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MASTER'S THESIS

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Writer: Sankaranarayanan Subramanian	………………………………………… (Writer's signature)

Faculty Supervisor:
Prof. Daniel Karunakaran, Ph.D
(University of Stavanger, Subsea 7 Norway)

External Supervisor(s):
Dr. Qiang Chen, Ph.D (Subsea 7 Norway)

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Analysis and Optimization of Rigid Pipeline Installation with Inline Structures

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ABSTRACT

Advanced modern technologies and growing demand for oil and gas has led to the discovery and development of smaller and remote fields that were once considered uneconomical. They are made economically more viable by employing a subsea development scheme and directing the output to existing platform for production and processing instead of having their own platform. This has necessitated the introduction of inline structures in the pipelines with the possibility to connect these remote fields when they are developed for production.

However the presence of these structures introduces many installation challenges including increased weight and additional environmental loading. In some cases this might drastically reduce the limiting sea state for installation.

For the scope of the thesis work, any structure in the middle of the pipeline with stiffness and weight greater than the pipeline is considered as an inline structure. A riser and pipeline installation using J-Tube pull in method is considered as the case study for analysis in the thesis. Analysis and parametric study of the installation is made with emphasis on the initiation phase to determine the limiting sea state for the safe installation of the pipeline.

The main focus of the thesis would be to analyze the possibilities to optimize the limiting sea state for the installation of the J-tube seal with the help of buoyancy units by creating a neutrally buoyant catenary during installation. An attempt to develop a generalized optimization procedure to determine the optimal buoyancy unit configuration for all inline structure installation is made although the results indicate that it might be very case specific and a general method might not exist. Analysis to understand the influence of the type of buoyancy unit, the position on the pipeline catenary, net buoyancy, number of buoyancy modules and various other parametric studies are made. In addition, challenges encountered during an inline structure installation and the modifications required to carry out the installation from the vessel is briefly discussed.

The analysis reveals that geometry of the buoyancy does not have appreciable impact. A sensitivity study on the added mass of the buoyancy shows that an increased added mass reduces the buckling utilization by its out-of-phase dynamic response with that of the catenary. Sagbend buckling is the most critical concern for installation and it is at its maximum when the structure is at the sagbend. It also reveals that the best results are achieved when the net buoyancy of the module is equal to the excess weight in the catenary due to the structure. A buoyancy unit that is offset from the structure provides better result than a similar module connected over the structure and also better results than the use of multiple buoyancy modules although this might be very case specific.

Key Words: Inline structures, Buoyancy, Rigid Pipeline, Pipeline Installation, Orcaflex, Riflex.

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Stavanger, 14th June, 2013

Sankar Subramanian

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SYMBOLS

SYMBOLS – LATIN CHARACTERS

AM_X - Added Mass in x-direction

AM_Y - Added Mass in y-direction

AM_Z - Added Mass in z-direction

C_{AZ} - Non dimensional added Mass Coefficient in z-direction

C_{dx} - Non dimensional drag co-efficient in x-direction

C_{dz} - Non dimensional drag co-efficient in z-direction

CD_X - Drag force co-efficient in x-direction

CD_Y - Drag force co-efficient in y-direction

CD_Z - Drag force co-efficient in z-direction

D_o - Outer diameter

E - Young's modulus

f_y - Characteristic yield strength

f_u - Characteristic tensile strength

fy,temp - De-rating values due to the temperature of the yield stress

fu,temp - De-rating values due to the temperature of the tensile stress

M_{Sd} - Design moment

M_p - Plastic moment capacity of the pipe

S_{Sd} - Design effective axial force

L_{Sd} - Design Load

L_f - Functional Load

L_e - Environmental Load

L_a - Accidental Load

L_i - Incidental Load

P_e - External Pressure

P_i - Internal pressure

P_d - Design pressure

P_{min} - Minimum internal pressure that can be sustained.

P_C - Characteristic collapse pressure

R_{rd} - Design Resistance

S_p - Plastic axial tension capacity of the pipe

t - Nominal pipe wall thickness (un-corroded)

t_2 - Characteristic wall thickness; t for pipelines prior to operation

W_d - Design Water depth

SYMBOLS – GREEK CHARACTERS

γ_m - Material resistance factor

γ_{SC} - Safety class resistance factor

γ_F - Functional Load factor

γ_E - Environmental Load factor

γ_C - Conditional Load factor

α_C - Flow stress parameter

α_U - The material strength factor.

α_{fab} - Fabrication Factor

ρ_{sea} - Density of sea water

ν - Poisson's Ratio

ABBREVIATIONS

ALS	–	Accidental Limit State
BM	-	Bending Moment
CRA	–	Corrosion resistant Alloys
COG	–	Center of Gravity
DNV	–	Det Norske Veritas
DMA	–	Dead Man Anchor
DVL	–	Diverless Latch
DP	-	Dynamic Positioning
FBE	–	Fusion Bonded Epoxy
FLS	–	Fatigue limit State
GOM	-	Gulf of Mexico
ILT	-	Inline Structures
ISO	-	International Standards Organization
JIP	-	Joint Industry Project
JONSWAP	-	Joint North Sea Wave Project
LRFD	–	Load Resistance Factor Design
MBR	–	Minimum Bend Radius
PLUTO	–	Pipeline Under the Ocean
PLET	–	Pipeline End Terminal
PHS	–	PLET Handling System
PLEM	–	Pipeline End Manifold
ROV	–	Remotely Operated Vehicle
SAWL	-	Submerged Arc Welding (Single Longitudinal Weld Seam)
SMYS	-	Specified minimum Yield Strength
SMTS	–	Specified Minimum Tensile Strength

SLS	–	Serviceable Limit State
UOE	-	Pipe fabrication process for welded pipes, expanded
VIV	–	Vortex Induced Vibration
ULS	–	Ultimate Limit State

1. INTRODUCTION

1.1 BACKGROUND

Pipeline is the most efficient and cheapest mode of transportation of the hydrocarbons to land for processing and distribution. Extensive business and engineering considerations go into the pipeline installation process. Offshore pipeline installation process has a proven track record. However many technical challenges are encountered besides weather, water depth and installation vehicle capability and need to be addressed carefully during an installation process.

Pipeline engineering is a science in its own right. Many advances have been made in the installation process and the design of installation vehicles. There are various types of installation methods and the choice is made based on the project requirements and many other factors. Reel lay used in the thesis is one of the fastest installation methods as the pipeline is welded in an onshore facility and spooled into the reel as very long segments. Figure 1.1 shows a reel lay vessel with vertical reel.

Figure 1.1Reel Lay Pipeline Installation Vessel – Seven Oceans [31]

In addition to pipelines, many inline and end structures like Wye, Tee joints, Pipeline End Terminals (PLET) and Sleds are installed in the catenary between pipe segments. Advanced modern technology has made it possible to develop smaller and remote fields. It is economically beneficial to process their output at existing fields nearby. Inline structures facilitate future tie-in of pipelines coming from these fields. This would avoid the installation of separate trunk lines [13].

Figure 1.2 Very Large Inline Sled [28]

Some of these inline structures are very large and can weigh as much as 136 metric tons [28] as shown in Figure 1.2. These large inline structures introduce many installation challenges due to increased weight in the catenary and suffer additional environmental loads. Also they might necessitate changes to the installation process itself including vessel and process modifications and contingency operations. During installation, they impose huge stress and bending on the pipeline. If the allowable limit of the pipe strength is breached then it will result in a phenomenon called local buckling shown in Figure 1.3 which results in the gross deformation of the pipe. In deep water, local buckling might initiate a more global instability where, driven by external pressure, the collapse propagates along the pipeline, often at high velocity. This phenomenon is known as propagation buckling [5, P.13]. This might eventually result in the flooding of pipeline and require an expensive and time consuming abandonment and recovery operation to complete the installation. Figure 1.4 shows the installation of an Inline structure.

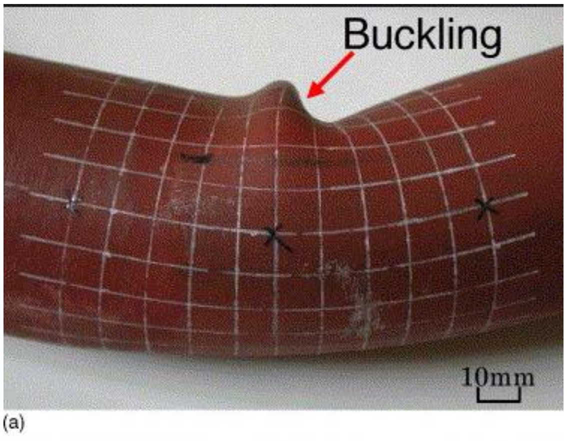

Figure 1.3Local Buckling in Pipeline [30]

Figure 1.4Inline Structure (Tee) Installation [6]

Proper considerations and analysis must be made to select the optimal installation method and process to overcome the technical difficulties. Buckling is the chief failure mode during installation. The main focus of the installation analysis is to identify the safe limiting sea state that would keep the buckling utilization of the pipeline under the allowable limits. The industry practice is to use buoyancy modules to improve the limiting sea state for installation. The extra buoyancy provided by the buoyancy module reduces the weight of the inline structure and consequently stress and bending moment in the pipeline. However it is very hard to generalize the buoyancy requirement for installation process. The buoyancy requirements vary depending on a number of project parameters including the weight and shape of the inline structure, water depth and vessel capabilities. Extensive analysis is required to arrive at the optimal configuration of buoyancy. Figure 1.5 shows the installation of an inline structure with buoyancy modules attached.

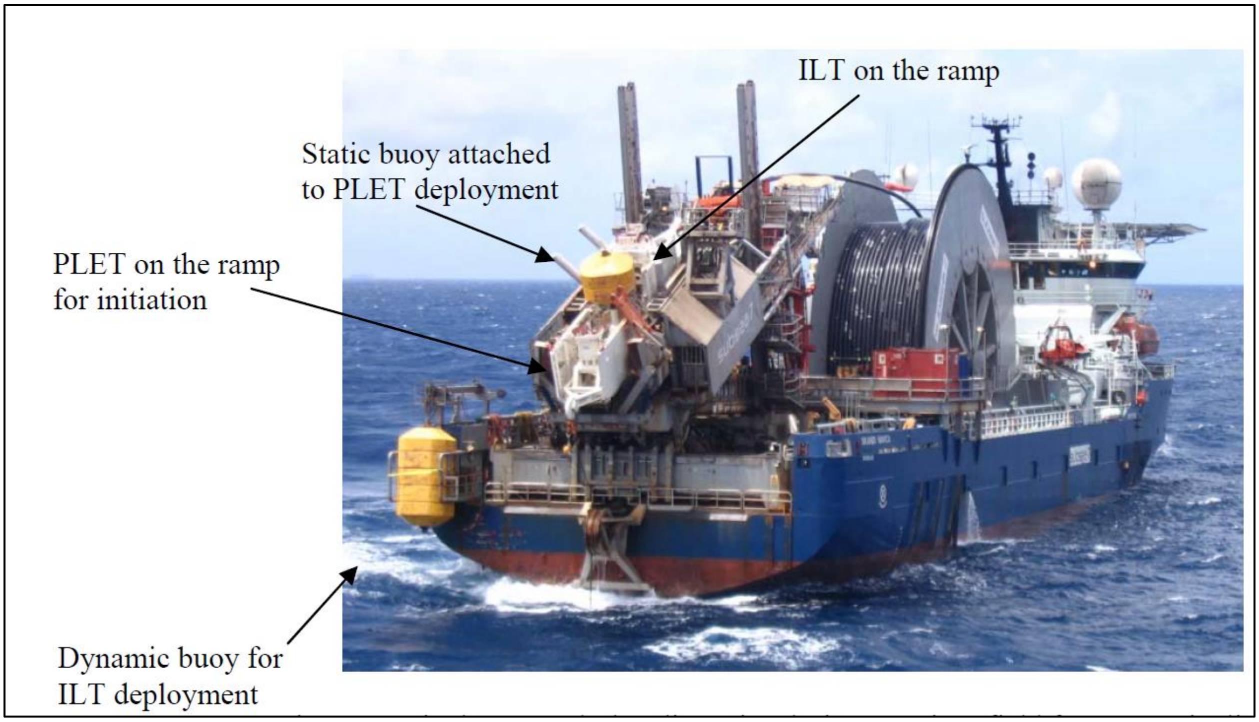

Figure 1.5Installation of Inline Structure with Buoyancy Modules [29]

1.2 THESIS PURPOSE AND SCOPE

In this thesis, installation of pipeline with inline structures will be studied in detail and the optimization of the installation process will be attempted using buoyancy modules.

During installation of pipeline with inline structures, pipeline will be subjected to additional loads in terms of bending moment, tension (axial force), and rotational effect due to the offset of COG and external hydrostatic load due to the presence of the structure. The inline structure passes through various stages of the installation process and the load on the pipeline will be different at each stage. The Figure 1.6 shows the installation of an inline SLED.

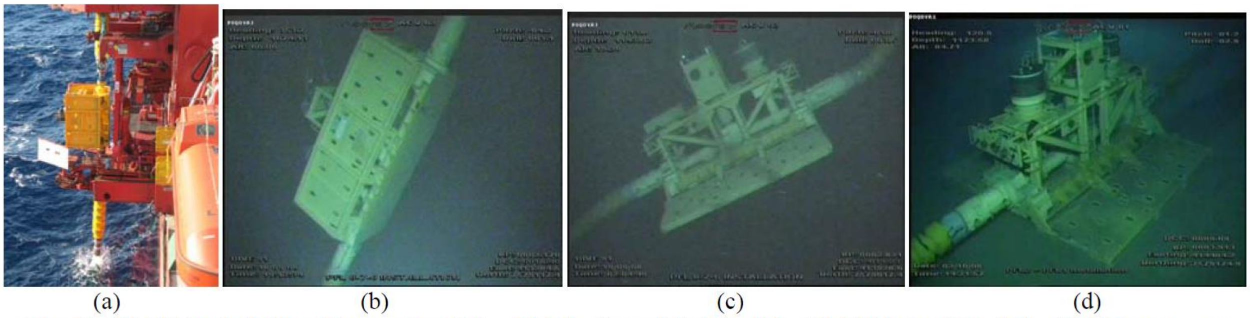

Fig. 7 - SLED Installation Sequence: (a) – SLED at work table, (b) – SLED lowering, (c) – SLED near sea floor with mudmat opened, (d) - SLED landed

Figure 1.6Installation steps [15]

The loading on the pipeline is especially pronounced at the sagbend as the pipeline approaches the seabed. Sometimes they drastically reduce the limiting sea state permitted for the installation process. This might have huge economic consequences because of waiting on weather of the installation vessel and result in consequent project delays. Hence the installation process needs to be optimized to improve the limiting sea state using buoyancy units during the critical parts of the operation.

The purpose of the thesis is to study the installation of rigid pipeline with inline structures and to analyze and understand the various parameters governing the installation process. Further on, optimization of the limiting sea state for the installation process is carried out using buoyancy modules and an attempt to obtain a general optimization procedure is made.

Scope of the thesis:

- Literature review of pipeline installation, inline and end structure installation (Books and published journal papers)
- Identify and study challenges with regard to inline structure installation.
- Analysis of installation process and parameter study to identify the limiting sea state
- **Optimization of the installation process to increase the installation limiting sea state.**
- A general procedure to determine the optimal buoyancy module configuration for an inline structure installation.
- Discussion of the analysis results and parametric study
- Conclusion and Recommendation

Optimization of the installation process using buoyancy module to increase the limiting sea state is the primary focus of the thesis.

1.3 THESIS ORGANIZATION

Chapter 2: (Offshore pipelines) This chapter briefly summarizes the background and various aspects of offshore pipelines. It includes a short description of various concepts, components, Materials, Challenges of offshore pipeline installations and major pipeline projects in the world.

Chapter 3: (Pipeline Installation Methods) This chapter provides information on various installation methods available and briefly discusses the different advantages and disadvantages of those methods. It also summarizes the basics of concept selection and factors influencing the decision.

Chapter 4: (Design Methodology & Loads) This chapter discusses the various standards and codes employed in the industry for pipeline design and installation. It also summarizes the design methodology for the installation process.

This chapter summarizes various environmental and functional loads encountered during the installation process.

Chapter 5: (Inline and End Structures Installation) This chapter describes the pipeline installation with inline and end structures and discusses the various challenges encountered and solutions practiced especially the usage of buoyancy modules.

Chapter 6: (Case study and Analysis) describes a typical North Sea pipeline installation project and various analysis performed to ensure the pipeline integrity and establish the limiting sea state for the installation process.

Chapter 7: (Optimization Process) describes in detail various analysis performed using buoyancy module to determine the most optimal configuration to improve the limiting sea state for the installation process. Various parametric studies are performed using different buoyancy modules.

Chapter 8: (Conclusion and Recommendations) summarizes the results of the analysis and states the conclusion of the thesis and makes recommendations for any future work.

2. OFFSHORE PIPELINES

2.1 HISTORICAL BACKGROUND

The offshore petroleum industry has a relatively short history with the first well in ocean waters drilled in the Gulf of Mexico in 1947 in 6 m water depth. The earliest petroleum pipelines date from before 1947 and were constructed in the shallow water in the Gulf of Maracaibo and the Caspian Sea off Azerbaijan [4, p.6]

Since then many major pipeline construction projects have been completed across the world connecting the distant offshore field to the land. They form a very vital part of the oil and gas industry. They are expensive and the increasing demand of oil and gas has in resulted newer and advanced technologies.

Oil and Gas has to be transported to the market. They can be transported via tankers or pipelines. Pipeline is the most common and preferred mode of transportation for the following reasons:

- Safer
- Environment friendly
- Least energy requirement
- Lowest maintenance costs
- Minimal impact on land use pattern
- Negligible loss of product in transit
- High reliability

Pipelines have been successfully installed in water depths of 2500 m and technology and feasibility for installation in water depths of greater than 3000 m are being studied. This chapter will briefly discuss the different aspects of pipelines with respect to offshore industry.

2.2 PIPELINE SYSTEM COMPONENTS

While a subsea pipeline refers to the section of the pipeline under water, an offshore pipeline system is not confined to it. 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 [1]. Figure 2.1 shows the schematics of a subsea pipeline system for a fixed platform.

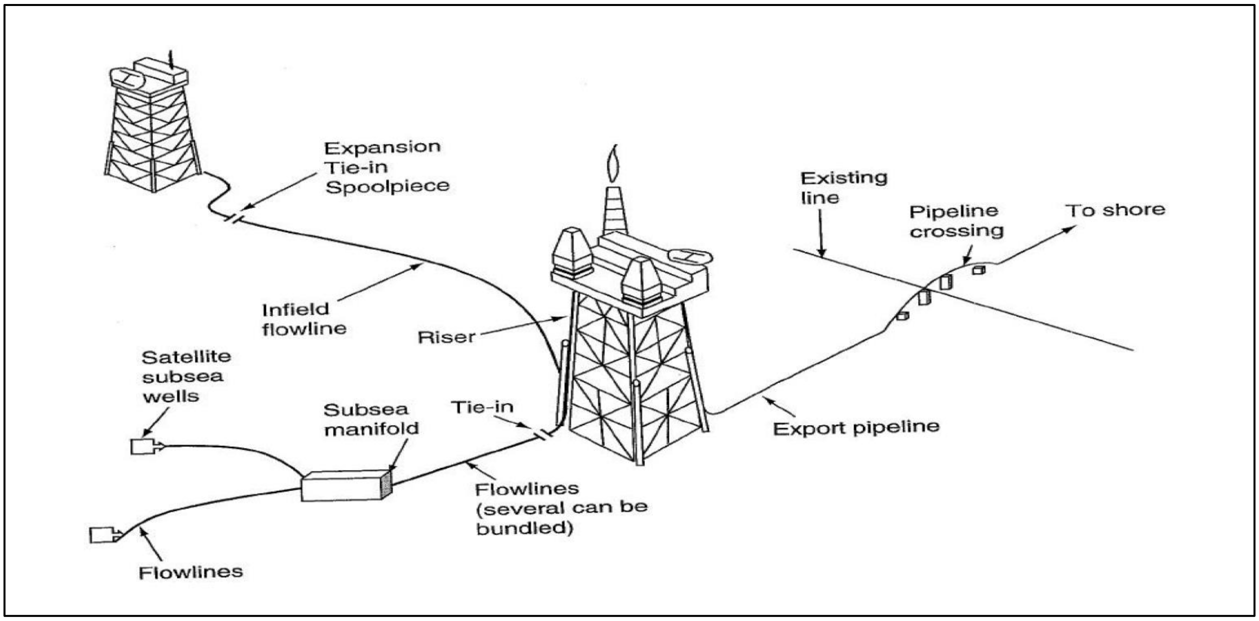

Figure 2.1 Offshore pipeline System [2]

An offshore pipeline system will typically comprise of:

RISERS

Risers are vertical section of the pipeline system that connects the subsea pipeline to the topside equipment on the platform. There are many different types of risers including drilling, production, export and water injection risers. Riser concepts vary depending upon the platform type. Some of the riser concepts used in floating offshore production platforms are stated below [21]

- Flexible risers
- Steel catenary risers
- Hybrid riser towers
- Single hybrid risers(SLOR)
- Grouped SLOR

J tube risers used in the thesis is a concept used in fixed platforms. In the thesis, no riser specific or J-tube Pull-In analysis is performed.

VALVE ASSEMBLIES

Inline valves like ball valves and check valves along with other support structures to control the well flow and establish desired flow assurance.

PIG LAUNCHERS AND RECEIVERS

These are structures connected to pipeline to send and receive pigs.

INLINE AND END STRUCTURES

Various inline structures like Tees and Wyes and End structures like PLET are an integral part of pipeline system. They are also installed along with the pipes to improve the efficiency of the installation process and keep the cost low.

INTERNAL AND EXTERNAL COATING AND ANTI-CORROSION SYSTEMS

Internal coating is carried out to prevent internal corrosion, to resist erosion, and to improve the flow assurance characteristics of the fluid. Fusion bonded Epoxy (FBE) is the most common internal anti-corrosion coating. [1]

External coating is done to prevent corrosion, protect the pipeline from impact, to establish the desired weight/buoyancy for the whole unit and to offer thermal insulation. Hot applied enamel coating is the traditional option. However more sophisticated three layered polyolefin coatings are gaining ground. FBE is also used but it is not common.

Anodes are installed at predetermined length to prevent corrosion. In addition, based on the requirement, the pipeline system might have a cement coating, buckle arrestor and numerous other components.

2.3 PIPELINE TYPES & CONCEPTS

RIGID PIPE

Rigid pipelines are the most common type of pipeline due to their ease of fabrication, low cost and good mechanical properties. They are usually made out of carbon steel and manganese with several other alloying materials. Various concepts of pipelines like pipe-in-pipe, sandwich pipes and single steel pipes are examples of rigid pipeline. Single carbon steel pipelines are the most commonly used pipeline in the offshore industry due to their low cost and high strength. Rigid pipelines with various degrees of ductility, strength, toughness and weldability are developed from shallow to deep waters.

Some of the major problems with rigid pipelines are external corrosion and its large weight. Internal corrosion and erosion are also an issue depending upon the fluid transported. They are also subjected to higher fatigue life cycles compared to flexible pipelines.

FLEXIBLES

Unbonded flexible pipes are an alternative to rigid steel flow lines and risers. They are constructed from concentric layers of metals and polymeric thermoplastic materials. Each layer has a specific function and each layer is added from inside outward. The important layers as extended from the inside are the carcass (Prevents the collapse of the thermoplastic liner as a result of internal pressure), thermoplastic pipe liner (Contains the hydrocarbon fluids), Steel pressure containment layers (layers that take the impact load, internal pressure and longitudinal forces) and a plastic outer sheath (Protects the pipe from external corrosion).

When used as a riser for floating platforms, the main advantage of flexible pipe is their excellent dynamic characteristics under extreme conditions compared to rigid pipelines. In general they have a relatively good insulating and chemical compatibility properties and serves as better flow lines or risers compared to rigid pipelines. They function as expansion spools when used as tie-in jumpers to accommodate flowline walking and other pipeline expansion phenomenon. However as flow lines for long distance, they are expensive and hence only used as infield flow lines for shorter length.

COMPOSITE

Composite pipes are constructed out of one of the composite materials such as epoxy reinforced with glass fiber, carbon fiber or silicon nitride. This method completely eliminates the pipeline corrosion and at the same time provides high strength. The biggest constraint is the manufacturing cost.

2.4 STEEL PIPELINE MATERIALS AND GRADES

Pipeline material selection is one of the most important steps leading to the success of the pipeline system with respect to meeting operational requirements through the expected lifetime of the system.

According to DNV [3, p.92], the selection of material for the pipeline should be based upon

- Fluid being transported
- Loads on the pipeline
- Temperature
- Possible failure modes during installation and operation
- Water depth

The following material characteristics should be considered:

- Mechanical properties (mainly strength)
- Hardness
- Fracture toughness
- Fatigue resistance
- Weldability
- Corrosion resistance

In addition to this, as always, cost of the pipeline will be a governing factor.

With respect to installation, ductility is another important material property that needs to be given due consideration. Ductility decreases with increase in strength. Right balance between strength and ductility needs to be achieved. As the strength of the steel is increased the gap between yield and tensile strength is decreased and consequently the ductility of the material in the elastic range is narrowed. This means that if the pipe is subjected to excessive tension during the installation process due to adverse weather, then pipe might fail by tensile tearing rather than deforming and remaining intact. If the pipe is intact, the weakened section can be replaced while a complete loss of pipeline to seabed will necessitate recovery operation and increased cost and loss of time.

