER	-114.8	-53.2	57.8	.0	-239.2	-.027	.070	26.
392	SAGBEND	-2767.0	-1999.3	1.4	.0	104.5	.012	.093	35.
398	SEABED	-2827.0	-2000.0	.1	6.2	36.9	.004	.091	34.

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OFFPIPE - OFFSHORE PIPELAY ANALYSIS SYSTEM - VERSION 2.05 X DATE - 6/ 6/2011 TIME - 9:24: 8 PAGE 22
PROJECT - 2000waterdepth JOB NO. 1
USER ID - ML LICENSEE: J. P. KENNY CASE 1
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O V E R B E N D P I P E S U P P O R T G E O M E T R Y

STATION NO.	LOCATION	PIPE NODE	SUPT NODE	PIPE COORDINATES X (M)	PIPE COORDINATES Y (M)	PIPE COORDINATES ANGLE (DEG)	SUPPORT COORDINATES X (M)	SUPPORT COORDINATES Y (M)	SUPPORT COORDINATES ANGLE (DEG)	VERTICAL REACTION (KN)	VERTICAL SEPARATION (M)
1	LAYBARGE	1	2	89.337	.500	.04	89.350	.500	.00	14.60	.000
2	LAYBARGE	3	4	76.770	.500	-.02	76.777	.500	.00	36.71	.000
3	TENSIONR	5	6	70.646	.500	.00	70.650	.500	.00	9.05	.000
4	LAYBARGE	7	8	62.996	.500	.01	63.000	.500	.00	31.33	.000
5	LAYBARGE	9	10	51.051	.500	.00	51.055	.500	.00	32.97	.000
6	LAYBARGE	11	12	40.884	.500	.00	40.888	.500	.00	25.89	.000
7	LAYBARGE	13	14	31.248	.500	.01	31.252	.500	.00	41.71	.000
8	TENSIONR	15	16	25.723	.500	-.03	25.727	.500	.00	-40.08	.000
9	TENSIONR	17	18	16.373	.500	.19	16.377	.500	.00	82.30	.000
10	LAYBARGE	19	20	3.295	.319	1.66	3.300	.320	1.76	162.98	.000
11	STINGER	22	23	-9.997	-.385	4.75	-9.993	-.385	4.41	233.33	.000
12	STINGER	24	25	-19.931	-1.537	8.73	-19.926	-1.536	8.82	367.34	.000
13	STINGER	26	27	-29.746	-3.449	13.25	-29.742	-3.448	13.23	271.55	.000
14	STINGER	28	29	-39.385	-6.110	17.63	-39.381	-6.108	17.63	293.13	.000
15	STINGER	30	31	-48.792	-9.504	22.05	-48.788	-9.502	22.04	287.00	.000
16	STINGER	32	33	-57.910	-13.611	26.45	-57.906	-13.609	26.45	279.80	.000
17	STINGER	34	35	-66.685	-18.407	30.86	-66.681	-18.404	30.86	268.05	.000
18	STINGER	36	37	-75.065	-23.863	35.27	-75.062	-23.860	35.27	266.26	.000
19	STINGER	38	39	-83.001	-29.947	39.68	-82.998	-29.943	39.68	262.78	.000
20	STINGER	40	41	-90.447	-36.623	44.10	-90.443	-36.619	44.08	273.77	.000
21	STINGER	42	43	-97.357	-43.851	48.45	-97.354	-43.848	48.49	223.58	.000
22	STINGER	44	45	-103.690	-51.590	53.08	-103.688	-51.586	52.90	427.08	.000
23	STINGER	46	47	-109.411	-59.792	56.57	-109.409	-59.788	57.31	65.30	.000
24	STINGER	48	49	-114.810	-68.212	57.83	-114.482	-68.405	61.72	.00	.381

P R O F I L E   P L O T   F I L E   I N F O R M A T I O N

RECORD 1ST	RECORD LAST	ROW NO.	PLOT NO.	PLOT TYPE	TIME (SECS)	HORIZ AXIS CODE	HORIZ AXIS TITLE	VERTI AXIS CODE	VERTI AXIS TITLE	TITLE	X MIN	X MAX	Y MIN	Y MAX
1	14	1	1	1	.0	1	PIPE HORIZONTA	2	PIPE ELEVETION	PIPELINE ELEVAT	.00	.00	.00	.00
15	28	2	1	1	.0	1	PIPE HORIZONTA	14	TOTAL VON MISE	PIPELINE ELEVAT	.00	.00	.00	.00
29	42	3	2	1	.0	1	PIPE HORIZONTA	10	VERTICAL MOMEN	VERTICAL BENDIN	.00	.00	.00	.00
43	56	4	2	1	.0	1	PIPE HORIZONTA	15	PERCENT YIELD	VERTICAL BENDIN	.00	.00	.00	.00