To allow an adequate window between yield and tensile strength, it is usual to specify a minimum ratio between the yield strength and the tensile strength. Typical ratios used in pipe specifications are 0.92 longitudinal for a sweet service pipeline and 0.95 for a sour service pipeline. [4, p.40]

Based on the strength of the material (Yield and tensile strength), API provides a grading system shown in Table 2.1.

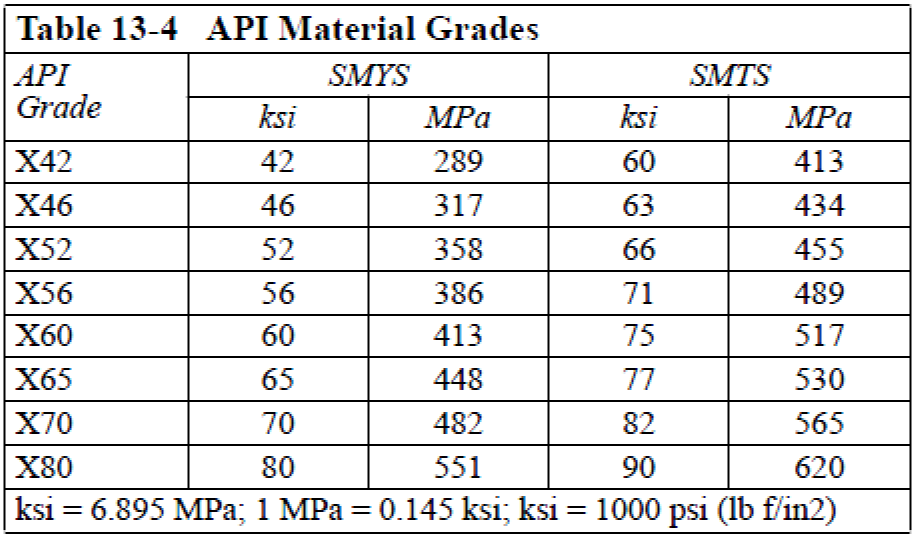

Table 13-4 API Material Grades

API Grade	*SMYS*		*SMTS*	
	ksi	*MPa*	*ksi*	*MPa*
X42	42	289	60	413
X46	46	317	63	434
X52	52	358	66	455
X56	56	386	71	489
X60	60	413	75	517
X65	65	448	77	530
X70	70	482	82	565
X80	80	551	90	620

ksi = 6.895 MPa; 1 MPa = 0.145 ksi; ksi = 1000 psi (lb f/in2)

Table 2.1 API Material Grades [3, p. 212]

API identifies steel grade by yield strength as X42 to X80 where the number refers to the yield strength in pounds per square inch (psi). For example, X65 has yield strength of 65 psi. In addition to the API 5L specification, purchasers usually impose additional specifications with regard to the composition of the steel. This includes very specific chemical composition of the steel with the inclusion of impurities (various metals and alloys) to attain very specific material properties. Some of the metals added are Si, Al, Ca, Ni, N, V, NB, Ti, P in addition to carbon and manganese. These elements are added to increase the strength of the steel. [4, p. 26]

A delicate balance between strength, toughness and weldability is required for an efficient pipeline. A pipeline must have high strength while retaining ductility, toughness and weldability. There is conflict between these properties as an increase in strength is usually attained at the cost of other properties. Strength is the ability of the pipeline to resist longitudinal and transverse tensile forces imposed during service and installation. Ductility is the ability of the pipe to absorb some of the stress imposed during operation and installation by deformation.

Toughness is the ability to withstand impact loads. Weldability is the ability and ease of production of a quality weld and heat affected zone of required strength and toughness. For subsea pipelines the prime factor driving the need for weldability is economy. Faster the ability to produce good welds, the faster the installation operation is and lesser the cost spent on lay barge.[4, p. 27].

Pipelines are described based on the material composition and some of the important types are named below [25]:

- Carbon-Manganese steel
- Duplex
- Cladded Carbon Steel with Corrosion Resistant Alloys (CRA)
- Chrome Pipeline

2.5 MAJOR PIPELINE PROJECTS

Pipeline design and installation varies in complexity depending on the seabed profile, water depth, configuration and interaction with other systems on the seabed, length, geography and installation parameters. Water depth is one of the most important parameters dictating the complexity of the project. The record for the deepest and longest pipeline installation is constantly rewritten.

Some the major and most complex pipeline projects in the world are listed in the Table 2.2

Table 2.2 Major Offshore Pipeline Projects [5, p.2][22][23][24]

Properties	Blue Stream	Mardi Gras	Independence Trail	Nord Stream	Langeled	Perdido
Product	Gas	Oil/Gas	Gas	Gas	Gas	Oil
From-To Location	Russia-Turkey	5 fields in GOM	Fields in GOM	Russia - Germany	Norway (Nyhamna) to England (Easington)	GOM
Length	396 Km	750 Km (Total)	200 Km	1224 Km Twin Lines	1200 Km	13 Km
Operation Date	2003	2006	2007	2012	2006	2009
Capacity	16 Billion m^3/a	-	850 MMscf/d	55 Billion m^3/a	25.5 Billion m^3/a	-
Diameter	24”	16” – 30”	24”	48”	42” – 44”	18”
Grade	X65	X65	X65	SAWL 485	SAWL 485	X65
Maximum Water Depth	2150m	1310-2225	2450m	210 m	1000 m	2500 – 2900 m
Company/ Vessel	Saipem 7000	Technip’s Solitaire Herema’s DCV Balder	Allseas Solitaire & Lorelay	AllSeas Solitaire & Saipem’s Castoro Dieci	Subsea 7 Acergy Piper	Technip Deep Blue
Installation Method	J Lay	J and S Lay	J Lay	S Lay	S Lay	Reel lay
Cost	2.5B$	1 B$	0.28B$	7.4 B Euros	£1.7 B	-
Special Features	Deepest Offshore Pipeline, 2003	Most complex subsea pipeline system	One of the world’s deepest pipeline	World’s Longest and biggest pipeline	One of the World’s Longest and biggest pipeline	One of the world’s deepest pipeline

3. PIPELINE INSTALLATION METHODS

3.1 INTRODUCTION:

Pipeline installation is one of the important stages of offshore field development. The choice of installation method is influenced by the water depth, pipeline type and material, time and cost among other things. The sophistication and innovation required during installation are enormous and it has developed into a science in its own right. There are 4 major pipeline installation methods, each with its own benefits and short comings.

1. S-Lay
2. J-Lay
3. Reel Lay
4. Towing

3.2 S-LAY

S-Lay is one of the oldest and commonly employed methods of pipeline installation. It has acquired the name because the pipeline starts in a horizontal position on the vessel and acquires a characteristic S-shape on the way to the seabed. A linearly-arranged series of stations weld 12-24 m lengths to the free end of the line. The welds are tested and coated and the vessel moves forward, paying the line into the sea. The pipe leaves at the stern of the vessel via a sloping ramp with rollers. At the end of the ramp, the pipeline comes in contact with a long boom-like curved structure known as stinger. The stinger is either rigid or articulated open frame structure that supports the pipe on v-shaped rollers. The angle suspended by the stinger can be adjusted to accommodate installation at various depths. The suspended pipeline is held by tensioners that are usually located on the ramp. The section of the pipe on the stinger is subjected to bending and high tension. If the length of stinger is too short, the pipeline leaving the stinger will undergo excessive bending at the end of the stinger and will buckle. This buckle might fracture the pipeline and subsequently flood the line (wet buckle). This will in turn increase the weight of the pipeline which might become too heavy to be held by tensioners resulting in the loss of the line [5].

The pipeline bends twice during the S-lay. The upper curved part is known as overbend. This curvature can be controlled by controlling the tension on the pipeline and changing the angle of the stinger. Further down, it straightens and then gradually bends in the opposite direction and it is termed as sagbend. The maximum curvature occurs closer to the seabed at the sagbend. It is essential to ensure that the pipeline can sustain the combined load of bending and external pressure at the sagbend. Any buckling might result in the initiation of propagation buckling.

One of the main functions of the lay vessels is to maintain the tension that holds the pipe and controls its shape. In older vessels this tension is reacted by mooring lines. Modern vessels have Dynamic Positioning system to control their position. This is achieved by thrusters which are computer controlled using GPS.

Traditionally S-lay has been the main pipe installation method for water depths up to 1000 m. Recently, S-lay water depth has been nearly doubled by the design and installation of longer articulated stingers on DP enabled vessels with high tension capacities. Although modern vessels can apply very high tension, it comes at a significant cost to operation. Hence most of the pipelines are installed empty to minimize the tension requirements. Figure 3.1 shows S lay configuration along with loads experienced by various sections of the pipeline.

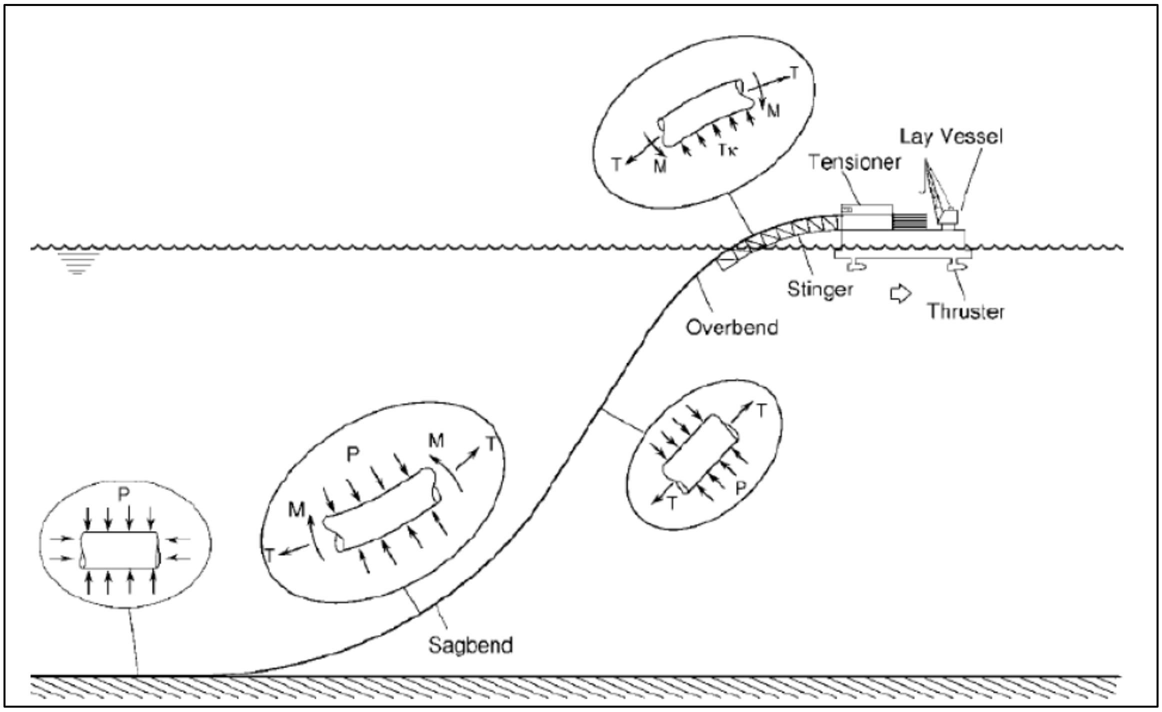

Figure 3.1 Schematic Representation of S-lay Pipeline Installation and Pipeline Loading [5]

Advantages:

- S Lay can handle very shallow water by adjusting the stinger angle accordingly.
- The long firing line provides opportunity to perform better welding and thorough nondestructive testing.
- The lay speed is faster than J Lay

Disadvantages:

- There is larger wave action and load on the stinger and the pipeline as it enters the water.
- It cannot handle very deep water as the tension and buckling limits are breached.
- It cannot weather wane easily under rough weather.

3.3 J-LAY

J-lay is an alternative installation method in which the pipeline leaves the vessel from a nearly vertical position. The tower angle varies between 0 to 15 degrees. As the pipeline approaches the seabed it attains the characteristic J-Shape from which the name J-Lay is derived. As the water depth increases the tension requirements goes up in a conventional S-lay configuration and the stinger shape becomes more complex. These tough requirements are overcome in J-lay and also the suspended length is reduced in comparison to s-lay.

However the vertical stance of the stinger leaves the vessel with just one welding and inspection station usually. To overcome this longer pipe section are used to increase the speed and efficiency of the operation. They usually consist of two to four 12 m sections pre-welded on shore. Each multiple length section is then raised to the tower aligned with the suspended pipe, welded to it, inspected and coated. An additional advantage of lower tension in the line on the seabed translates into shorter free spans. Figure 3.2 shows J lay installation along with loads experienced by various sections of the pipeline.

J-lay is slower than the conventional S-lay but it can install pipes even at a water depth of 3350 m. Loads experienced by such deep water lay are described below:

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

Also in deep waters the possibility of propagation buckling should not be overlooked and installation of buckle arrestors is usually obligatory [5].

Advantages of J-Lay [4, p. 363]

- The steep ramp angle means that tension is only dictated by the need to limit bending in the sagbend. Hence the tension requirements are usually lesser than S-Lay
- There is no need for stinger
- There is far lesser wave splash zone loads
- The lesser tension means that free spans are smaller and the complex seabed profiles are better negotiated.
- It is better suited for congested area as it can be better positioned than S-lay vessel. This is because the reduced tension ensures that the touch down point is not as far behind the barge.
- It can weathervane better in severe weather.

Disadvantages

- Because of the steep ramp angle which can accommodate only fewer simultaneous operations, the lay speed is slower.
- The added weight of the ramp high up in the vessel might affect its stability in rough weather
- It is not suited for shallow waters as the ramp angle has to be lowered to a smaller angle.

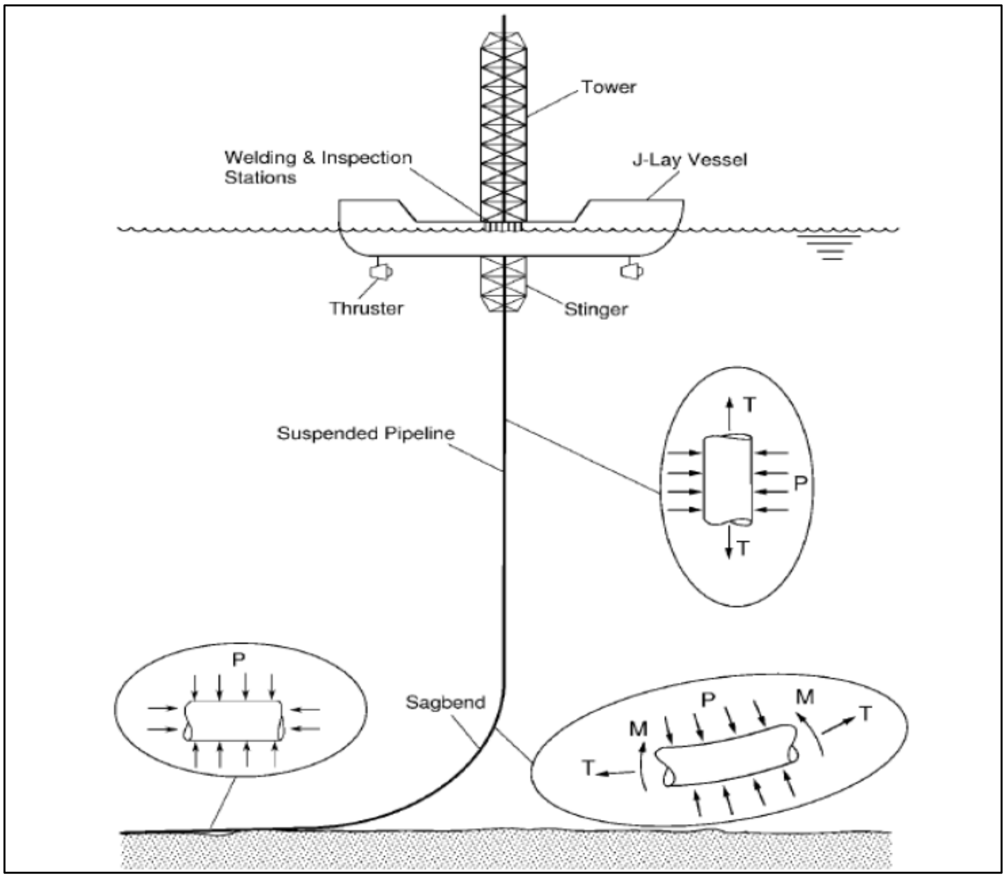

Figure 3.2 Schematic Representation of J-lay Pipeline Installation and Pipeline Loading [5]

3.4 REEL LAY METHOD:

Reeling is one of the most versatile and cost efficient method of pipeline installation methods. The first significant pipeline installation using reeling was carried out under the Pipelines under the Ocean (PLUTO) project during world war II to carry fuel to allied ships in Normandy from England.

In reeling method, several kilometers of pipeline are fabricated at an onshore spool base. Then they are wound onto a large diameter reel mounted on a pipeline installation vessel which travels to the project location and starts the installation process by unreeling the pipeline.

This facilitates the existing reel vessels to lay at a speed of up to two knots per hour. Most of the fabrication process – assembly, welding, inspection, and coating are done on-shore which results in significant reduction in installation time and cost of the process.

One of the earliest reel laying vessel is Sante Fe's 'Chickasaw'. It is a vessel built in 1970, a flatbed barge equipped with a horizontal reel with a 6.1 m radius hub. It has installed a plethora of pipelines primarily in Gulf of Mexico.

The next major development in reeling technology is sante Fe's Apache, a vessel equipped with a vertical reel. The vessel is capable of handling up to 16 inch pipeline.

Nowadays, Reel Lay vessels are capable of installing upto 18" diameter pipelines. Reel lay in excess of 450-500 T top tension is currently not available as they give rise to higher residual strain post installation. [6]

The mechanism of spooling and unspooling initiates certain bending curvature to the pipeline that causes it to go into the plastic range of the material. In the case of Apache reel with 8.23m radius, a 12-inch pipeline bends to maximum strain of 1.93% and 16-strain pipeline to 2.41% strain. To avoid local buckling the pipeline wall thickness and mechanical properties of the pipe should be chosen properly. [5, p.44]

There are two types of reel lay methods as shown in Figure 3.3 and Figure 3.4

1. Vertical
   This employs a spool that is placed vertical in the reel vessel and installed using a J-lay assembly after straightening.

2. Horizontal
   In this method, the spool is placed horizontally on the lay vessel and is installed using a S-lay assembly with the help of a stinger.

The advantages and disadvantages for reeling installation method are described below:

Advantages:

a. Improved control on fabrication standards since it happens at the spool base.
b. Influence of bad weather is reduced due to fast installation speed.
c. Minimum preparation to assemble spools of various sizes of pipes for continuous installation.
d. Can also be used for pipeline bundles.

Disadvantages:

a. Maximum pipeline size limited up to 18-inch diameter.
b. Relatively thick wall thickness required to accommodate the plastic strain induced during the process of spooling and unspooling.

c. Limited length of pipeline that can be reeled into a single reel. The larger the diameter, the lesser the length of pipeline that can be reeled.
d. Cement coating cannot be performed and if any internal lining is made then it needs proper analysis to avoid wrinkling.

Figure 3.3 Reel Lay Vessel – Vertical Reel – Subsea7's Seven Navica [7]

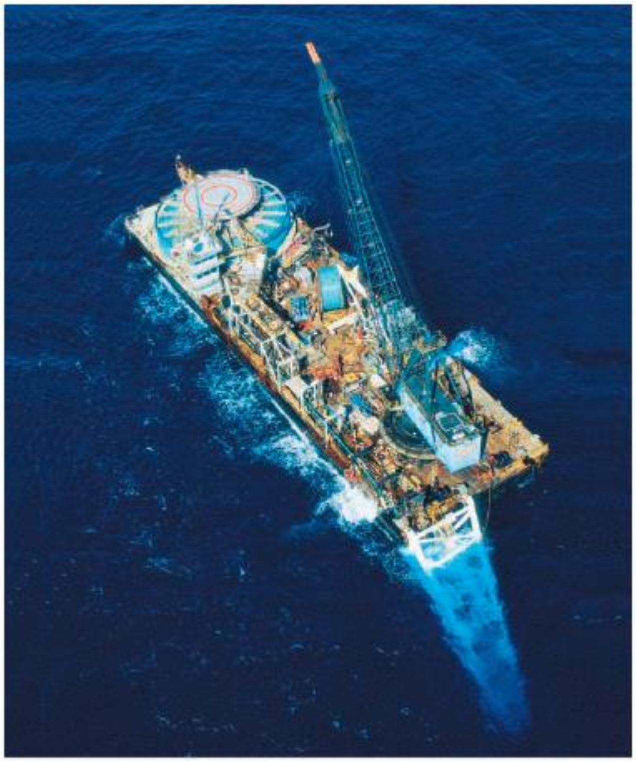

Figure 3.4 Reel Lay Vessel – Horizontal Reel – Sante Fe's Chickasaw [5]

3.5 TOWING

Towing is another method of pipeline installation that is ideal for shorter pipeline sections, shore approaches as well as bundles. A section of pipeline is constructed onshore and is then towed to the installation site. An advantage of this method is that welding, inspection and testing are conducted onshore before installation. There are 4 different types of towing methods. They are stated below with a schematic representation shown in Figure 3.5 through Figure 3.8.

1. Surface Tow
2. Controlled Depth Tow
3. Off-Bottom Tow
4. Bottom Tow

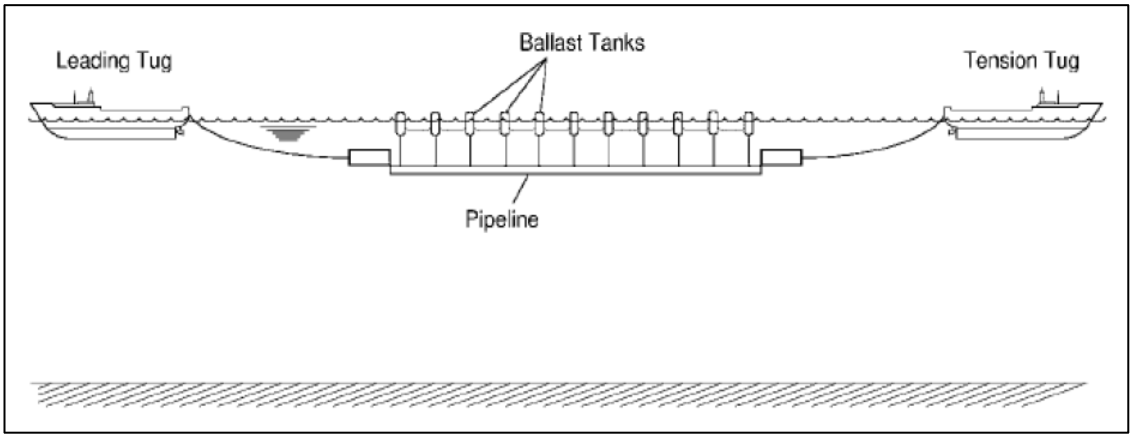

Figure 3.5 Schematic of a surface Tow [5]

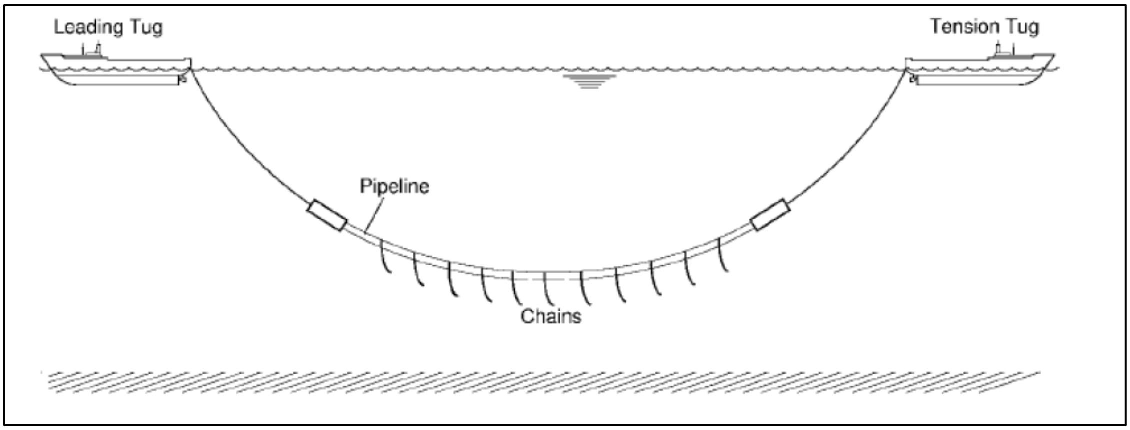

Figure 3.6 Schematic of Controlled Depth Tow [5]

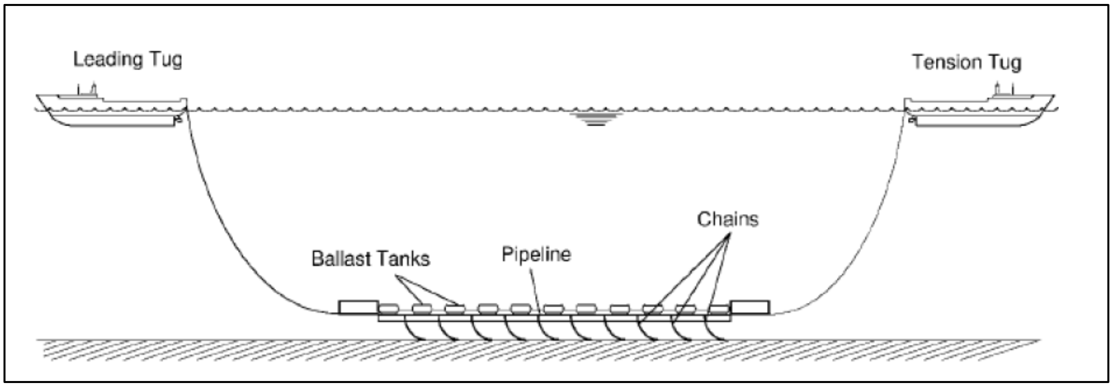

Figure 3.7 Schematic of Off-bottom Tow [5]

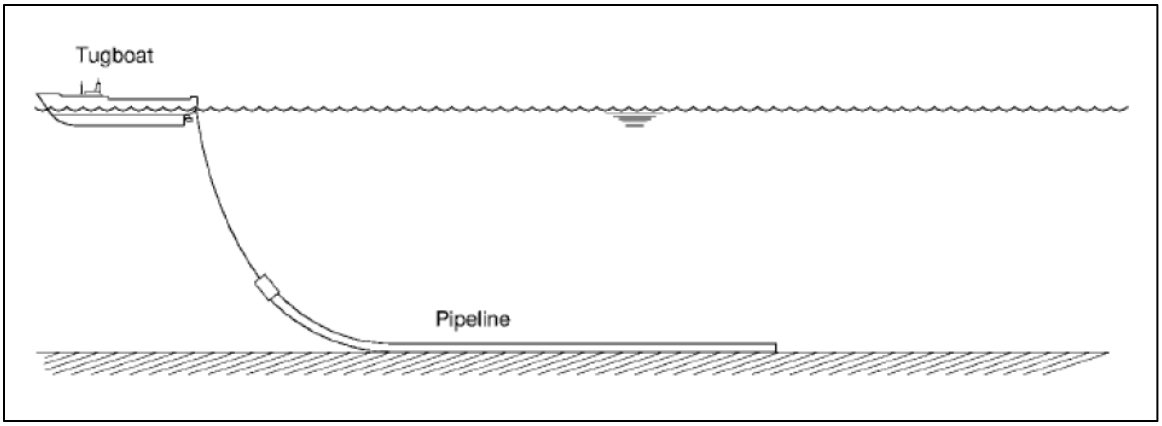

Figure 3.8 Schematic of Bottom Tow [5]

3.6 CONCEPT SELECTION AND INFLUENCING FACTORS:

Various factors influence the selection of installation method.

- Water depth
- Type of pipeline
- Overall cost
- Project duration – lay speed
- Vessel availability
- Project complexity

Based on the advantages and disadvantages discussed earlier, reel lay offers a time and cost efficient installation option. The only constrain is that the diameter of the pipeline is currently restricted to 18". It can handle very deep water as well as shallow waters.

Larger pipeline installation has to choose between S lay and J lay. While both methods offer similar results and there is not much to choose between them in deep water, S lay provides slightly faster lay speed and is more suited for shallow water. However when it comes to very deep water J lay is the only option as S lay cannot handle the tension and buckling requirements at such depth.

Some projects are more complex due to the water depth varying from shallow to very deep and might need multiple vessels to handle this variation of water depth. The advent of vessels like Seven Borealis which is fitted with both S lay and J lay installation equipment helps to handle the project complexity better by hiring just one vessel instead of multiple vessels to install pipeline sections in shallow and deep water. Figure 3.9 shows Seven Borealis.

Figure 3.9 S and J Lay Installation Vessel – Seven Borealis [32]

3.6 INSTALLATION PROCESS

All the installation methods described above with the exception of towing will comprise of the following phases during the installation process. Independent analysis is required to identify and analyze various parameters governed by these phases of installation.

3.6.1 INITIATION

Initiation phase consists of several steps and begins with the step when the pipe head is paid out from the vessel, passes the ramp, through the splash zone, traverses the water depth, through the sagbend and ends when it reaches the seabed. With respect to installation analysis the output of the initiation phase is an initiation lay table with various pipe payout steps. The bending moment at the top and sagbend along with tension would be the limiting parameters during this phase. Dynamic analysis need to be performed for the critical steps especially when the pull head or other structures in the catenary are at the sagbend [8].

Initiation occupies a significant part of the overall pipeline installation phases and has numerous interfaces including geotechnical, mooring, construction, naval etc.

During initiation analysis, step by step pay out analysis should be done until the structure is laid down on the seabed. For each step the pipeline pay out, vessel movement and any change in ramp angle should be defined.

3.6.2 NORMAL LAY

Normal lay is the continuous laying phase of the installation. The ship moves forward as it pays out the pipe. Normal lay analysis is performed prior to the initiation analysis in order to determine the installation parameters like optimum ramp angle, limiting sea state at the end of initiation. Normal lay analysis should be carried out for the maximum and minimum water depth and also account for any significant slopes in the seabed profile.

3.6.3 LAYDOWN

Pipeline laydown phase begins once the pipeline reaches the target laydown area. The end termination structure like second end PLET is welded to the last segment of the pipeline and lowered down to the seabed.

The analysis would include a step by step table with various laydown wire payout steps as the vessel moves forward until the PLET is laid down on the seabed at the target location. It should include an analysis report for empty and flooded condition and other contingency plans as might be required for the proper landing of the end structure.

3.6.4 A&R

Abandonment and Recovery phase takes place if the pipeline has to be abandoned in the middle of the installation operation. It might take place in case of an accidental flooding of the pipeline and the integrity of the installation operation and vessel capabilities are breached or it might be prompted by weather phenomenon and excessive sea state. During A&R operation, the pipeline is clamped and cut and an A&R head is welded onto the end of the pipeline and laid down at the seabed by paying out the A&R wire while the vessel moves forward. The operation and the analysis is very similar to the laydown phase.

3.7 INITIATION METHODS

A number of methods are available for initiating the pipeline installation process. Seabed features, obstacles, cost are some of the factors which determine the choice of initiation method.

Some of the methods are [9]:

- Surface Initiation
- Vertical initiation
- Return Sheave Initiation

- Hold Back Cable Initiation
- Launched Riser initiation
- Bow String Initiation
- Vertical Pull-In Initiation
- Pipe-on-Pipe Initiation
- J-Tube Initiation
- Live Initiation
- Shore Pull In Initiation

There are two main methods used for Rigid Pipeline Initiation [10, p.30].

SEABED ANCHOR

Seabed anchor initiation consists of a wire running from an initiation head/PLET at the end of the pipe to a fixed anchor point on the seabed. The vessel moves forward as the pipe is paid out. Dead Man Anchor (DMA) and suction pile are examples of this type.

RETURN SHEAVE INITIATION

Return sheave initiation, sometimes referred to as diverless latch (DVL) consists of a return wire running from the pipe initiation head, through a sheave on the seabed and back to a winch on the vessel. With this method of initiation the vessel is at a distance from the target box and pays out the pipe. A return sheave initiation is generally used if there is a space limitation on the seabed. Indeed, subsea congestion and access alongside structures influences the method of initiation to be used.

J-TUBE PULL IN METHOD

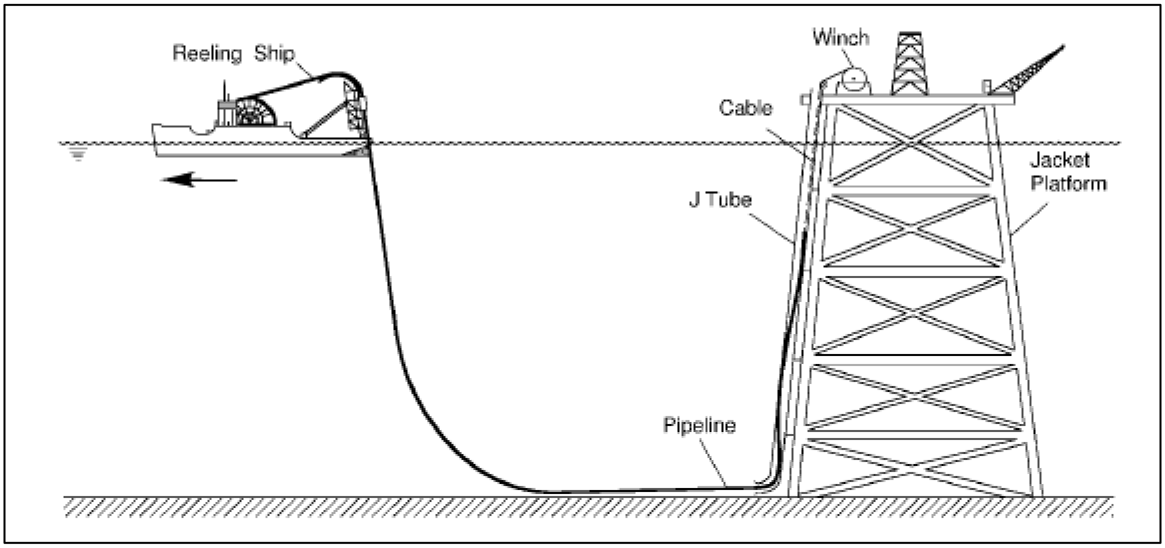

Figure 3.10 Schematic representation of J-Tube Pull In Method [5]

The case study made in the thesis employs J-Tube pull in initiation method and hence it is briefly described here. However no analysis pertaining to the pull in method is performed in the thesis. Figure 3.10 shows the schematics of a J Tube Pull in method. The riser is pulled up an existing J-tube in this type of initiation to avoid tie-in spools and a continuous pipeline to the top side. The pipeline undergoes plastic deformation as it traverses the bend in the J-tube and the diameter is restricted to 14” because of this constraint. The large bending forces inside the J-tube, high pull in loads at the topside and the pipe diameter are the constraining parameters.

4. DESIGN METHODOLOGY AND LOADS

4.1 DESIGN CODES

Pipeline design and installation is a vital and major part of any field development project. Hence it is strictly governed by established standards throughout its life-cycle from design to fabrication, installation, commissioning, operation and decommissioning.

There are a number of design codes in existence today. The choice of a particular code will be decided by the geographical location of the project, the countries legislation and the operator of the field. Additional requirements can be placed on top of the code as requirements arise.

For installation analysis, the pipeline code requirements are mainly directed towards determining the allowable equivalent stresses or bending moment applied to the pipeline.

Some of the major codes used across the world are briefly discussed below [11] [12]:

DNV OS-101

This is the most widely used code in the world and is universally adopted in Norway. It is a comprehensive code which uses a safety class approach for all aspects of pipeline design. DNV assigns a LOW safety class for pipeline installation process due to the absence of internal pressure and reduced number of failure mechanisms during installation.

DNV uses a LRFD design method to define the limit states of various operations. It checks primarily for buckling under a combination of internal pressure, external pressure, and tension/compression loads and applied bending moment.

PD 8010 PART 2

This is used in UK sector on the North Sea and supersedes BS8010. Part 1 deals with onshore pipeline and Part 2 with offshore pipeline.

API RP 1111

This is primarily used in America and West Africa and uses a strain based criteria.

EN 14161

The EN 14161 is the European code for design of petroleum and gas transport systems. It is mainly based on ISO 13623.

ISO 13623

The ISO 13623 is the first international code prepared for liquid and gas pipeline transportation systems.

4.2 DESIGN FORMAT AND METHODOLOGY

Design standards of DNV for pipeline installation are based upon Load and Resistance Factor Design (LRFD) format [3, p.67].

The fundamental principle of the LRFD method is that the design load effects, L_{sd}, do not exceed the design resistances, R_{Rd}, for all kinds of failure modes under all loading scenarios.

$$f\left(\left(\frac{L_{Sd}}{R_{Rd}}\right)_i\right) \leq 1 \qquad \text{Eq. (4.1)}$$

Where,

i – Different loading types that enters the limit state.

4.2.1 LIMIT STATE DESIGN

DNV FS 101 employs a design methodology based on ‘Limit state’ for pipeline design and installation. It is the minimum requirement to be satisfied for the safe installation. DNV identifies four different failure modes and a limit state is assigned to each of them.

The different limit state categories are [25]:

- Ultimate limit state
- Fatigue limit state
- Serviceability limit state
- Accidental limit state

The pipeline has to satisfy each of these limit state for its structural integrity. It is the limit between the acceptable and unacceptable condition. The Table 4.1 shows all possible failure modes grouped under the corresponding limit states [3, p.71].

Table 4.1 Link between scenarios and limit states [3, p.71]

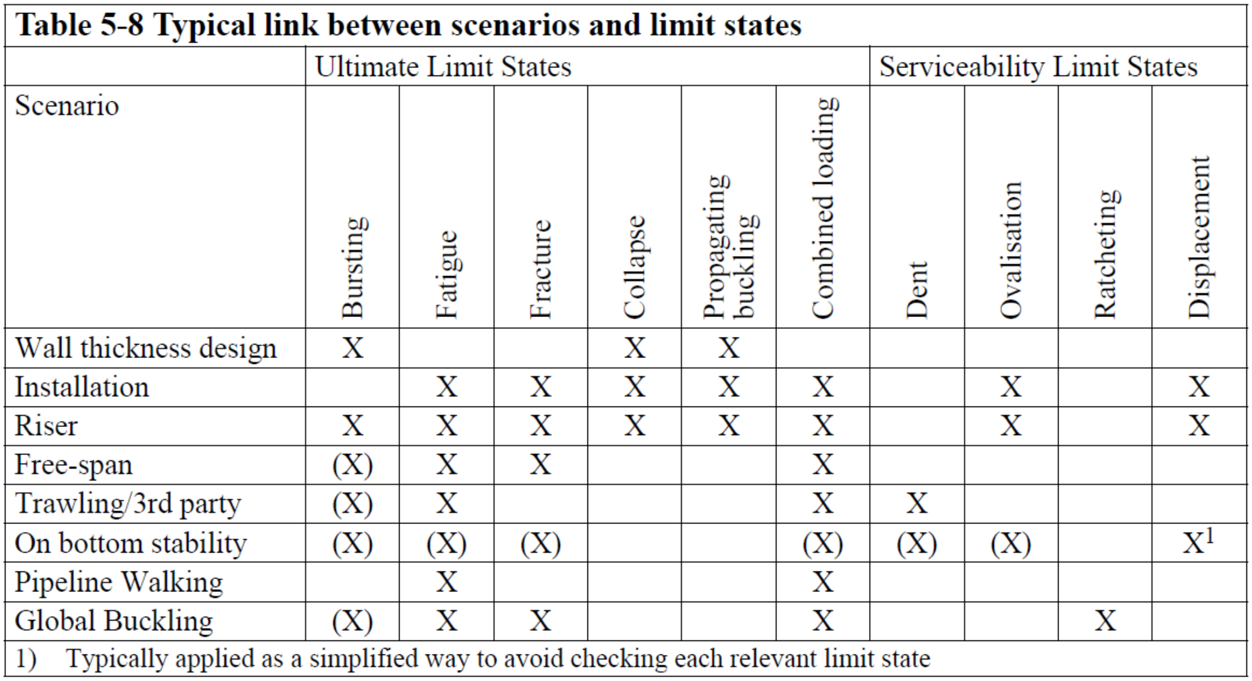

Table 5-8 Typical link between scenarios and limit states

	Ultimate Limit States						Serviceability Limit States			
Scenario	Bursting	Fatigue	Fracture	Collapse	Propagating buckling	Combined loading	Dent	Ovalisation	Ratcheting	Displacement
Wall thickness design	X			X	X					
Installation		X	X	X	X	X		X		X
Riser	X	X	X	X	X	X		X		X
Free-span	(X)	X	X			X				
Trawling/3rd party	(X)	X				X	X			
On bottom stability	(X)	(X)	(X)			(X)	(X)	(X)		X[1]
Pipeline Walking		X				X				
Global Buckling	(X)	X	X			X			X	

1) Typically applied as a simplified way to avoid checking each relevant limit state

Ultimate Limit State

ULS is concerned with the structural integrity and strength of the structure. As such the structure is designed with very low probability of reaching this state as the consequences are often severe. Hence the design process should result in a pipeline with strength and integrity that strictly adheres to DNV standards. ULS is considered as the governing design limit in the thesis.

The following should be covered under ULS for pipelines:

- ➢ Bursting
- ➢ Collapse
- ➢ Local and global buckling
- ➢ Propagation buckling

Fatigue Limit State

The FLS involves the fatigue damage resulting from cycling loads and accumulated throughout its life. The structure is designed such that its life, accounting for fatigue damage from all sources, meets or exceeds the design life. The loads are induced by waves and current.

Serviceability Limit State

The SLS involves the disruption of use of the structure as intended. For pipelines, this includes the following:

- Excessive ovality of cross section (initial or progressive).
- Excessive deflection or vibration.

Accidental Limit State

The ALS involves damage or failure due to unusual, accidental, or unplanned loading conditions such as:

- Dropped objects (impact loading)
- Explosion and/or fire
- Severe earthquakes or environments

4.2.2 LOCAL BUCKLING

Local buckling is one of the major considerations of pipeline installation. Local buckling implies the gross deformation of the cross section [3, p.72]

The following criteria shall be fulfilled with respect to local buckling:

- System collapse (external pressure only)
- Propagation buckling (external pressure only)
- Combined loading criteria (interaction between external pressure, axial force and bending moment)

Many parameters contribute to the onset of local buckling during installation. Normally, a pipeline is subjected to a combination of external pressure, axial forces (tension and compression) and bending moment. Combined loading is one of the most common causes for local buckling during installation and will be considered in the thesis.

Large accumulated plastic strain might aggravate local buckling [3, p.72] . Reel lay that introduces considerable plastic strain to the pipe should be paid extra attention to buckling analysis.

4.2.2.1 Local Buckling Design Methodologies

DNV OS F101 considers 2 approaches to local buckling.

- Load controlled Condition (LC Condition)
- Displacement controlled Condition (DC condition)

A load controlled condition is one in which the structural response is governed by imposed loads. This is the approach used for sagbend. DNV employs LRFD approach to LC conditions. LC condition is used in the thesis.

A displacement controlled condition is one in which the structural response is primarily governed by imposed geometric displacements. An example of purely displacement controlled condition is a pipeline bent into conformity with a continuous curved structure such as a J-Tube [3, p. 74]. For displacement controlled conditions, a strain based design approach is used. A strain based approach can often utilize a higher proportion of the pipe strength [12, p.12].

4.2.2.2 Local Buckling – External over pressure only

The external pressure at any point along the pipeline shall fulfill the following criterion [3, p.73]:

$$P_e - P_{min} \le \frac{P_c\,(t_1)}{\gamma_m \cdot \gamma_{SC}} \qquad \text{Eq. (4.2)}$$

Where

P_{min} is the minimum internal pressure that can be sustained. During installation, it is taken as zero as the pipeline is usually installed empty.

4.2.2.3 Local Buckling – Combined loading criteria

Pipelines subjected to combined bending moment, effective axial force and external overpressure shall be designed according to the following criterion at all cross sections:

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}}{\alpha_c \cdot S_p(t_2)}\right\}^2\right\}^2 + \left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{P_e - P_{min}}{P_c\,(t_2)}\right\}^2 \le 1 \qquad \text{Eq. (4.3)}$$

$$15 \le D/t_2 \le 45, \qquad P_i < P_e, \qquad |S_{Sd}|/S_p < 0.4$$

Where

P_i - Internal pressure

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

P_c - Characteristic collapse pressure defined in Eq. 4.2

P_e - External pressure

M_{Sd} - Design moment; Eq. 4.9

S_{Sd} - Design effective axial force; Eq. 4.10

M_p - Plastic moment capacity of the pipe;

$$M_p(t_2) = f_y\,(D_o - t_2)^2 t_2 \qquad \text{Eq. (4.4)}$$

S_p - Plastic axial tension capacity of the pipe;

$$S_p\,(t_2) = f_y\,\pi\,(D_o - t_2)\,t_2 \qquad \text{Eq. (4.5)}$$

D_o - Outer Diameter

t - Nominal pipe wall thickness (un-corroded)

t_2 - Characteristic wall thickness; t for pipelines prior to operation

γ_m - Material resistance factor defined in Table 4.3

γ_{SC} - Safety class resistance factor defined in Table 4.5

α_C - Flow stress parameter

The characteristic material strength f_y and f_u to be used in limit state criteria are:

$$f_y = (SMYS - f_{y,temp}).\ \alpha_U \qquad \text{Eq. (4.6)}$$

$$f_u = (SMTS - f_u,temp).\ \alpha_U \qquad \text{Eq. (4.7)}$$

$f_{y,temp}$ & f_u,temp - The de-rating values due to the temperature on the yield stress and the tensile strength respectively.

α_U - The material strength factor. Refer Table 4.2

SMYS - Specified minimum yield Strength

SMTS - Specified minimum tensile Strength

4.2.2.3.1 Utilization

DNV introduces the concept of ‘utilization’ to define the combined loading due to bending moment, axial load and external pressure based upon LRFD principles. The installation conditions should be analyzed to ensure that the utilization never goes beyond 1. All the load and resistance factors should be selected based on the criteria defined in DNV. A value greater than 1 signifies a failure due to buckling induced by excessive bending moment or loss of tension at the top or sagbend. Eq 4.3 defines the utilization criteria for buckling analysis.

4.2.2.3.2 Limiting Sea State

Limiting sea state for the installation operation is defined based on utilization results. The significant wave height that results in a buckling utilization of less than 1 for all the steps of installation process is termed as the limiting sea state for that phase of the installation operation.

4.2.3 MATERIAL AND LOAD FACTORS

Material load and resistance factors suggested by DNV are listed below.

Material Strength Factor

Materials strength specified are for materials of 100% purity. However there are always impurities introduced into the material before or during the fabrication of pipelines. To accommodate the loss in strength from these impurities, DNV introduces a material strength factor as defined in Table 4.2. Material strength factor of 0.96 is used in the thesis.

Table 4.2 Material Strength Factor [3, p.69]

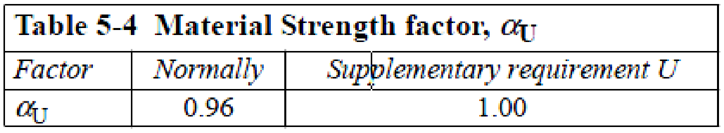

Table 5-4 Material Strength factor, α_U

Factor	*Normally*	*Supplementary requirement U*
α_U	0.96	1.00

Material Resistance Factor

Material resistance factor is a partial safety factor which transforms the characteristic resistance to a lower resistance and is shown in Table 4.3

Table 4.3 Material Resistance Factor [3, p.67]

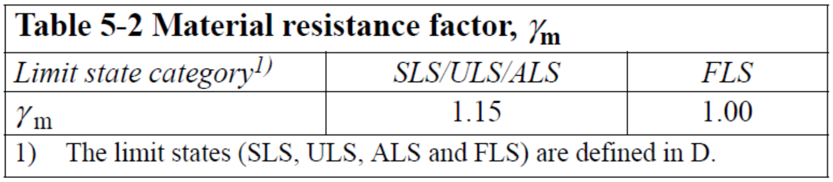

Table 5-2 Material resistance factor, γ_m

Limit state category[1)]	*SLS/ULS/ALS*	*FLS*
γ_m	1.15	1.00

1) The limit states (SLS, ULS, ALS and FLS) are defined in D.

Condition Load Effect Factor

Condition load effect factors are applied based on specific conditions they are defined for and they are applied in addition to the load effect factors. Table 4.4 defines the condition load effect factors defined by DNV and the condition 'otherwise' is used for installation.

Table 4.4 Conditional Load Effect factor [3, p.76]

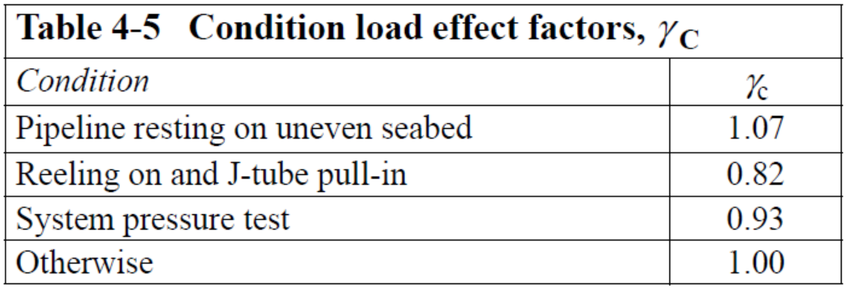

Table 4-5 Condition load effect factors, γ_C

Condition	γ_c
Pipeline resting on uneven seabed	1.07
Reeling on and J-tube pull-in	0.82
System pressure test	0.93
Otherwise	1.00

Safety Class and Safety Class Resistance Factor

Safety class is designated based on the fluid being carried and the location of the field and duration of operation. Pipeline installation is usually categorized under low category as they are mostly installed empty.

Table 4.5 defines the safety class resistance factors defined by DNV and a safety class resistance factor of 1.04 is used in the thesis.

Table 4.5 Safety Class Resistance Factors [3, p.68]

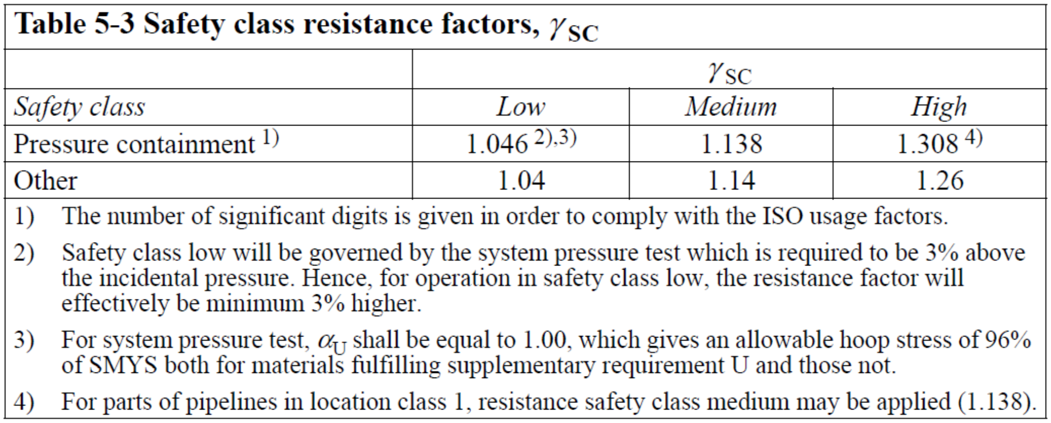

Table 5-3 Safety class resistance factors, γ_{SC}

	γ_{SC}		
Safety class	*Low*	*Medium*	*High*
Pressure containment 1)	1.046 2),3)	1.138	1.308 4)
Other	1.04	1.14	1.26

1) The number of significant digits is given in order to comply with the ISO usage factors.

2) Safety class low will be governed by the system pressure test which is required to be 3% above the incidental pressure. Hence, for operation in safety class low, the resistance factor will effectively be minimum 3% higher.

3) For system pressure test, α_U shall be equal to 1.00, which gives an allowable hoop stress of 96% of SMYS both for materials fulfilling supplementary requirement U and those not.

4) For parts of pipelines in location class 1, resistance safety class medium may be applied (1.138).

Fabrication Factor

For pipe manufacturing processes that introduce cold deformations giving different strength in tension and compression, fabrication factor α_{fab} is used and is shown in Table 4.6.

Table 4.6 Fabrication Factor

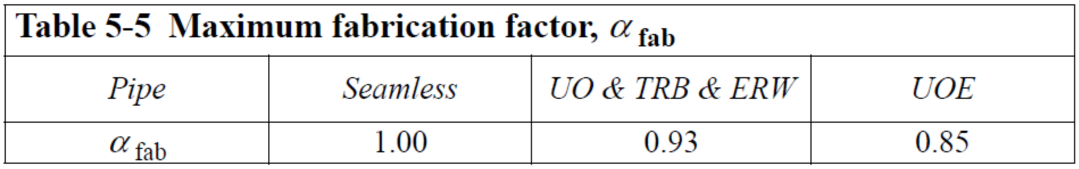

Table 5-5 Maximum fabrication factor, α_{fab}

Pipe	*Seamless*	*UO & TRB & ERW*	*UOE*
α_{fab}	1.00	0.93	0.85

The Table 4.7 provides the list of design load and resistance factors used in the thesis:

Table 4.7 Load and Resistance factors used in the thesis

Load factors	Symbol	Case a	Case b	Limit state
Functional load factor	γ_F	1,2	1,1	ULS
Environmental load factor	γ_E	0,7	1,3	ULS
Condition load effect factor	γ_C	1		ULS
Safety class resistance factor	γ_{SC}	1,04		ULS
Material resistance factor	γ_m	1,15		ULS
Fabrication factor	α_{fab}	0,85		ULS
Material strength factor	α_u	0,96		ULS

4.2.4 DESIGN LOAD AND CHARACTERISTIC LOAD

Design Load Effect

The design load is calculated as the sum of individual functional, environmental, incidental and accidental load after taking into account the corresponding load factors [3, p.60]. The load factors are described in Table 4.7.

$$L_{Sd} = L_F \cdot \gamma_F \cdot \gamma_c + L_E \cdot \gamma_E + L_I \cdot \gamma_F \cdot \gamma_c + L_A \cdot \gamma_A \cdot \gamma_c \qquad \text{Eq. (4.8)}$$

Where,

L_{Sd} – Design Load

L_F - Functional Load

L_E - Environmental Load

L_I - Incidental Load

L_A - Accidental Load

γ_F - Load Effect Factor for Functional Loads

γ_E - Load Effect Factor for Environmental Loads

γ_A - Load Effect Factor for Accidental Loads

γ_C - Condition Load Effect Factor

$$M_{Sd} = M_F \cdot \gamma_F \cdot \gamma_c + M_E \cdot \gamma_E + M_I \cdot \gamma_F \cdot \gamma_c + M_A \cdot \gamma_A \cdot \gamma_c \qquad \text{Eq. (4.9)}$$

M_{Sd} – Design Moment

M_F - Functional Moment

M_E - Environmental Moment

M_I - Incidental Moment

M_A - Accidental Moment

$$S_{Sd} = S \cdot \gamma_F \cdot \gamma_c + S_E \cdot \gamma_E + S_I \cdot \gamma_F \cdot \gamma_c + S_A \cdot \gamma_A \cdot \gamma_c \qquad \text{Eq. (4.10)}$$

S_{Sd} – Effective Design Axial Force

S_F - Functional Axial Force

S_E - Environmental Axial Force

S_I - Incidental Axial Force

S_A - Accidental Axial Force

Characteristic Load:

Characteristic load is defined as the most probable maximum load in N years. It is a quantified load effect to be used as input to the design load effect calculation taking into consideration the contributions from functional, environmental and interference load effects.

The characteristic load will be the most critical 100 year load effect. The most critical 100-year load effect is normally governed by extreme functional, extreme environmental, extreme interference or accidental load effect. Table 4.8 shows the different characteristic loads.

Table 4.8 Characteristic Loads [3, p.60]

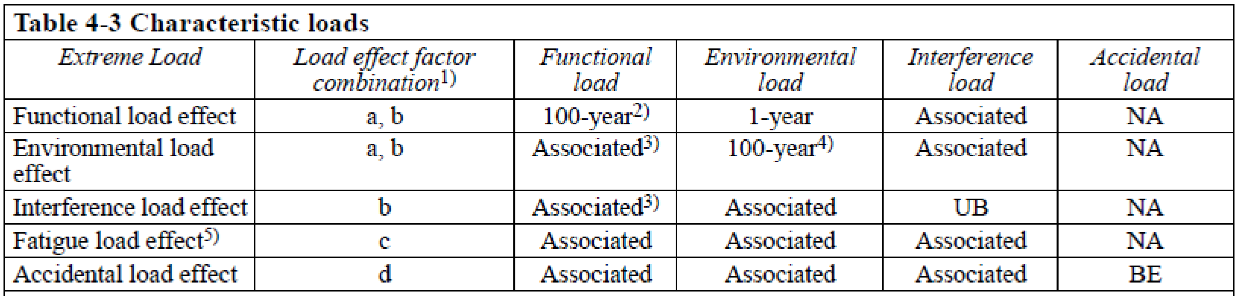

Table 4-3 Characteristic loads

Extreme Load	*Load effect factor combination*1)	*Functional load*	*Environmental load*	*Interference load*	*Accidental load*
Functional load effect	a, b	100-year2)	1-year	Associated	NA
Environmental load effect	a, b	Associated3)	100-year4)	Associated	NA
Interference load effect	b	Associated3)	Associated	UB	NA
Fatigue load effect5)	c	Associated	Associated	Associated	NA
Accidental load effect	d	Associated	Associated	Associated	BE

4.2.5 SYSTEM CHECK AND LOCAL CHECK

The design load effect is calculated for the characteristic load for all load effect combination using corresponding load effect factors. Table 4.9 shows the load effect factor combinations for various types of limit state designs.

Table 4.9 Load Effect Factor Combinations [3, p.61]

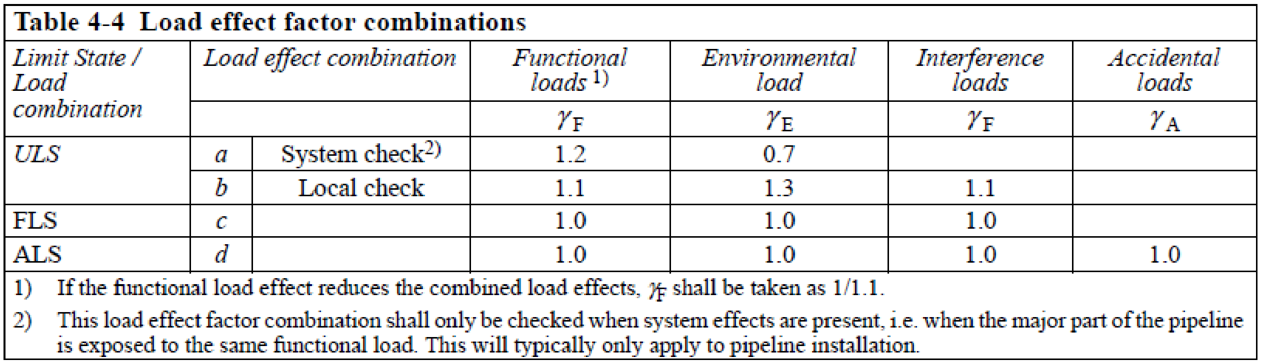

Table 4-4 Load effect factor combinations

Limit State / Load combination	*Load effect combination*		*Functional loads* 1)	*Environmental load*	*Interference loads*	*Accidental loads*
			γ_F	γ_E	γ_F	γ_A
ULS	*a*	System check2)	1.2	0.7		
	b	Local check	1.1	1.3	1.1	
FLS	*c*		1.0	1.0	1.0	
ALS	*d*		1.0	1.0	1.0	1.0

1) If the functional load effect reduces the combined load effects, γ_F shall be taken as 1/1.1.

2) This load effect factor combination shall only be checked when system effects are present, i.e. when the major part of the pipeline is exposed to the same functional load. This will typically only apply to pipeline installation.

Two different load effect combinations are used in DNV OS F101 to express the load effect for local checks and system or global checks. Load effect (a) is considered only when system effects are present. Load effect (b) is considered for local effect checks.

System check assumes that the pipeline will fail at its weakest point and it is combined with the extreme low resistance. It also assumes that the whole pipeline is subjected to the same load over time. In case of pipeline installation, it may be argued that the system effects are not present because an extreme environmental load is not likely to occur when the weakest pipe section is at the most exposed location. However the whole system will undergo the same deformation over the time during installation as it is initiated and laid down on the seafloor resulting in a system effect on the pipelines. Since extreme environmental load is not likely to occur, a more representative and conservative environment load effect factor of 0.7 is used along with a functional load effect factor of 1.2.

While calculating the local effect, a conservative environmental load effect of 1.3 is used to provide better safety. Both local and global checks are performed during installation and the maximum of the two utilization factors is considered during the limiting state determination for the installation operation.

4.3 LOADS ON PIPELINE

DNV classifies pipeline loads into the following categories.

- Functional
- Environmental
- Interference

FUNCTIONAL LOADS

DNV classifies the loads arising from the physical existence of the pipeline and its intended use as functional load.

The effects of the following phenomenon are grouped under functional loads:

- Weight
- External hydrostatic pressure
- Internal Pressure
- Static hydrodynamic loads during installation
- Temperature of content
- Seabed reaction

DNV OS F101 section B102 provides a complete list.

ENVIRONMENTAL LOAD

Loads on the pipeline that are caused by surrounding environment are grouped under environmental load. Some of the important environmental loads are wave and current loads.

Morison's Equation provides the force on a slender structure in a fluid as the sum of an Inertial force component and drag force component. It is stated as below for a unit length of pipe:

$$F = C_m \rho \frac{\pi}{4} D^2 \dot{u} + C_d \frac{1}{2} \rho D u |u| \qquad \text{Eq.(4.11)}$$

Where,

F - Force on the structure
C_m - Added Mass Coefficient
u - Water particle velocity
$\dot{u}$ - Water particle Acceleration
C_d - Drag Coefficient
D - Diameter of the pipe

INTERFERENCE LOADS

Loads which are imposed on the pipeline due to 3rd party activity are termed as interference load.

Major interference loads include
- Trawl impact
- Anchoring
- Vessel impact
- Dropped object

ACCIDENTAL LOADS

Loads that are imposed on the pipeline under abnormal and unplanned condition and which has the probability of occurrence of less than 10^{-2} within a year, it shall be classified as accidental load. Otherwise, they are similar to the interference loads [3, E102, p.59].

Typical accidental loads include
- Extreme wave and current loads
- Vessel impact
- Dropped object
- Explosion
- Wet buckle and accidental water filling during installation

5. INLINE AND END STRUCTURES INSTALLATION

5.1 INTRODUCTION

As such pipelines require either a first end or second end PLET to connect them to manifolds. There are numerous other structures that go at the beginning, in the middle or at the end of a pipeline system. They pose a number of installation challenges from the moment they leave the vessel to the stage they are installed on the seabed. This chapter will describe the various limitations and challenges of inline structure installation and solutions developed to overcome them.

5.2 TYPES OF STRUCTURES

Various structures are integrated within a pipeline system catenary for efficient field development in addition to the pipeline itself. There is no definite method for classification. On a broad basis they can be classified as follows:

1. End structures:
    First end and second end PLET/PLEM.

2. Inline Structures:
    J-tube seals, Inline Tees, WYES, Inline SLEDs/PLETs

PLET or PLEM is a subsea structure connected to either ends of a pipeline facilitating connection between the rigid pipeline and other subsea structures like manifolds or trees using spools or jumpers. Mud mat, a foundation structure on which the PLET sits on the seabed is also installed along with PLET. The PLEM used to initiate pipelay is termed as first-end PLEM and a PLEM installed on completion of the pipelay is termed as second-end PLEM or a second-end structure in general.

Inline tees and wyes are structures that facilitate future tie-ins from nearby fields under development or yet to be developed. In the absence of these structures, the only other option would be to perform a Hot Tap operation on the pipeline to establish new connection or install a new pipeline system. Both the options are time consuming and expensive.

J-tube seal is an inline structure used to close the bellmouth of a J-tube and thereby preventing the escape of inhibitors used to prevent the formation of marine growth after the installation of the risers. Figure 5.1 shows the J tube seal analyzed in the thesis.

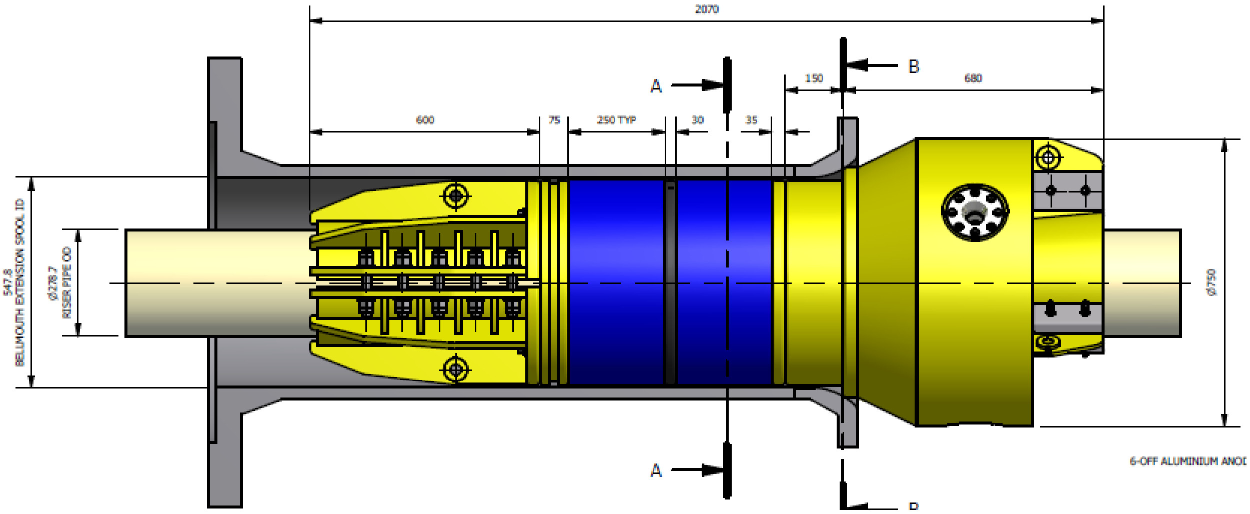

Figure 5.1 J-Tube seal with riser and pipeline sections [26]

5.3 INLINE STRUCTURE INSTALLATION PROCEDURE

Installation of an inline structure will require a separate analysis stage where vessel movement, pipe payout and ramp angle changes are specified. The following procedure is used as guideline for Inline structure Installation in Offshore [14, p.31]:

1) Calculate pipe cut location.

2) Continue pipelay until the cut location is in the work station. Stop the vessel.

3) Ensure the vessel is in the optimum location with respect to the touch down point and the pipe is showing zero lift. This will ensure there is minimal moment released when the pipeline is cut.

4) Clamp the pipeline in the hang off clamp.

5) Cut the pipeline in the work station.

6) Weld the inline structure to the pipeline.

7) Once the inline structure has been welded to the lower section of pipeline and the weld has passed the inspection, the upper section of pipeline which is still in the tensioner can then be welded to the structure. At this stage the pipeline catenary is still supported in the pipe clamp.

8) After welding is completed and the weld has passed the inspection, the clamp can be released and the tension transferred to the tensioner. At this stage the mass of the structure in air will contribute to an increase in the bending moment in the pipeline at the tensioner exit. This will be controlled by the PLET alignment frame on the ramp which will support the inline structure. The vessel may need to make a forward movement to raise the inline structure and reduce bending stress in the pipe at the tensioner.

9) An analysis stage should be included above and below the water line to demonstrate that the pipe stresses remain within allowable limits.

10) A series of pipe payouts and vessel forward movements are then required until the inline structure is located on the seabed. The ramp angle may be reduced as required to control stress around the inline structure during laydown. This may have an effect on the environmental and excursion envelopes.

11) The pipeline touchdown position will generally be monitored by an ROV to ensure the lay tables are being followed correctly. For inline structures a single ROV may cover both the structure location in the water column and the touchdown position or two ROV’s may be required.

5.4 ANALYSIS

Each inline or end structure has to go through 4 different stages during installation [15]:

- Deck handling and Lifting
- Splash Zone
- Passage through water column along the pipeline catenary
- Laydown at the bottom.

Analysis of an installation process should cover all the stages described above. In general, the analysis should cover the following phases of the installation process:

- When the structure goes overboard through splash zone
- Initiation of the structure along with pipeline (including the installation of the buoyancy modules)
- Normal pipelay stage
- Laydown of the structure at the seabed
- Abandonment and recovery checks in case of emergencies

The following types of analysis should be performed to ensure integrity of the pipeline:

- Static analysis for each stage (Initiation, Normal lay and Laydown and A&R)
- Regular wave dynamic analysis for each step of installation operation.
- Irregular wave dynamic analysis for critical cases.
- Analysis of both empty and flooded conditions.
- Local buckling check under combined loading condition (Axial loading, bending moment, external pressure)

In case of local buckling check, the following should be verified for various wave headings and corresponding critical wave period.

- Top utilization
- Sagbend Utilization

In addition, special attention should be given to the analysis of the stage when the structure is at the sagbend of the pipeline catenary. This is the stage when the pipeline is subjected to maximum loading and more susceptible to local buckling.

5.5 CHALLENGES & LIMITATIONS DURING INLINE AND END STRUCTURE INSTALLATION

Installation of inline structures and end structures introduces many challenges and additional loading on the pipeline system and sometimes can drastically reduce the limiting sea state for the installation operation. Hence they require careful analysis to identify and overcome those challenges.

Figure 5.2 First End PLET Initiation [27, p.51]

The technical challenges and general limitations are listed below:

1. Hydrodynamic loading – Current and Wave Loading

Current along the direction of installation increases tension requirements while the current against the direction of installation increases compression and one of the governing factors for the buckling utilization of the pipeline. Wave introduces dynamic loading in the pipeline catenary. It is often unpredictable when the system is complex and requires time domain analysis to fully understand it.

Strong current influences inline structure installation in terms of curve laying, vessel positioning and landing. Strong bottom current might necessitate longer layback distance to negate the effect of current during landing and result in higher dynamic tension due to increased weight of catenary.

2. Splash zone wave loading

When a large structure is lowered through the splash zone, the splash zone wave forces introduces very large force on the structure which is transferred to the pipeline resulting in high top bending moment. This might compromise top bending utilization of the pipeline.

3. Structure rotation during lowering

Due to the COG offset and the installation vessel motion, the inline structure has a tendency to rotate. To a certain extent, the twisting moment is resisted by the torsional stiffness of the flowline. There are several causes for the rotation:

- COG offset
- Current
- Residual pipeline tension from reeling or sagbend

If an in-line structure is being installed there may be residual twist in the pipeline (significantly greater if pipe is not straightened) which needs to be resisted to ensure structure lands level [12].

In order to achieve the required orientation relative to the seabed, the prevention of rotation of inline structures like WYE is essential. The requirements are strict: tolerances on orientation are generally plus and minus 5 degrees [16].

4. Loading on pipeline due to the structures weight and higher stiffness

5. Curve Laying

The frictional resistance offered by the structure and load on the structure as it slides on the seabed needs to be considered during curve laying. Curve laying with inline structures in the catenary is made difficult for the following reasons [15]:

1. The layback distance with heavy inline structures is higher than the normal lay. The flowline static bottom tension is high.
2. Heavy inline structure causes high dynamic tension in the line. When there is strong bottom current, the flowline is lifted and the friction between the seabed and the flowline is reduced and it might move the curve.

6. Buoyancy module and flowline clash

The buoyancy module could clash with the pipeline especially when it is being deployed as the buoyancy module stands very close to the flowline in a near vertical position. There is a possibility of rigging getting tangled with the flowline. Analysis might be required to study this scenario in the presence of strong current.

7. Multiple inline structures

There might be as many as 3 structures along the catenary during a deep water installation. This would require careful and extensive analysis. Multiple heavy structures increase the weight and dynamic tension in the catenary.

8. Fatigue

Sometimes installation operation might be put on hold for various reasons with the inline structure suspended in the catenary and they require fatigue analysis. Fatigue analysis should take into consideration the cumulative damage experienced by the pipeline for each stage of the installation.

9. Temporary loss of tension as the structure passes through the tensioners

When the structure is large and irregularly shaped, the tensioners have to be opened to allow the passage of the structure. In this case either the pipe has to be clamped or the rest of the tensioners in the firing line have to take the extra load to support the pipeline. Any excessive vessel excursion or a large wave force can increase the tension in the flowline and compromise its integrity.

10. Buoyancy module rigging snatching loads.

As the heavy inline structure moves vertically up and down, the rigging of the buoyancy module goes slack and taut in each cycle. If this load on the rigging is sufficiently large, the rigging might snap resulting in the loss of the buoyancy unit. This can be prevented by including a polyester segment into the rigging which can accommodate the snatching load. Dynamic analysis should be carried out to make sure the snatch loads are within the safe limits.

11. Vessel limitation

- Handling space and platform for installing the structure
- Lifting and tensioning capacity limitations
- DP capabilities to maintain the vessel excursion within limits
- Cannot weather vane during the splash zone lowering stage[15]

12. Economic constraints

Installation of large structures might need an extra support vessel to assist in landing with required degree of accuracy.

13. Choice of installation method

Installation of heavy structures will influence the installation method. S- Lay stinger may not handle the weight of the structure or the structure might be too large to pass through the firing line in which case an alternate installation method has to be adopted. J lay is a possible option and the benefits of installing large structures using J-lay methodology are [6]:

- Structure is not limited in size by the need to pass through the firing line
- Structure does not see any significant bending strain in the overbend
- There is no requirement for foldable mud mats reducing the amount of moving parts
- No need to sacrifice redundancy on lay vessel as no tensioners need to be opened

14. Issues with Buoyancy [17]:

- Handling and deployment – Might even require separate handling systems installed.
- The hydrodynamic added mass introduced by the large units.

5.6 SOLUTIONS

1. Vessel Modifications

Structures might weigh 20Te and might be too large to pass through the firing line [17].

- Stinger might have to be strengthened in case of a S lay vessel to handle the excess weight
- A dedicated Buoyancy handling system might be required
- The firing line might have to be enlarged or modified to allow the passage of larger structures.

2. Reduction of Inline structure and Pipeline Catenary Mass

By reducing the weight of the catenary, the installation limit states can be improved. Some of the methods for reducing the installation loads [15]

- Single Buoyancy Module
- Multiple Buoyancy Module
- Using a support vessels crane whiplash to land the structure.

Buoyancy modules are often used to take up some of the weight of the pipeline and the inline structure. They are discussed in detail in section 5.7. In general, Buoyancy unit connected serves the following purposes:

- To keep the structure neutrally buoyant
- Stable in rotation
- Reduces sagbend stress as the structure approaches the seabed

3. Contingency Operations

A contingency intervention procedure is normally required during the installation of inline structure to establish upright position of the structure during installation if the rotation of the structure is more than the prescribed limit. Normally the intervention will be performed through a support vehicle. A ROV will attach the winch wire from the support vehicle to the structure and the upright force will be applied. Figure 5.3 shows the schematics of a contingency operation performed with the help of a support vehicle to keep the upright stability and preventing the structure rotation.

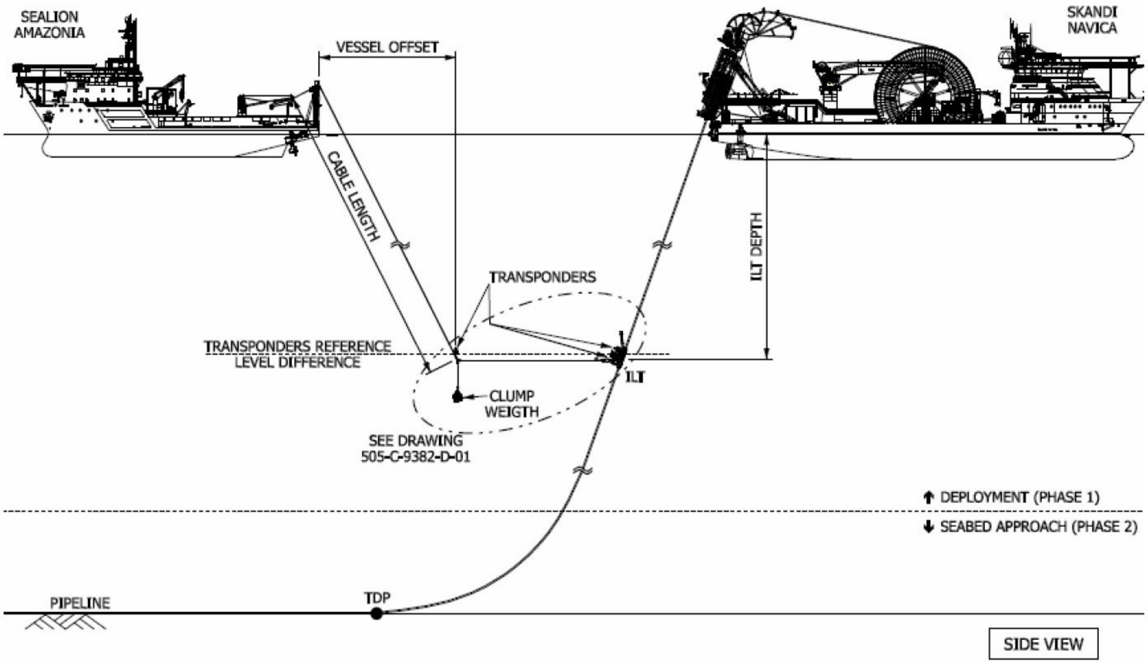

Figure 5.3 Contingency operations to prevent rotation of Inline Structure during Installation [17]

4. Installation Process Modifications

In case of very large structures that cannot pass through the firing line, the usual installation process is modified to accommodate them. One of the options is to let the pipeline pass through the firing line and then cut it and weld the structure and continue the installation process by welding the pipe again.

5.7 BUOYANCY MODULES

Buoyancy modules are manufactured out of materials of low density with high strength that can withstand the hydrodynamic loads. Buoyancy modules are usually made up of one of the following materials [18]:

- Polyurethane Foam
- Co-polymer Foam
- Syntactic Foam

Each of these materials has its unique material properties which makes them suitable for an operation. The choice is made based on the following requirements:

- Operating depth and duty cycle
- Maximum depth
- Buoyancy required
- Geometry of the element
- Method of attachment
- Method of Installation

Figure 5.4 Cylindrical Modular Buoyancy Units [18]

Buoyancy attachment and release is a very important part of the operation. It is dictated by the pipeline installation method, vessel space and handling restrictions. Buoyancy modules can be attached to the pipeline by the following means:

- As shell modules directly on the pipeline (Figure 5.6).
- As a direct cast-on coating
- As modular units using tether. This is the typical option for large buoyancy units.

Buoyancy module can be attached either directly to the pipeline or using a tether to the catenary. Various banding systems to secure the buoyancy modules to the catenary are available with quick release mechanisms. The quick release mechanisms are operated by ROV's to release the buoyancy modules at the desired water depth after installation. Figure 5.7 shows a quick release mechanism and a ROV releasing it.

Large buoyancy units employ modular design which allows the net buoyancy to be adjusted to the operational depth by either adding or removing the modules. Typically, installations of inline structures use modular buoyancy modules. Figure 5.4 and Figure 5.5 shows a modular buoyancy unit with cylindrical and square cross section.

Figure 5.5 Square Cross Section Modular Buoyancy Unit [18]

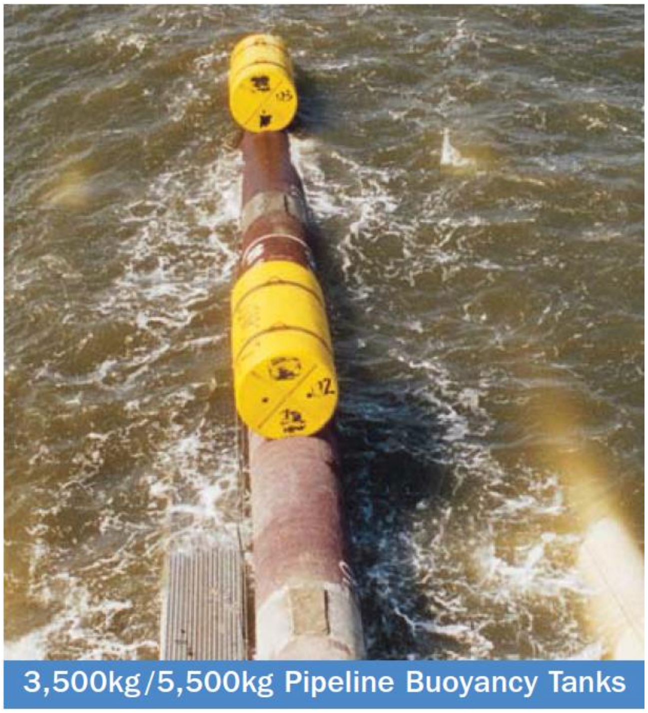

Figure 5.6 Pipeline Installation with Buoyancy Modules attached directly to Pipeline [18]

Figure 5.7 Quick Release Pipeline Buoyancy System and Installation Configurations [18]

6. CASE STUDY AND ANALYSIS

6.1 INTRODUCTION

A typical offshore project in the Norwegian North Sea is considered as the basis for the thesis. The satellite field is located in an average depth of 200 m. The hydrocarbon output is sent to an existing platform which is about 12 km from the field. The riser and pipeline installation at the field using J-tube initiation method is analyzed in the case study. This pipeline has a J tube seal in the middle of the catenary which is considered as an inline structure for the scope of the thesis. Analysis and optimization of the installation process with the help of buoyancy module will form the core of the thesis work. The reeling, J tube pull in process and the stress/strain induced and pipe utilization during those stages of the operation will not be studied here.

6.2 CASE STUDY PROPERTIES

This section provides the field, material, environmental and vessel properties.

6.2.1 FIELD AND MATERIAL PROPERTIES

Field Data

The general field data are summarized in Table 6.1. The deepest part of the seabed is located at 228, however the average water depth is 217 m and it is used for external pressure calculations.

Table 6.1 Table of Field Properties

Field Properties	Values
Field	A typical North Sea Offshore Project
Type of Hydrocarbon resource	Oil
Average depth	195 m to 228 m
Design Depth	228 m
Sea Water Density	1026 kg/m^3
Design Pressure	200 bar
Design Temperature	85^o C

Pipeline and Material Data

The pipe and riser section are made up of the same backing steel and clad. However the coating thickness varies. Their properties are summarized in Table 6.2.

Table 6.2 Pipeline and Material Data

Description	10” Pipeline		10” Riser	
Steel Outer Diameter	271.7	mm	271.7	mm
Total Outer Diameter	362.7	mm	281.7	mm
Average Wall Thickness	13.7	mm	13.7	mm
Cladding thickness	3	mm	3	mm
Coating Thickness	45.5	mm	4.7	mm
Total Weight in Air (Empty)	140.6	Kg/m	109.1	Kg/m
Total Submerged weight (Empty)	34.6	Kg/m	45.5	Kg/m
Total submerged weight (Flooded)	80.3	Kg/m	91.2	Kg/m
Specific Gravity (empty)	1.33		1.71	
Specific Gravity (Flooded)	1.76		2.43	

Steel Properties

The properties of backing steel used are summarized in Table 6.3.

Table 6.3 Steel Properties

Description	Value	Unit
Density,	7850	Kg/m^3
Young’s Modulus	207	Gpa
Poisson’s ratio, v	0.3	0.3
SMYS(1)	456.2	Mpa
SMTS(1)	554.7	Mpa
Material	DNV SAWL 415	

(1) Based on the as-built pipe data

J-Tube Seal Properties

The J-tube is approximately 2 m long and its properties are summarized in Table 6.4.

Table 6.4 J-Tube Sea Properties

Description	Value	Unit
Weight in Air	1.1	Te
Submerged Weight	0.8	Te
Length	2	m

Buoyancy Properties

A modular buoyancy module of square cross section with net buoyancy equal to 788 kg is used throughout the thesis. The properties of the buoyancy module are summarized in Table 6.5. The calculation of buoyancy properties are detailed in Appendix D.

Table 6.5 Buoyancy Properties

Description	Value	Unit
Net Buoyancy	788	kg
Mass in Air	1546	kg
Base Dimension	1.12 * 1.12	m
Buoyancy Displacement Volume	2.277	m^3
Buoyancy Height	1.815	m
Added Mass in z-direction	1050	kg
Drag Force Coefficient	610	kg/m

6.2.2 ENVIRONMENTAL PROPERTIES

Current Profile

The current velocity varies with water depth. Table 6.6 shows this variation. Extreme 1 Year profile with 180^o current direction is used in the thesis. Figure 6.1 shows the schematic of current direction.

Table 6.6 Current Profile

Depth	Extreme 1 Year Profile	50% of 1 Year Profile	25 % of 1 Year Profile
m	m/s	m/s	m/s
0	0.95	0.48	0.24
30	0.91	0.46	0.23
75	0.85	0.43	0.21
3 m from seabed	0.66	0.33	0.17

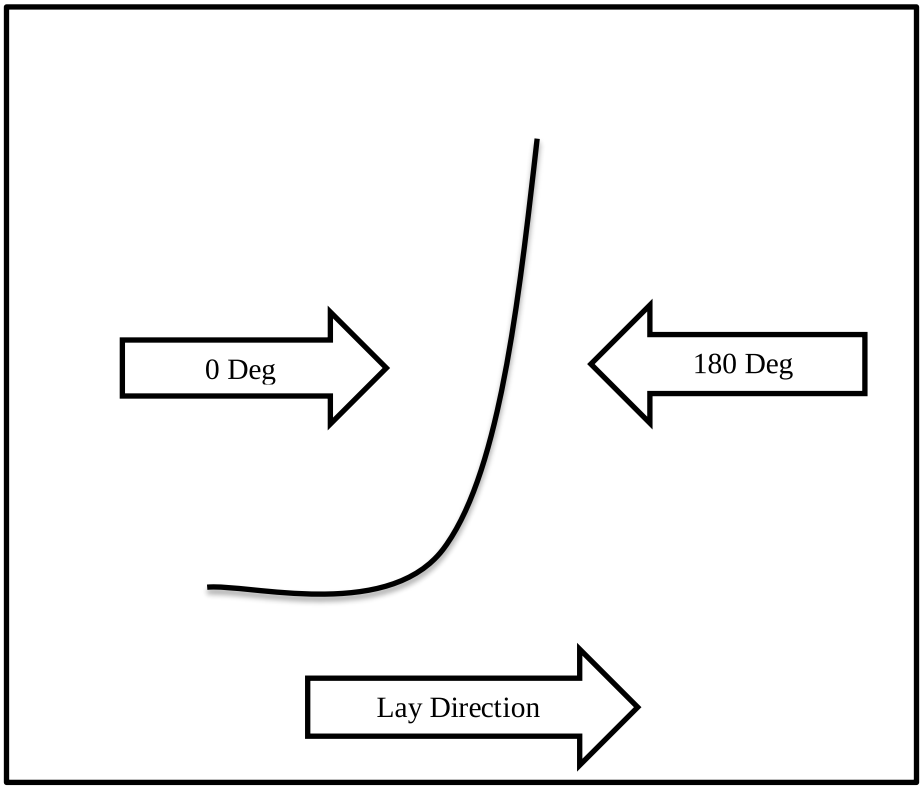

Figure 6.1 Depiction of Current Direction

6.2.3 VESSEL DATA

Vessel Capacity

The weight of the pipe catenary is supported either through the tensioners or the clamp. The tension capacities of the pipelay equipment are summarized in Table 6.7.

Table 6.7 Vessel Tension capacities

Equipment	Rating
A&R Winch	250 Te
Tensioner	205 Te
Hang Off Clamp	205 Te

Wave Direction Critical Cases

Prior wave heading and wave period sensitivity study has resulted in the following critical cases presented in Table 6.8 for pipeline installation using this specific vessel. This sensitivity study result is very specific to the concerned vessel.

Table 6.8 Wave Direction Critical Cases

Group No:	Group Classification		Critical Cases		Comments
	Wave Heading	Wave period T_p	Wave Heading	Wave period T_p	
	[Deg]	[s]	[Deg]	[s]	
1	0-30	<=8	30	8	Top Utilization
2	0-30	>8	0	12	
3	60-90	All	60	11	
4	90-120	All	120	9	
5	150-180	All	150	9	
6	All	All	60	9	Sagbend Utilization
7	All	All	90	7	Tension

The main scope of the thesis is the optimization of the limiting sea state using buoyancy module. Hence most of the analysis work is concentrated on the critical case corresponding to sagbend utilization (group 6) where the buoyancy modules are put to use. Figure 6.2 shows the schematic of wave directions.

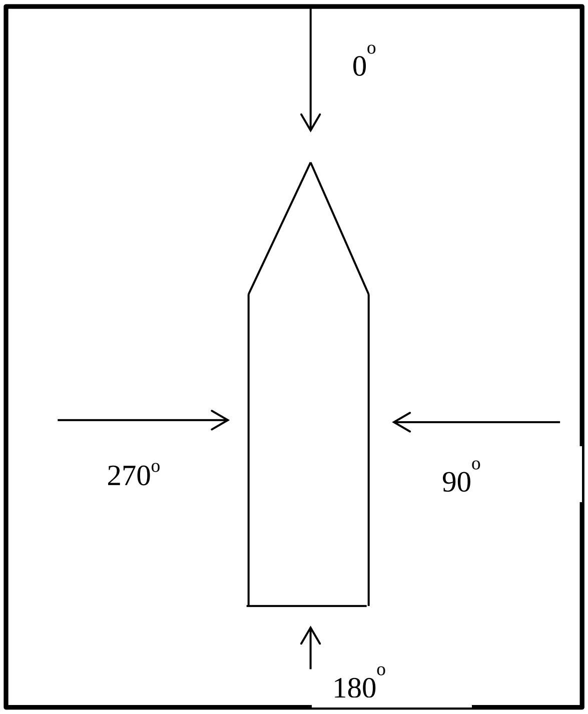

Figure 6.2 Depiction of Wave Direction

6.3 INITIATION ANALYSIS

The main purpose of the installation analysis is to determine the safe limiting sea state for the installation process based on the limit state design criteria proposed by DNV. Besides the limiting sea state, a few other parameters are established through analysis. The validity of the installation method, optimum ramp angle and the vessel position should also be established for the various stages of the installation. However, we will discuss them theoretically and only the safe limiting sea state analysis is performed under the scope of the thesis.

6.3.1 OPTIMUM RAMP ANGLE

A reel laying vessel can adjust its lay ramp to accommodate different configurations of the catenary to cater to various water depths. It will employ a large ramp angle for deep water and a smaller ramp angle for shallow water. A large ramp angle, say 90 ° will result in vary large buckling close to the seabed near the touch down point of the catenary in shallow waters. A very small ramp angle, say 35 ° will result in a long catenary and higher tension requirements but more importantly greater dynamic loading closer to the top end of the catenary where the pipe is clamped to the vessel compromising the top buckling utilization even at a very low sea state. In shallow waters, a ramp angle of 60 or 65 degrees is considered to be optimum for the reel lay vessel used in the thesis. The ramp angle can be adjusted only in fixed steps and 60.55 ° is used in the thesis.

6.3.2 ANALYSIS OF INITIATION STEPS

Initiation of the installation is performed by pulling the pull-in wire attached to the Pull-in head from the top of the platform using a winch. The pipe is paid out in steps from the vessel. The riser section is paid out first followed by the pipeline with the inline structure located in the middle. The payout step can be as small as a few meters during the critical stages of the operation and it could be 50-100 meters at other stages. The vessel position is normally fixed during this initiation phase. However it can be moved back and forth to adjust the tension requirements and also to obtain the desired catenary to adjust the landing angles of the J Tube seal due to variation in seabed profile.

This analysis is performed using Orcaflex. The exact catenary length that results in zero bending moment at the top is identified for each step and then static analysis is performed. The results of the static analysis are used in Riflex as the input for the dynamic analysis.

Identification of the Critical Step during Initiation

In the current analysis, 32 steps of pay out were identified as shown in Appendix E in Table E.1. The step with the lowest limiting sea state will be treated as the critical step and the optimization process will begin from there. Since the analysis is focused on buckling utilization close to sagbend near seabed, dynamic check and utilization factors are calculated only for those steps. Each of these steps has to be analyzed to identify the limiting sea state for the initiation phase. The position of the structure in the catenary and the location where the maximum static and dynamic bending moment occurs as measured from the J-tube end is presented in Table 6.9. The corresponding utilization results are presented in Table E.2 in Appendix E.

Table 6.9 Summary of Analysis of Initiation Phase without Buoyancy

Description: Analysis of the Initiation Phase without Buoyancy **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Ramp Angle: 60.55^{o}**							
		Step 24		**Step 25**		**Step 26**	
		Sagbend	Structure	Sagbend	Structure	Sagbend	Structure
Structure Position	[m]	220		190		166	
Static BM	[kNm]	141	160	152	185	198	198
Maximum Static BM Position	[m]	219		180		166	
Dynamic BM	[kNm]	144	50	222	165	224	224
Maximum Dynamic BM Position	[m]	178		178		167	
Total BM	[kNm]	285	215	374	350	422	422
Utilization	--	0.73		1,28		1,6	

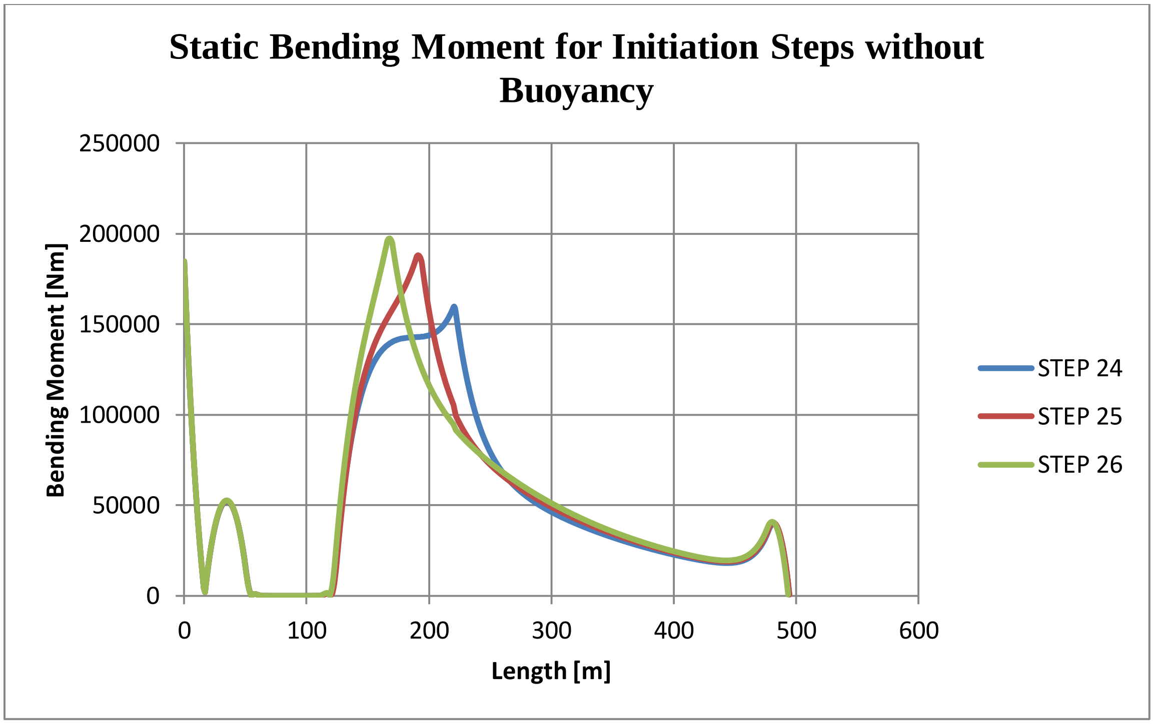

Figure 6.3 Static Bending Moment for Initiation Steps without Buoyancy

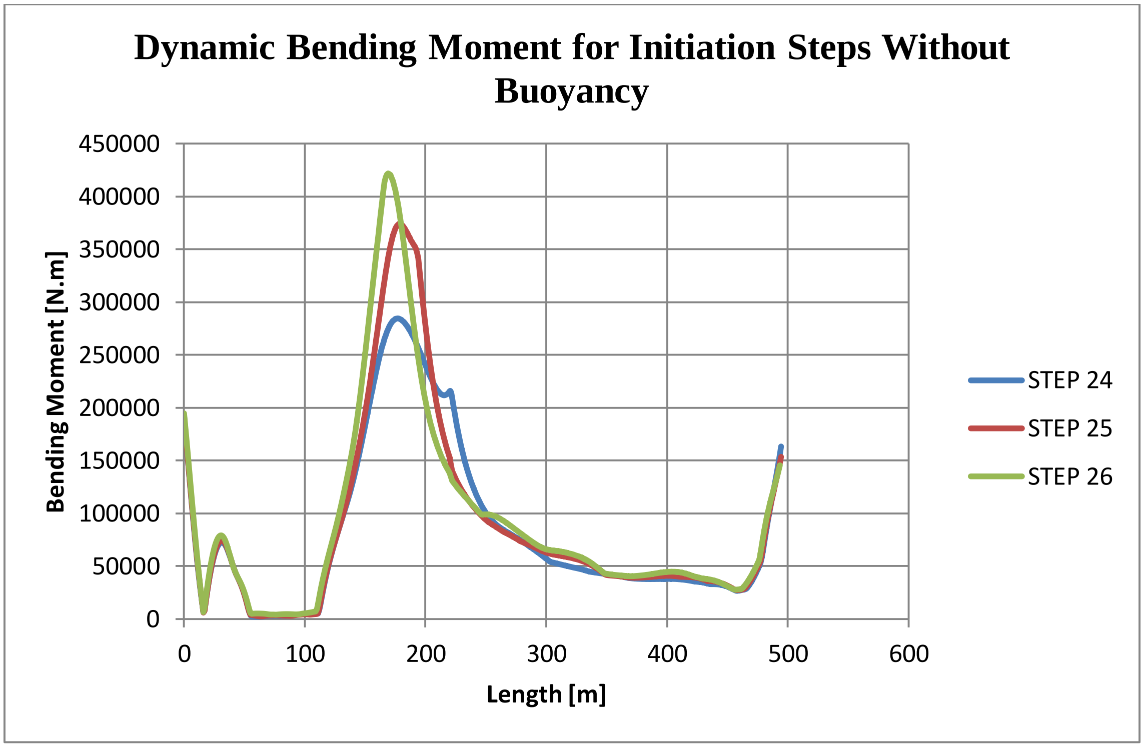

Figure 6.4 Dynamic Bending Moment for Initiation Steps without Buoyancy

Observations and Discussions

- The maximum static bending occurs at the structure in all the steps as seen in Figure 6.3. However the maximum dynamic bending moment occurs at the sagbend of the catenary away from the structure in steps 24 and 25 as seen in Figure 6.4.
- Step 26 is the critical step with maximum bending moment of 422 kNm as seen in Figure 6.4. This is because the structure is located in the most critical section of the sagbend and the additional mass of the structure at the sagbend has resulted in increased dynamic response. The exact position of this critical step might be a few meters to either side of the current step 26 configuration but step 26 as discussed here is still considered as the critical step in the thesis.
- Step 27 results in a bending moment of 318 kNm and a utilization factor of 0.93 as the structure has already cleared the sagbend section of the catenary (Refer Table E.2 in Appendix E).
- For step 26 and the initiation phase in general, the limiting sea state is 1.4 m which yields a maximum bending moment of 329 kNm at sagbend and a utilization of 0.93 as indicated in Appendix E in Table E.2.
- The very high bending moment in the beginning of the catenary at segment length 1 to 10 m is due to the interaction between the J tube and the riser section and is ignored. (Referring to Figure 6.3 and Figure 6.4 here and all the bending moment figures that follows)

6.3.3 ANALYSIS OF VARIOUS CATENARY CONFIGURATIONS

This analysis is performed to understand the dynamic response of the pipeline catenary at the water depth of 217 m. This section compares the dynamic analysis results for different combinations of the components present in the current pipeline catenary and analyses the variation in the bending moment and utilization in each case.

Table 6.10 shows the maximum bending moment during each case along with the catenary segment where it occurs. Figure 6.5 and Figure 6.6 shows the corresponding static and dynamic bending moments.

The utilization results are presented in Table E.3 in Appendix E.

The following configurations are analyzed and compared:

- Initiation scenario with riser and pipeline section along with the inline structure.
- Initiation with only the riser section on either ends of inline structure.
- Initiation with only the pipeline section on either ends of inline structure.
- Initiation with only the riser section.
- Initiation with only the pipeline section.

Table 6.10 Summary of Analysis of Different Pipeline Catenary Configurations

Description: Analysis of various Catenary component configurations
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^{o}
Net Buoyancy: 788 Kg
Volume: 2.277 m^{3}
Step : 26 (Structure near critical sagbend section)

No:	**Scenario Description**	**Static Bending Moment**	**Total Dynamic Bending Moment**	**Buckling Utilization**	**Total Catenary**	**Maximum BM section**
		[kNm]	[kNm]		[m]	[m]
1	Initiation with structure + Riser	167	316	0,88	491	166
2	Initiation with structure + Pipeline	187	380	1,29	492	166
3	Initiation with structure + pipeline + Riser	198	422	1,6	493	167
4	Initiation with pipeline	118	283	0,74	491	153
5	Initiation with Riser	110	248	0,56	490	150

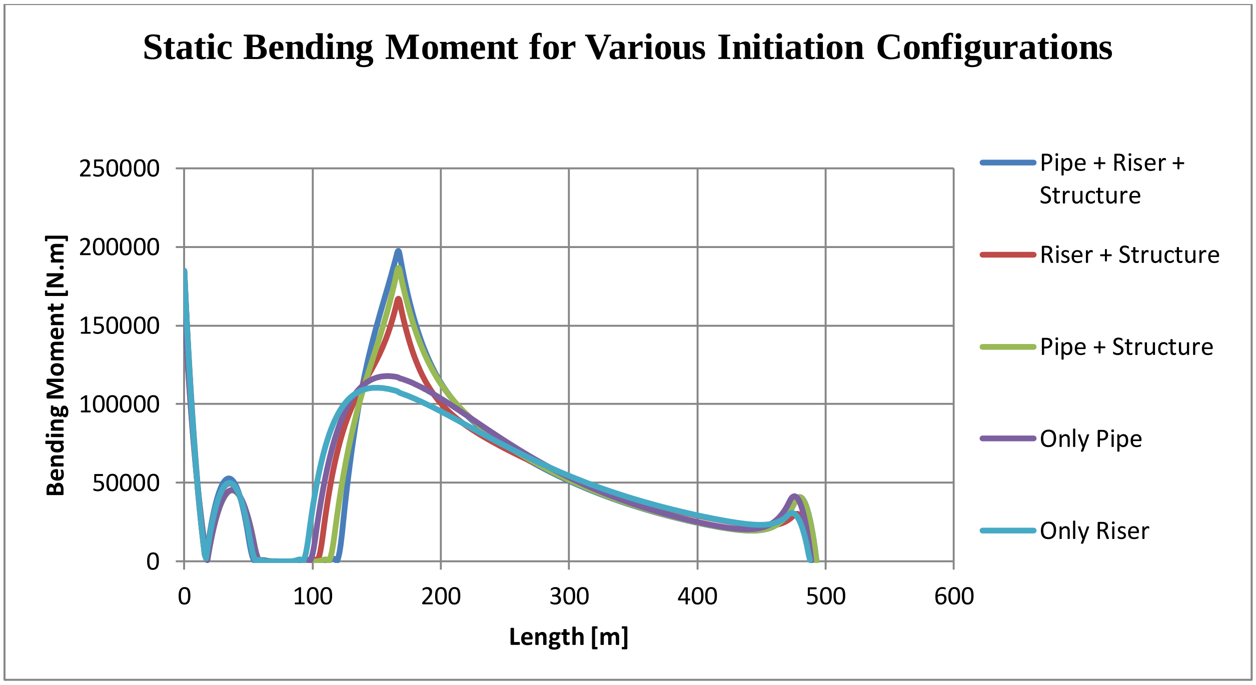

Figure 6.5 Static Bending Moment for Different Catenary Configurations

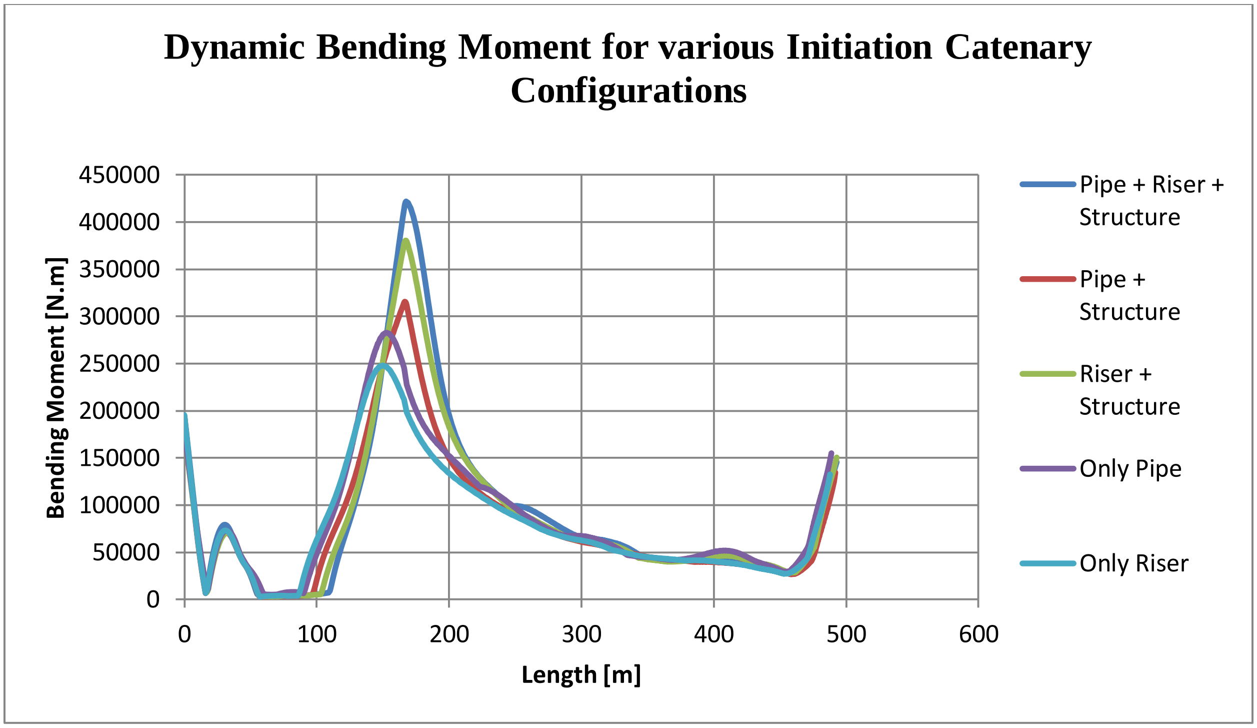

Figure 6.6 Dynamic Bending Moment for Different Catenary Configurations

Observations and Discussions

- Even with the presence of inline structure, the catenary length is almost the same for all the configurations. The inline structure is not heavy enough to bring any drastic change to catenary length. The maximum bending moment always occurs in the catenary segment at 166 m where the inline structure is located when compared to initiation of only pipe or riser in which case the maximum bending moment occurs at 153 or 150 m as measured from J tube end and is presented in Table 6.10.

- Comparing scenarios 1, 2 and 3 in Table 6.10, the worst utilization is observed for the configuration with riser, pipeline and inline structure combination. The difference in the weight and diameter of the pipe and riser results in a complicated dynamic response giving rise to a utilization which is higher than a configuration involving the structure and only pipeline as in scenarios 2 and 3 even though the pipeline (with added mass included) weighs more than the riser.

- A configuration with pipeline results in a utilization that is worse than a configuration with riser (Scenarios 1 and 2 in Table 6.10). Forces on a slender cylinder are governed by Morison’s equation as defined in section 4.3. The Pipeline has a marginally lesser submerged mass than riser. However, its larger diameter results in a much larger added mass. This larger total mass results in a higher inertial force component of the Morison’s equation resulting in higher bending moment and hence the higher utilization when compared with riser.

- It can be observed that a catenary with lesser mass results in lower bending moment as seen in Figure 6.5 and Figure 6.6. Hence the use of buoyancy module to reduce the weight of the structure in the catenary will result in lower bending moment and utilization.

7. OPTIMIZATION PROCESS

7.1 INTRODUCTION

The preliminary analysis of the initiation process discussed in section 6.3.2 has resulted in a limiting sea state of 1.4 m of significant wave height. The optimization of the limiting sea state begins by introducing a buoyancy module into the system to negate the excessive weight introduced by the inline structure.

The main focus of the thesis is to determine the configuration of the buoyancy module in terms of the net buoyancy, the attachment position/offset from the structure, number of buoyancy modules and the geometry that would yield the most optimal limiting sea state and also to establish a procedure that would help to determine this configuration.

As part of the optimization process, analyses are performed to assess:

- Influence of the buoyancy module when attached to the structure;
- Influence of the ratio of the net buoyancy to inline structure weight;
- Influence of buoyancy module attachment position defined by its offset from structure;
- Influence of the geometry of the buoyancy;
- Influence of multiple buoyancy module configuration.

7.2 INFLUENCE OF BUOYANCY MODULE ON THE CATENARY

During the installation process, buoyancy module is connected to the pipeline catenary and deployed. The module approaches the seabed along with the pipeline and inline structure. The inline structure passes through the sagbend with the buoyancy unit. Before the connection point on the pipe is pulled into the J-Tube, the module is disconnected from the catenary. This action is performed by a ROV.

The catenary experiences the maximum dynamic bending moment when the inline structure is at the sagbend. The buoyancy module helps to reduce the stress in the sagbend. It reduces the stress primarily:

- By providing net buoyancy which reduces the submerged weight of the inline structure/pipeline catenary and the static effects.
- By providing additional drag associated with the buoyancy module which acts as an additional resistance against the dynamic response of the pipeline catenary.

Also, when the buoyancy module is attached through a tether, the additional added mass associated with the buoyancy could help to reduce the dynamic response of the catenary by its own out-of-phase dynamic response to that of catenary. This is analyzed through a sensitivity study in section 7.5.

However, it should be noted that if the buoyancy module is directly attached to the structure without tether, then the additional added mass associated with the buoyancy will increase the dynamic response of the catenary. The added mass of the buoyancy becomes an integral part of the added mass of the catenary system and its dynamic response is in phase with that of the catenary.

Table 7.1 presents the bending moment experienced by the catenary for the different critical steps. The utilization results are presented in Table E.4 in Appendix E.

The analyses are performed for steps 24, 25 and 26 of pay out. The critical step of initiation might change with the inclusion of buoyancy. In this case, step 25 is the most critical step with a utilization factor of 1.5 as seen in Table 7.1.

Table 7.1 Summary of Analysis of Critical Steps of Initiation with Buoyancy Module

Description: Analysis of Critical Steps of Initiation with Buoyancy Module **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Ramp Angle: 60.55^o** **Net Buoyancy: 788 Kg** **Volume: 2.277 m^3**							
		Step 24		**Step 25**		**Step 26**	
		Sagbend	Structure	Sagbend	Structure	Sagbend	Structure
Structure Position	[m]	220		190		166	
Static BM	[kNm]	144	110	145	135	143	143
Maximum Static BM Position	[m]	170		163		167	
Dynamic BM	[kNm]	200	70	257	115	189	189
Maximum Dynamic BM Position	[m]	174		168		154	
Total BM	[kNm]	340	190	402	250	332	332
Utilization	--	1,06		1,5		1	

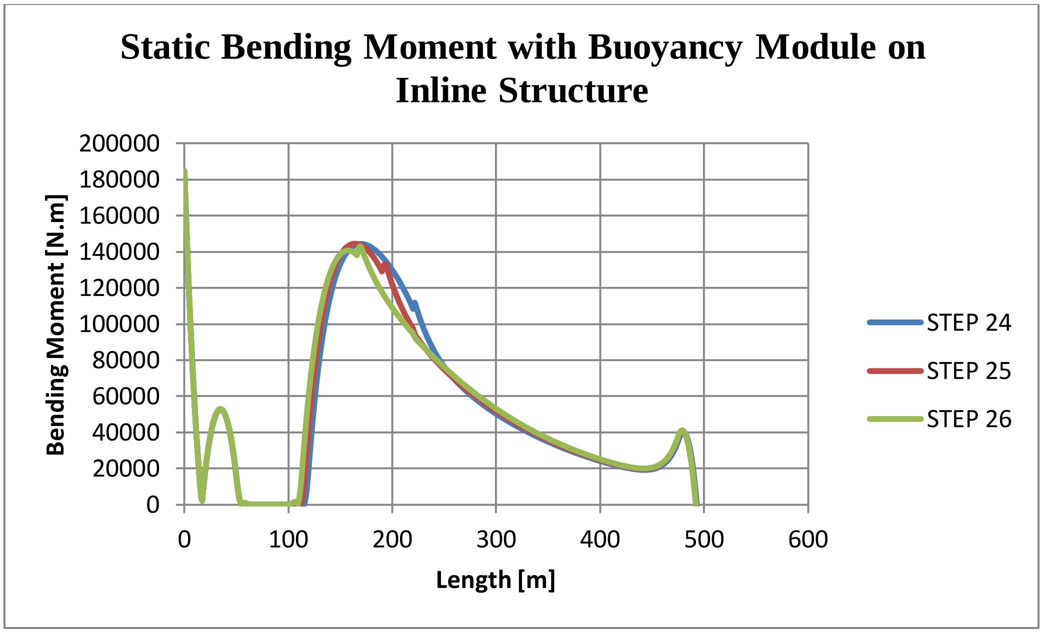

Figure 7.1 Static Bending Moment for Initiation Steps with Buoyancy

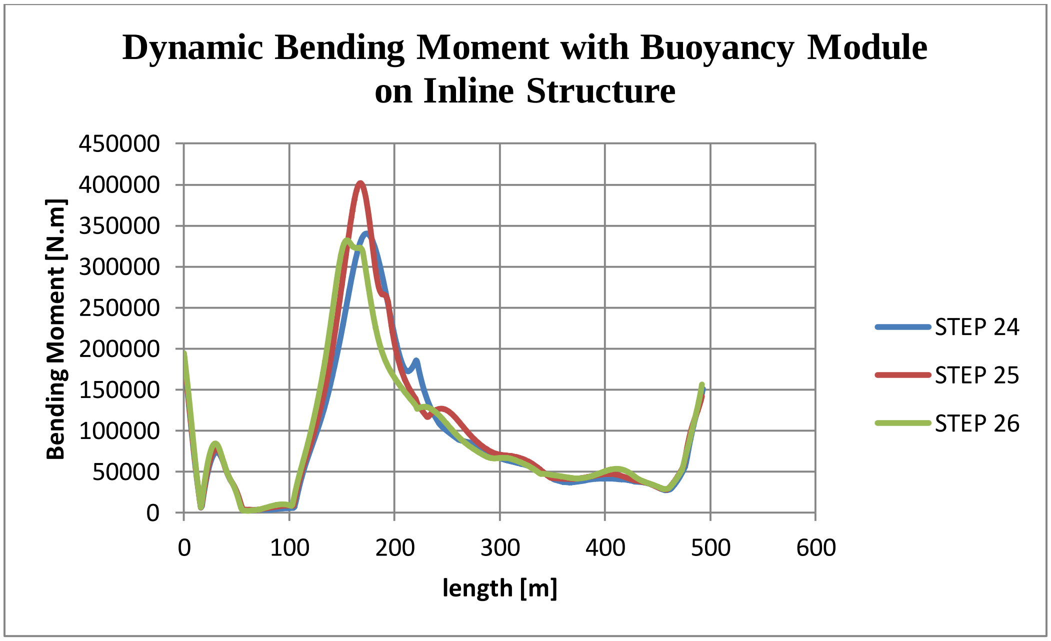

Figure 7.2 Dynamic Bending Moment for Initiation Steps with Buoyancy

Observations and Discussions

- The bending moment of step 26 is reduced to 332 kNm with a utilization of 1 as seen in Figure 7.2 and presented in Table 7.1. The buoyancy negates the structure's submerged weight and reduces the static bending moment and the utilization.

- The critical step has shifted to step 25 which experiences the worst utilization as shown in Table 7.1. The maximum bending moment for step 25 with buoyancy is 402 kNm and is located at 168 m (Refer Table 7.1 and Figure 7.2) when compared to the results without buoyancy module where step 25 experienced a bending moment of 374 kNm at 178 m (Refer Table 6.9).

- For Step 25 with buoyancy, the maximum bending moment occurs at a pipeline section in the sagbend below the structure and not over the structure. The extra buoyancy provided over the structure at 190 m has shifted the critical section of sagbend where the maximum dynamic bending moment occurs and has increased the bending moment at 168 m (Refer Table 7.1 and Figure 7.2). **In spite of using a buoyancy unit, the maximum bending moment still occurs at the sagbend and the effect of buoyancy module attached over the structure is negated. Hence it is critical to place a buoyancy module exactly over the location where the maximum bending moment occurs during all critical steps.**

7.2.1 COMPARISON OF STEP 26 WITH AND WITHOUT BUOYANCY MODULE

This section compares the results for step 26 with and without the buoyancy module and analyses the role of the buoyancy module in reducing the dynamic response of the pipeline. The variation of Static and Dynamic bending moment, tension and pipeline displacement are presented in Figure 7.3, Figure 7.4 and Figure 7.5 respectively.

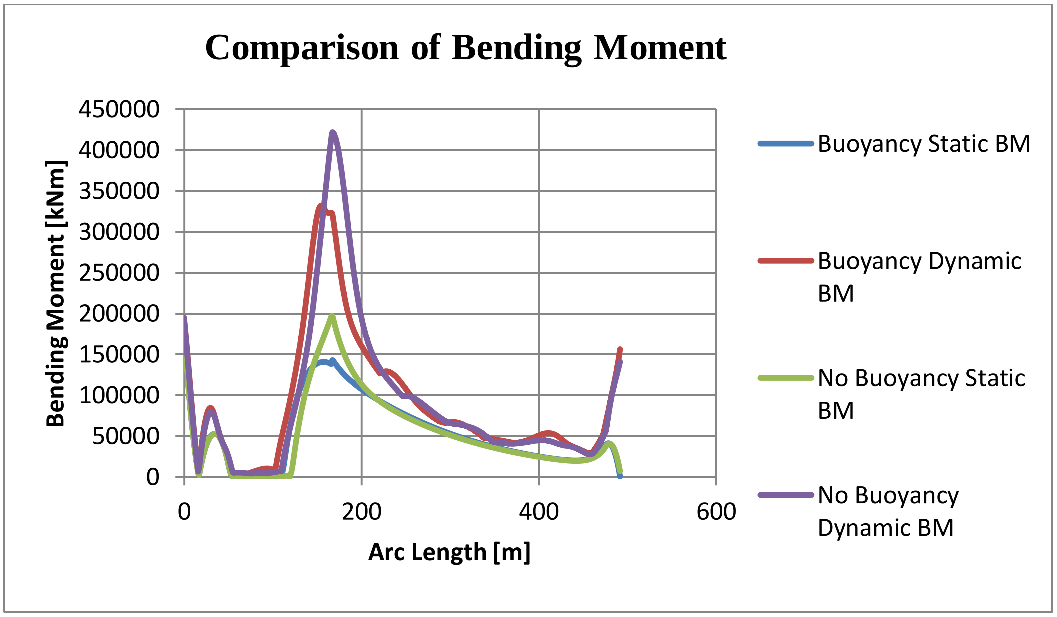

Figure 7.3 Comparison of Bending Moment With and Without Buoyancy for Step 26

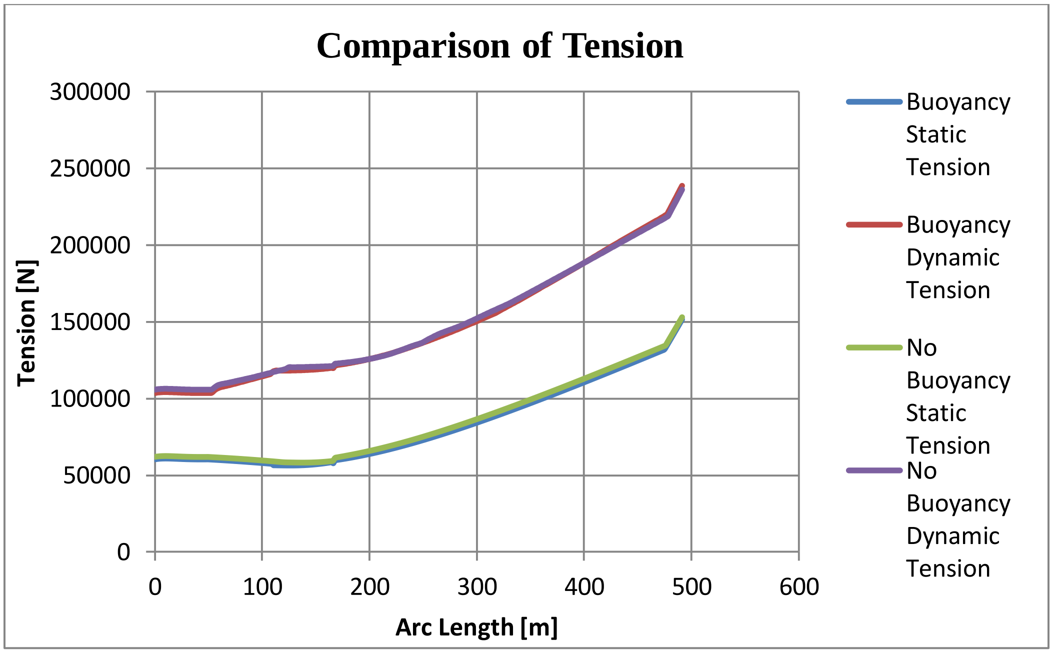

Figure 7.4 Comparison of Tension with and Without Buoyancy for Step 26

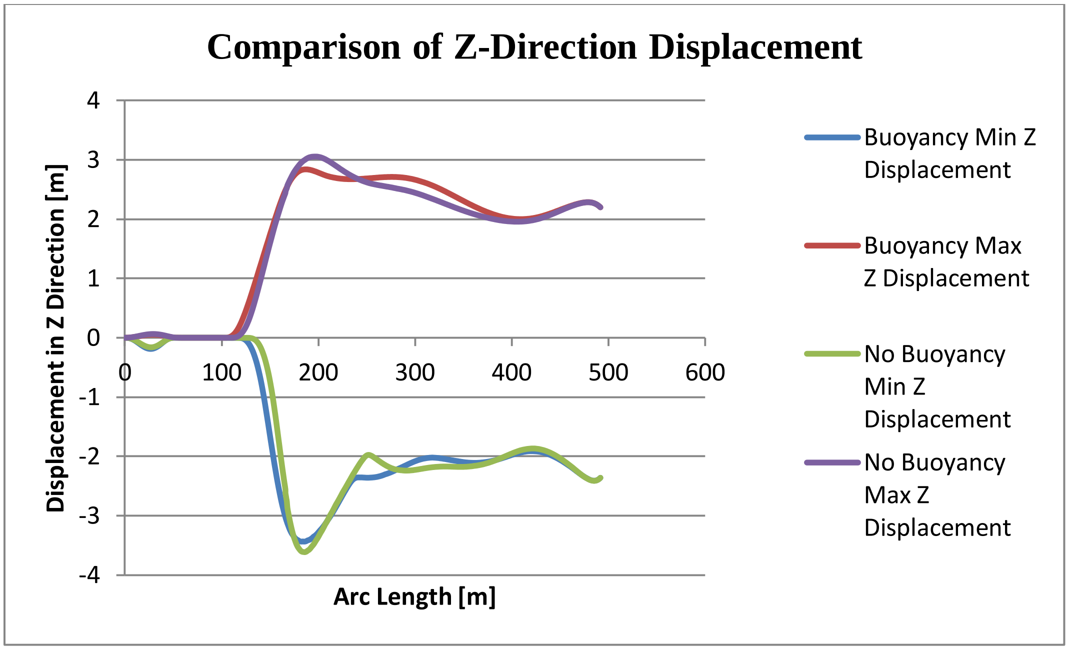

Figure 7.5 Comparison of Displacement in Z-Direction with and Without Buoyancy for Step 26

Observation and Discussions

- Buoyancy module brings down both static and dynamic bending moment as seen in Figure 7.3Figure 7.3. Dynamic moment is reduced to 332 kNm from 422 kNm. The utilization is brought to an acceptable value of 1 as shown in Table 7.1.
- There is no appreciable reduction in overall axial tension in the catenary by the introduction of the buoyancy module as seen in Figure 7.4.
- The displacement in Z direction is reduced at the sagbend by the introduction of buoyancy as seen in Figure 7.5. The displacement in the downward direction is more than the upward direction due to the effect of gravity as the catenary moves down.

7.3 INFLUENCE OF NET BUOYANCY TO INLINE STRUCTURE WEIGHT RATIO (SUBMERGED WEIGHT)

Usually, the net buoyancy is made equal to the excessive submerged mass of the inline structure over the pipeline mass. This will result in a pipeline catenary with uniform distribution of mass throughout. This section analyses the influence of various net buoyancy on the pipeline buckling utilization. While the buoyancy might be rigged at any point of the pipeline catenary, this particular analysis is performed by connecting the buoyancy module to the inline structure. To obtain a conclusive result, a similar analysis should be carried out at the final optimal attachment position as well but that is not performed in the thesis. Utilization results are presented in Table E.5 in Appendix E. Figure 7.6 shows the dynamic bending moment variation for different ratios.

Table 7.2 Summary of Net Buoyancy to Structure Weight Ratio Analysis

Description: Influence of Net Buoyancy to (Submerged) Structure Weight Ratio
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55
Step : 26 (Structure at sagbend 166 m)
Submerged Structure Mass: Approximately 800 Kg

Net Buoyancy	Ratio	Sagbend Bending Moment	Utilization
[kg]		[kNm]	
560	0,7	362	1,18
788	0,985	332	1
1080	1,35	343	1,1
1640	2,05	387	1,44

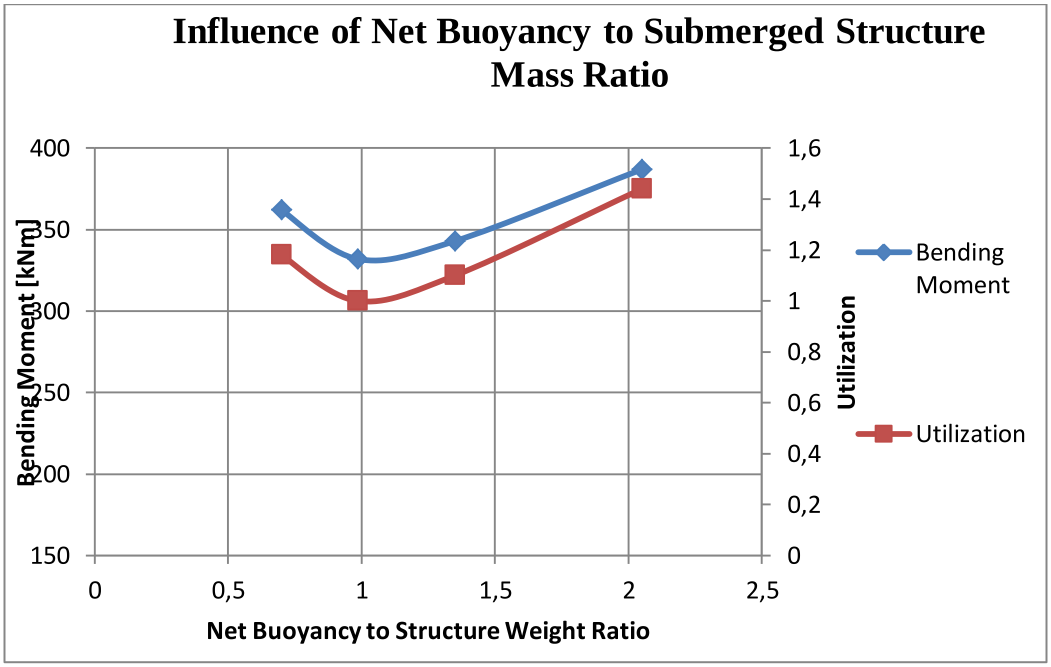

Figure 7.6 Influence of Net Buoyancy to Submerged Structure Mass Ratio

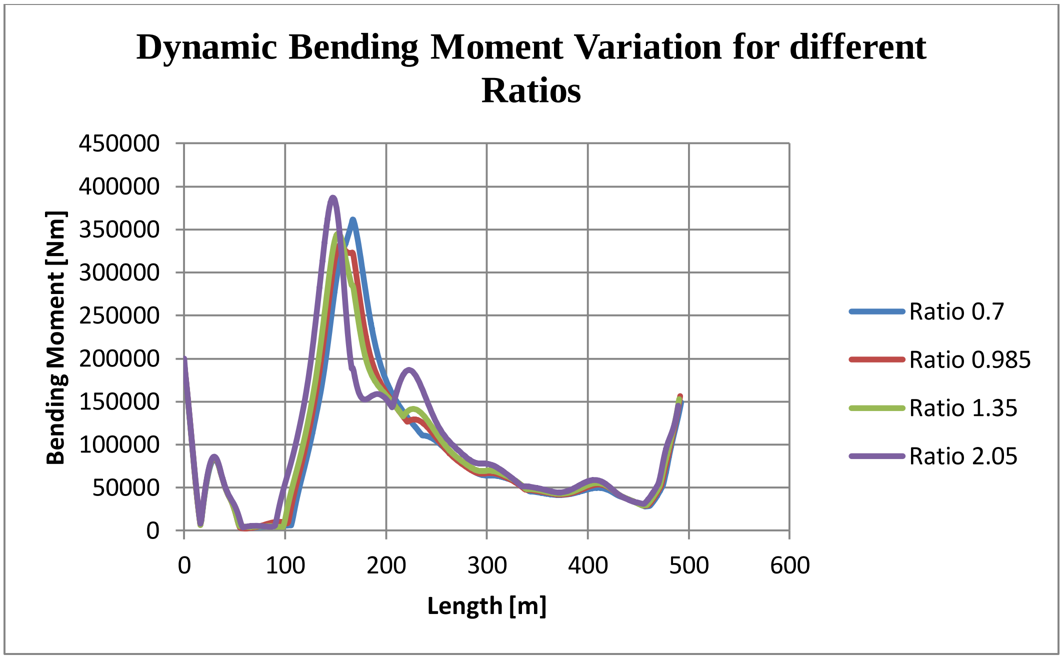

Figure 7.7 Dynamic Bending Moment for Various Net Buoyancy to Structure Weight ratio

Observations and Discussions

- A buoyancy unit whose net buoyancy to submerged structure mass ratio is approximately 1 gives the best result as seen in Table 7.2 and Figure 7.6. It makes the catenary mass uniform and the dynamic bending moment is least compared to other ratios.
- As the ratio is increased, the sagbend section experiencing the maximum bending moment is shifted more and more to the left of the structure resulting in very high bending moment of 387 kNm for a ratio of 2.05 as seen in Figure 7.7. This is because the higher net buoyancy provides very favorable dynamic response at the structure while the critical sagbend section below the structure suffers high bending moment.
- The dynamic bending moment for ratio 2.05 in Figure 7.7 also shows a larger dynamic response along the catenary between the structure and the top end.

7.4 INFLUENCE OF THE BUOYANCY MODULE ATTACHMENT POINT

The buoyancy module can be connected on the structure or anywhere in the pipeline catenary before and after the inline structure. Each of these configurations has different effect on the bending moment characteristics and pipeline utilization. This analysis is performed at the critical Steps 25 and 26 of the initiation process and the results are presented in Table 7.3 and Table 7.4 respectively. The utilization results are presented in Table E.6 and Table E.7 in Appendix E.

The negative position values in Table 7.3 indicate that the buoyancy module is attached towards the pipe section. Positive values indicate that the module is attached below the seal towards the riser section. Scenario 6 represented by an offset value of 0 m indicates that the buoyancy module is attached at the point where the J-Tube seal intersects with the riser section. Scenario 6 when the module is attached on the structure is taken as the base case with utilization factor of 1 as shown in Table 7.3.

Table 7.3 Summary of Analysis of the Buoyancy Module Attachment Position for Step 26

Description: Influence of Buoyancy Module Attachment Point
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^o
Net Buoyancy: 788 Kg
Volume: 2.277 m^3
Step : 26 (Structure at sagbend at 166 m from J tube End)
Total Catenary length: Approximately 492 m

Scenario	**Attachment point**	**Static Bending Moment**	**Maximum Static BM Position**	**Dynamic Bending Moment**	**Maximum Dynamic BM Position**	**Dynamic BM at Structure**	**Sagbend Buckling Utilization**
	[m]	[kNm]	[m]	[kNm]	[m]	[kNm]	
1	20	184	167	361	167	361	1,16
2	**10**	168	167	335	167	335	1
3	5	158	167	324	167	324	0,94
4	**2**	149	167	321	167	321	0,93
5	1	146	167	322	167	322	0,94
6	**0**	143	167	332	155	323	1
7	-0,5	142	158 & 167	338	156	324	1,04
8	-1	143	157	343	156	325	1,08
9	-2	146	161	353	156	332	1,14
10	-3	148	163	364	156	340	1,22
11	**-4**	151	166	375	157	347	1,29

Table 7.4 Summary of Analysis of the Buoyancy Module Attachment Position for Step 25

<table>
<tr><th colspan="8">Description: Influence of Buoyancy Module Attachment Point for Step 25
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^{o}
Net Buoyancy: 788 Kg
Volume: $2.277\ m^{3}$
Step : 25 (Structure at 190 m from the J tube end)
Total Catenary length: Approximately 492 m</th></tr>
<tr><th>Scenario</th><th>Attachment point</th><th>Maximum Static BM</th><th>Maximum Static BM Position</th><th>Maximum Dynamic BM</th><th>Maximum Dynamic BM Position</th><th>Dynamic BM at Structure</th><th>Sagbend Buckling Utilization</th></tr>
<tr><td></td><td>[m]</td><td>[kNm]</td><td>[m]</td><td>[kNm]</td><td>[m]</td><td>[kNm]</td><td></td></tr>
<tr><td>1</td><td>0</td><td>145</td><td>164</td><td>402</td><td>168</td><td>266</td><td>1,5</td></tr>
<tr><td>2</td><td>1</td><td>144</td><td>164</td><td>398</td><td>167</td><td>265</td><td>1,47</td></tr>
<tr><td>3</td><td>2</td><td>143</td><td>163</td><td>395</td><td>167</td><td>263</td><td>1,45</td></tr>
<tr><td>4</td><td>**5**</td><td>140</td><td>160</td><td>381</td><td>165</td><td>259</td><td>1,35</td></tr>
<tr><td>5</td><td>10</td><td>135</td><td>156</td><td>351</td><td>161</td><td>254</td><td>1,14</td></tr>
</table>

Figure 7.8 shows the variation of Dynamic Bending moment and the sagbend buckling utilization for various buoyancy connection positions. Figure 7.9 and Figure 7.10 shows the static and dynamic moment variation for selected buoyancy attachment positions (Scenarios 2, 4, 6 and 11).

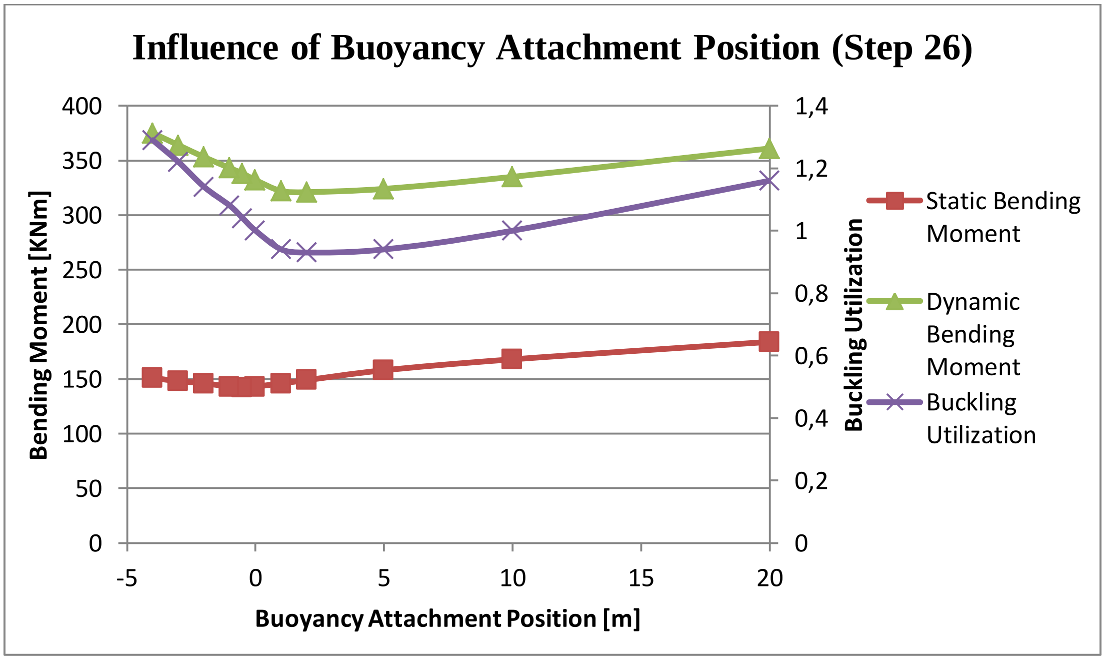

Figure 7.8 Variation of Bending Moment with Buoyancy Position for Step 26

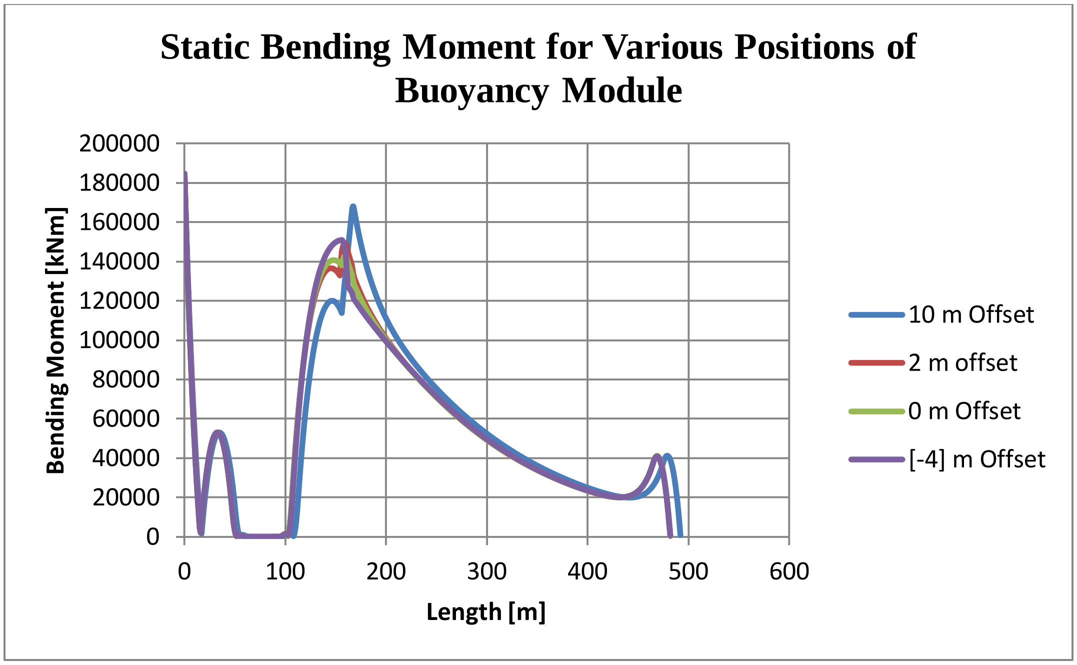

Figure 7.9 Static Bending Moment for Various Buoyancy Attachment Positions for Step 26

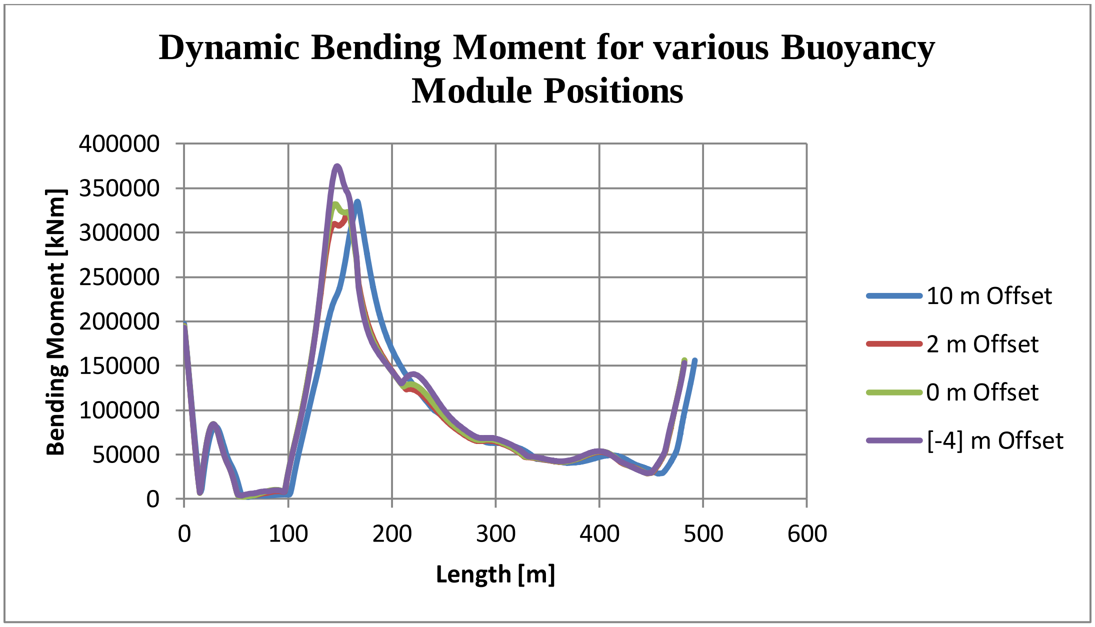

Figure 7.10 Dynamic Bending Moment for Various Buoyancy Attachment Positions for Step 26

Observations and Discussions

- As we offset the buoyancy unit farther from the structure into the riser section for step 26, the static and dynamic bending moment decreases and then increases again as shown in Figure 7.8. Around 10 m offset, the results are similar to 0 m offset with utilization factor of 1 (Refer Table 7.3).

- The best result is obtained when the offset is about 2 m. The inclusion of buoyancy module has slightly offset the critical sagbend position (which is characterized by maximum bending moment and utilization) to 155 m as shown by scenario 6 in Table 7.3. Scenario 4 shows that a 2 m offset brings the buoyancy unit towards the critical section of the sagbend that suffers maximum bending moment than a 0 m offset and hence provides a better result. However as the offset is increased more, the maximum bending moment once again occurs at the structure as seen in scenarios 1 to 5 in Table 7.3.

- However we cannot use 2 m offset as the optimal configuration because the inclusion of buoyancy module into the system changes the overall critical step for initiation. While a 2 m offset provides the best result for the step 26 configuration, the results are adverse for step 25 with 2 m offset. In case of an offset of 2 m for step 25, the maximum bending moment is 395 kNm with a utilization of 1.45 compared to an offset of 10 m which has a utilization of 1.14 (Refer to Table 7.4 in this section and Table E.7 in Appendix E).

- As shown in Table 7.3 for step 26, any offset towards the pipeline section results in adverse utilization results. This is because the buoyancy is being offset away from the critical sagbend section leaving it to suffer greater bending moment as seen in Figure 7.10.

- Similarly in case of Step 25 analysis, as presented in Table 7.4, any offset away from the structure and towards the critical sagbend section provides better result.

7.5 INFLUENCE OF BUOYANCY GEOMETRY

Drag and Added mass contribute to the dynamic response of all submerged objects. These parameters are defined by the volume and the geometry of the submerged structure. This section will analyze the influence of buoyancy geometry and the added mass component of the buoyancy on the dynamic response of the pipeline. Three different buoyancy shapes are considered – Cylindrical and square cross section modules and spherical units.

Cylindrical and square sections are the industry standards and are dictated by the ease of fabrication and deployment at offshore. Spherical module is analyzed only for theoretical reasons. Geometry of the structure determines the added mass and drag coefficients involved. A sensitivity study for step 26 presented in Table 7.5 is performed to analyze the influence of added mass and drag components in various directions before optimal geometry of a physical buoyancy unit is analyzed. The utilization results for added mass and drag coefficient variations are presented in Table E.8 and Table E.9 respectively in Appendix E.

Table 7.5 Summary of Added Mass and Drag Co-efficient Sensitivity Analysis

Description: Influence of Buoyancy Module Added Mass and Drag Co-efficient
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Buoyancy Attachment Segment Length: On the Structure at 166 m from J tube end
Initiation Step: 26 (Structure at critical sagbend location)
Net Buoyancy: 788 Kg
Volume: 2.277 m^3

Scenario No:	**CD_X**	**CD_Y**	**CD_Z**	**AM_X**	**AM_Y**	**AM_Z**	**Maximum Sagbend Dynamic Bending Moment**	**Buckling Utilization**	**Maximum Bending Moment Segment**
	[kg/m]	[kg/m]	[kg/m]	[kg]	[kg]	[kg]	[kNm]		[m]
Influence of Added Mass									
1	0	0	0	0	0	0	346	1,1	166
2	0	0	0	0	0	1000	342	1,07	166
3	0	0	0	0	0	2000	335	1,02	166
4	0	0	0	0	0	3000	324	0,95	166
5	0	0	0	0	0	4000	318	0,92	155
6	0	0	0	0	0	5000	316	0,9	150
7	0	0	0	2000	2000	0	346	1,1	166
Influence of Drag Co-efficient									
	0	0	0	0	0	0	346	1,1	166
8	0	0	1000	0	0	0	336	1,03	155
9	0	0	2000	0	0	0	338	1,04	155
10	0	0	3000	0	0	0	342	1,07	155
11	2000	2000	0	0	0	0	345	1,09	166
Influence of Added Mass and Drag Co-efficient									
12	0	0	1000	0	0	3000	327	0,97	156
13	0	0	2000	0	0	3000	332	1	156

Figure 7.11 and Figure 7.12 shows the variation of dynamic bending moment and utilization with added mass and drag coefficient respectively.

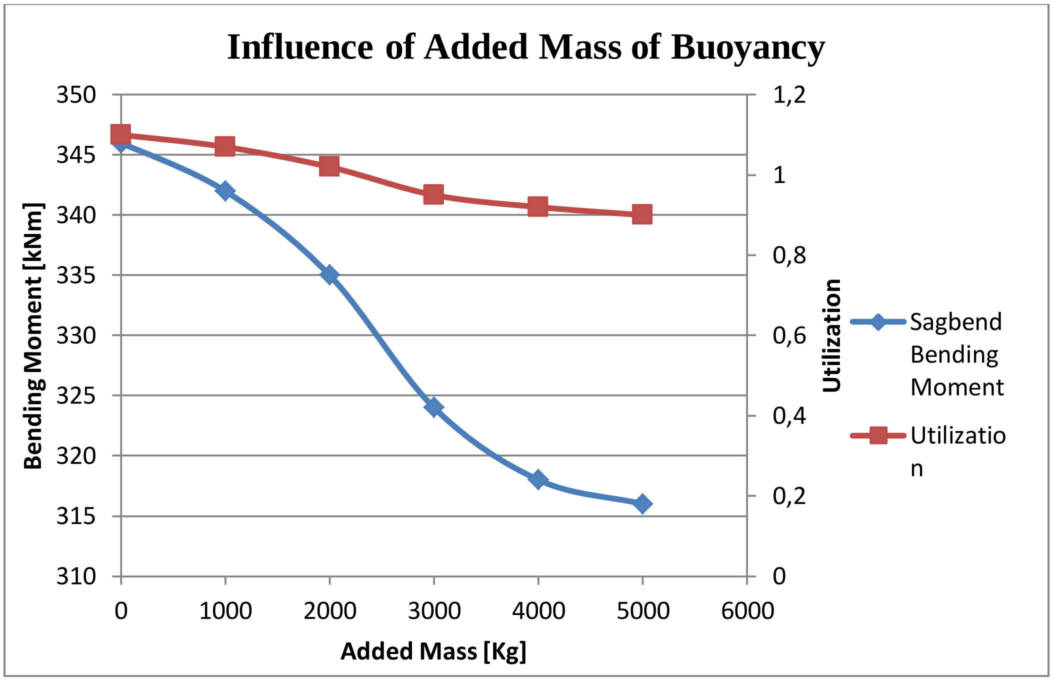

Figure 7.11 Influence of Added Mass of Buoyancy Module

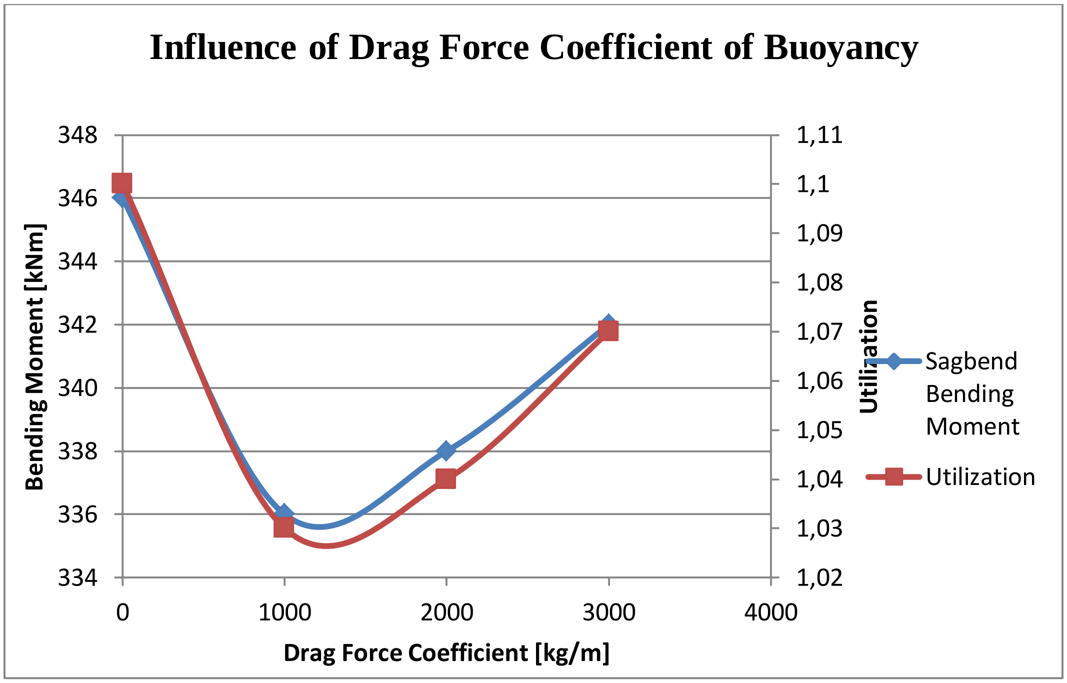

Figure 7.12 Influence of Drag Force Co-efficient of Buoyancy Module

Observations and Discussions

- Only the Drag and Added mass in the z-direction contribute to the bending moment. The corresponding components in x and y direction have very negligible effect as shown by scenario 7 and 11 in Table 7.5.

- The bending moment keeps decreasing with the increase in added mass. The increase in the added mass of the buoyancy module reduces the dynamic response of the pipeline at the structure because the added mass of the buoyancy is out-of-phase with the mass of the catenary. This results in a better buckling utilization at the structure. However very high values of added mass are not practically possible and the beneficial effects are negligible beyond a point. For the case analyzed, the improvement in utilization is marginal beyond 4000 kg as shown in Figure 7.11.

- Maximum bending moment at sagbend decreases and then increases with the increase in drag coefficient as seen in Figure 7.12. Also it is observed that the bending moment at the structure keeps decreasing. While the drag on the buoyancy unit lowers the dynamic response of pipeline at the structure (buoyancy attachment position), the bending moment of the pipeline at about 10 m below the structure starts to increase beyond a certain value of drag coefficient. This might be because the resistance brought about by the drag of the buoyancy results in low bending moment at the structure while contributing to an increased dynamic response at the section of the pipeline which is 10 m below the structure.

- **Scenarios 12 and 13 in Table 7.5 analyses the combined effect of added mass and drag and shows that a buoyancy module whose geometry contributes to the maximum possible added mass while keeping the drag as low as possible seems to be the optimal configuration for a given net buoyancy and volume.**

This analysis is not comprehensive. The added mass associated with the buoyancy helps to reduce dynamic response of the pipeline catenary when it is out-of-phase with the dynamic response of the catenary. However if the added mass of the buoyancy module is in phase with that of the catenary, then it will result in amplified dynamic response for the overall system and a higher utilization.

To obtain a conclusive result, this sensitivity analysis should be carried out by connecting the buoyancy at various positions of the catenary through a tether. One such analysis was made by connecting the buoyancy at an offset of 10 m from the structure and similar beneficial effect was observed due to the out-of-phase response of the added mass of buoyancy. This result is not presented in the thesis. To establish conclusive results, similar sensitivity analysis should be performed for various tether heights, water depth and other offset positions. However such extensive analysis is not performed in the thesis due to time constraints.

7.5.1 COMPARISON OF BUOYANCY UNITS WITH CYLINDRICAL AND SQUARE CROSS SECTION

The sensitivity study in section 7.5 established the contribution of added mass and drag force coefficient. In this section different cross sections, especially modules with square and cylindrical cross section are compared for a given volume and net buoyancy. Spherical modules are also studied however they might not be practical and there seems to be no company that manufactures very large spherical buoyancy modules.

The calculations of added mass and drag coefficients are presented in Appendix D. The utilization calculations are presented in Table E.10 in Appendix E.

Table 7.6 summarizes the bending moment and utilization for various geometries analyzed with a given net buoyancy and volume.

Table 7.6 Summary of Analysis of the Geometry of Buoyancy Modules

Description: Analysis of Geometry of Buoyancy Module **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Buoyancy Attachment Segment Length: On the structure at 166 m** **Initiation Step : 26** **Net Buoyancy: 788 kg** **Volume: 2.277 m^3**								
Cross Section: Cylinder								
Diameter	**Height**	**C_{DZ}**	**CD_Z**	**C_{AZ}**	**AM_Z**	**Maximum Sagbend Bending Moment**	**Utilization**	**Maximum Bending Moment Segment**
[m]	[m]	-	[kg/m]	-	[kg]	[kNm]		[m]
1	2.899	0.86	346	-	536	335	1,02	166
2	**0.724**	**1**	**1610**	**-**	**4293**	**328**	**0,98**	**151**
Cross Section: Square								
Side Dimension	**Height**	**C_{DZ}**	**CD_Z**	**C_{AZ}**	**AM_Z**	**Maximum Sagbend Bending Moment**	**Utilization**	**Maximum Bending Moment Segment**
[m]	[m]	-	[kg/m]	-	[kg]	[kNm]		[m]
1	2.277	0.885	453	0.325	758	332	1,01	156
2	0.569	1.16	2378	1.321	3079	334	1,02	152
Sphere								
Radius	**Height**	**C_{DZ}**	**CD_Z**	**C_{AZ}**	**AM_Z**	**Maximum Sagbend Bending Moment**	**Utilization**	**Maximum Bending Moment Segment**
[m]	[m]	-	[kg/m]	-	[kg]	[KNm]		[m]
0.816	-	0.5	536	0.5	1166	330	0,99	156

The results from Table 7.6 indicate that cylindrical modules with larger diameter provide better result due to greater added mass for a given volume and net buoyancy. However the difference is not appreciable and further analysis is required to arrive at any definite conclusion.

7.6 DETERMINATION OF OPTIMAL OFFSET POSITION

Section 7.4 analyzed the influence of attachment position for buoyancy during step 26. However offset of the buoyancy module might provide a different result at other critical steps of initiation. The optimal offset position can be determined only after making a similar study for other critical steps (Step 25 and 24). The utilization results are presented in Table E.11and Table E.12 in Appendix E. Table E.11 also shows the limiting sea state for the 10 m offset of buoyancy unit.

Table 7.7 Summary of Analysis for Buoyancy Module at 10 m Offset from the Structure

Description: Analysis for Buoyancy Module at 10 m Offset from the Structure **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Ramp Angle: 60.55^o** **Net Buoyancy: 788 Kg** **Volume: 2.277 m^3**							
		Step 24		**Step 25**		**Step 26**	
		Sagbend	Structure	Sagbend	Structure	Sagbend	Structure
Structure Position	[m]	220		190		166	
Static BM	[kNm]	142	135	135	157	168	168
Maximum Static BM Position	[m]	166		155		167	
Dynamic BM	[kNm]	211	53	215	98	167	167
Maximum Dynamic BM Position	[m]	170		161		166	
Total BM	[kNm]	353	193	350	255	335	335
Utilization	--	1,15		1,14		1	

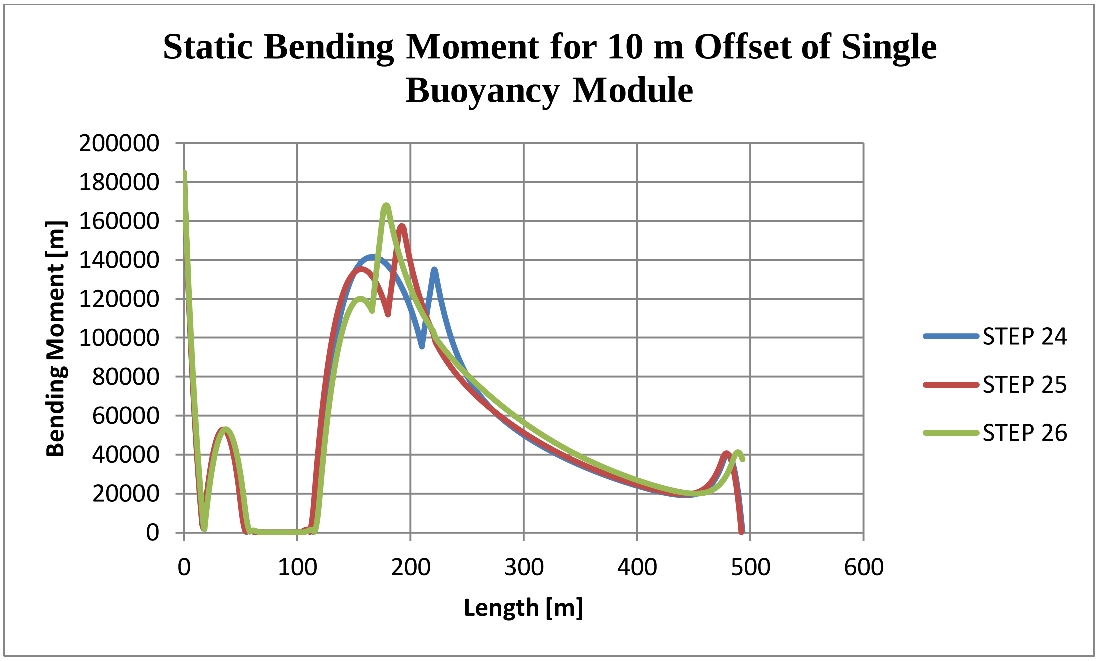

Figure 7.13 Static Bending Moment for 10 Offset of Single Buoyancy Module System

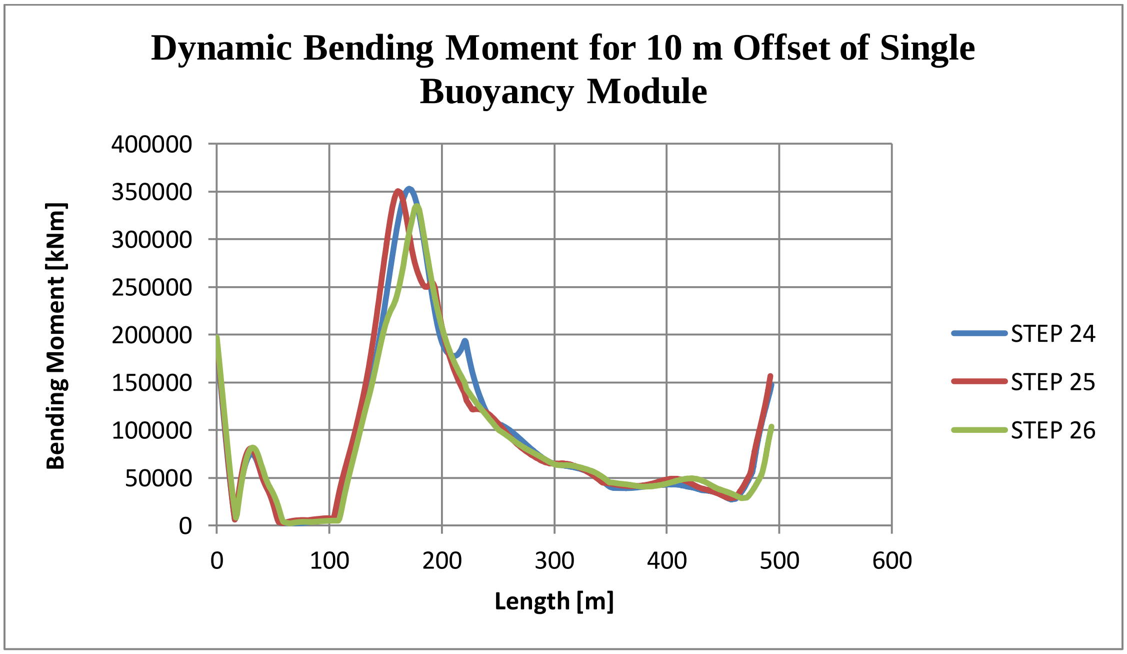

Figure 7.14 Dynamic Bending Moment for 10 Offset of Single Buoyancy Module System

Table 7.8 summarizes the bending moments and utilization variations for an offset of 20 m from the structure. Figure 7.15 shows the dynamic and static bending moment variations for a 20 m offset from the structure.

Table 7.8 Summary of Analysis for 20 m Offset of Single Buoyancy Module System

Description: Analysis for Buoyancy Module at 20 m Offset from the Structure **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Net Buoyancy: 788 Kg** **Volume: 2.277 m^3**							
		Step 24		**Step 25**		**Step 26**	
		Sagbend	Structure	Sagbend	Structure	Sagbend	Structure
Structure Position	[m]	220		190		166	
Static BM	[kNm]	137	150	125	175	184	184
Maximum Static BM Position	[m]	168		150		166	
Dynamic BM	[kNm]	217	50	145	185	177	177
Maximum Dynamic BM Position	[m]	168		154		166	
Total BM	[kNm]	354	200	270	260	361	361
Utilization	--	1,16		0,66		1,16	

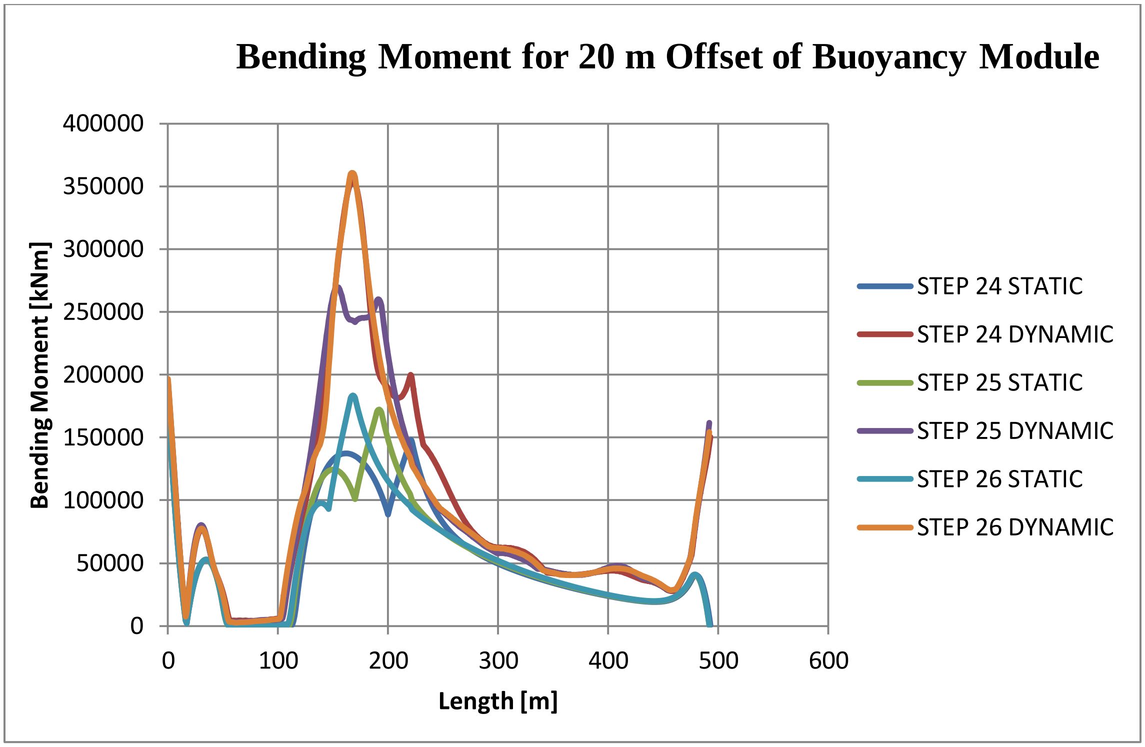

Figure 7.15 Bending Moment for 20 m Offset of Single Buoyancy Module

Observation and Discussions

- As seen from Table 7.7, a 10 m offset results in a better utilization for step 24 and 25 compared to the buoyancy unit attached on the structure. The buoyancy is brought closer to the critical section of the sagbend by the offset resulting in better utilization.

- A 20 m offset provides very good result for step 25 as seen in Table 7.8. This is because the buoyancy is much closer to the critical section of sagbend than a 10 m offset in case of step 25.

- However a 20 m offset takes the buoyancy unit away from sagbend during step 26 resulting in a bending moment of 361 kNm compared to 335 kNm experienced during a 10 m offset (Refer Table 7.8 and Table 7.7). Hence an offset of 10 m is preferred over all.

- Table E.11 in Appendix E shows that limiting sea state for step 24 and 25 with a 10 m offset of buoyancy unit as 1.8 m of significant wave height. This is also the optimal limiting sea state for the entire initiation operation.

- **In general, buoyancy offset position that balances the bending moment at the structure and the bending moment at the critical section of the sagbend below the structure is the most optimal offset position.**

7.7 INFLUENCE OF MULTIPLE BUOYANCY UNITS

It is observed in section 7.6 that an offset of buoyancy yields better result than attaching the buoyancy to the structure. In this section, influence of two buoyancy modules are analyzed with one unit connected directly on the structure and another unit offset towards the riser section. Both buoyancy modules are connected using a tether. Table 7.9 and Table 7.10 show the results for 10 m offset and 20 m offset respectively between the buoyancy units. The corresponding utilization results are presented in Table E.13 and Table E.14 in Appendix E.

Table 7.9 Summary of Analysis for 10 m Offset of a two Buoyancy Module System

Description: Analysis for Two Buoyancy Module system at 10 m Offset from each other **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Ramp Angle: 60.55°** **Net Buoyancy: 788 Kg** **Volume: 2.277 m^3**							
		Step 24		**Step 25**		**Step 26**	
		Sagbend	Structure	Sagbend	Structure	Sagbend	Structure
Structure Position	[m]	220		190		166	
Static BM	[kNm]	147	86	136	103	119	112
Maximum Static BM Position	[m]	160		148		135	
Dynamic BM	[kNm]	244	80	302	93	200	90
Maximum Dynamic BM Position	[m]	169		158		142	
Total BM	[kNm]	391	166	438	196	319	202
Utilization	--	1,42		1,79		0,95	

Table 7.10 Summary of Analysis for 20 m Offset of a two Buoyancy Module System

Description: Analysis for Two Buoyancy Module system at 20 m Offset from each other **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Net Buoyancy: 788 Kg** **Volume: 2.277 m^3**							
		Step 24		**Step 25**		**Step 26**	
		Sagbend	Structure	Sagbend	Structure	Sagbend	Structure
Structure Position	[m]	220		190		166	
Static BM	[kNm]	143	96	130	117	101	127
Maximum Static BM Position	[m]	156		143		135	
Dynamic BM	[kNm]	259	78	269	94	145	106
Maximum Dynamic BM Position	[m]	167		153		148	
Total BM	[kNm]	402	174	389	211	246	233
Utilization	--	1,51		1,42		0,51	

Figure 7.16 and Figure 7.17 show the variation in bending moments for 10 m and 20 m offset of two buoyancy module systems respectively. The static and dynamic bending moments for step 24, 25 and 26 are displayed in the same figure.

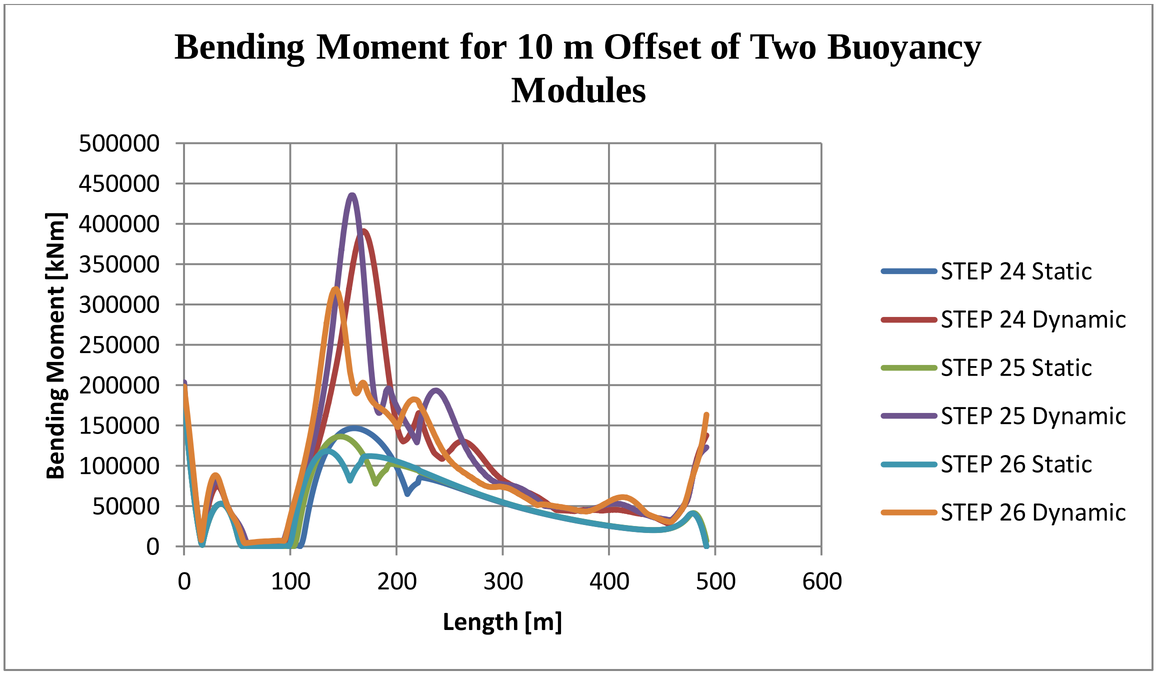

Figure 7.16 Bending Moment for 10 m Offset of Two Buoyancy Module

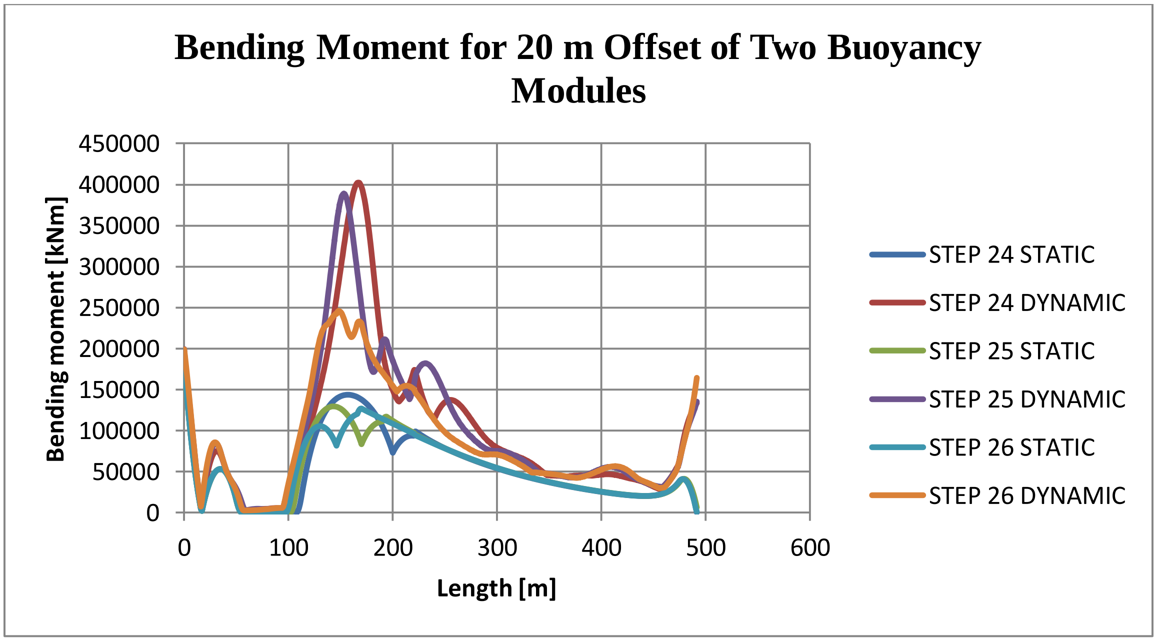

Figure 7.17 Bending Moment for 20 m Offset of Two Buoyancy Module

Observations and Discussions

- The results shown in Table 7.9 and Table 7.10 indicate that the use of two buoyancy units with an offset between them yields higher bending moments and worse utilization when compared to the use of a single buoyancy module which is offset from the structure.

- Results for Step 25 in Table 7.9 yields a utilization of 1.79 which is greater than the utilization of 1.14 obtained with single buoyancy module shown in Table 7.7. The sagbend is always the most critical section. When two buoyancy modules are used, the dynamic response of the section near the structure where the buoyancy modules are connected is not affected considerably, but the highest dynamic response is experienced by the lower part of the catenary. Hence the use of two buoyancy modules yields a higher bending moment when compared with one buoyancy module.

- Two buoyancy modules with 20 m offset yields better result than two buoyancy modules with 10 m offset as compared in Table 7.9 and Table 7.10. A 20 m offset brings the buoyancy closer to the critical section of the sagbend. It is still worse than the use of single buoyancy module described in section 7.6.

- J tube seal is an inline structure of relatively low mass. A heavier inline structure like a Tee or Wye joint or a large PLET/sled might provide a more favorable result with the use of multiple buoyancy modules compared to single buoyancy module. This analysis is not carried out in the thesis.

7.8 SENSITIVITY ANALYSIS OF TETHER LENGTH

Large and modular buoyancy units are usually attached to the structure through a tether.

There are two reasons why the buoyancy unit is not directly attached to the structure [17].

- ➢ Often the stinger which supports the structure is not designed to carry the extra weight of the buoyancy unit as well (in case of S Lay).
- ➢ The bending moment induced by the buoy on the pipeline might be too high if connected directly to the structure during the initial step.

Also, in most vessels the buoyancy deployment station is located at a certain distance from the firing line and hence a tether is required to enable deployment. However if the buoyancy is not big, it can be directly connected to the structure.

This section analyses the influence of tether length and tries to establish an optimum length.

Table 7.11 Summary of the Sensitivity Study on Tether Length

Description: Analysis for variation in Tether Length **Wave Heading: 60** **Wave Height: 2 m** **Wave Period: 9 s** **Net Buoyancy: 788 Kg** **Volume: 2.277 m^3**			
Tether Length	**Static Bending Moment**	**Dynamic Bending Moment**	**utilization**
[m]	[kNm]	[kNm]	
40	147	330	0,99
30	144	330	0,99
25	143	330	0,99
20	142	333	1,01
10	140	332	1,01
2	138	335	1,03

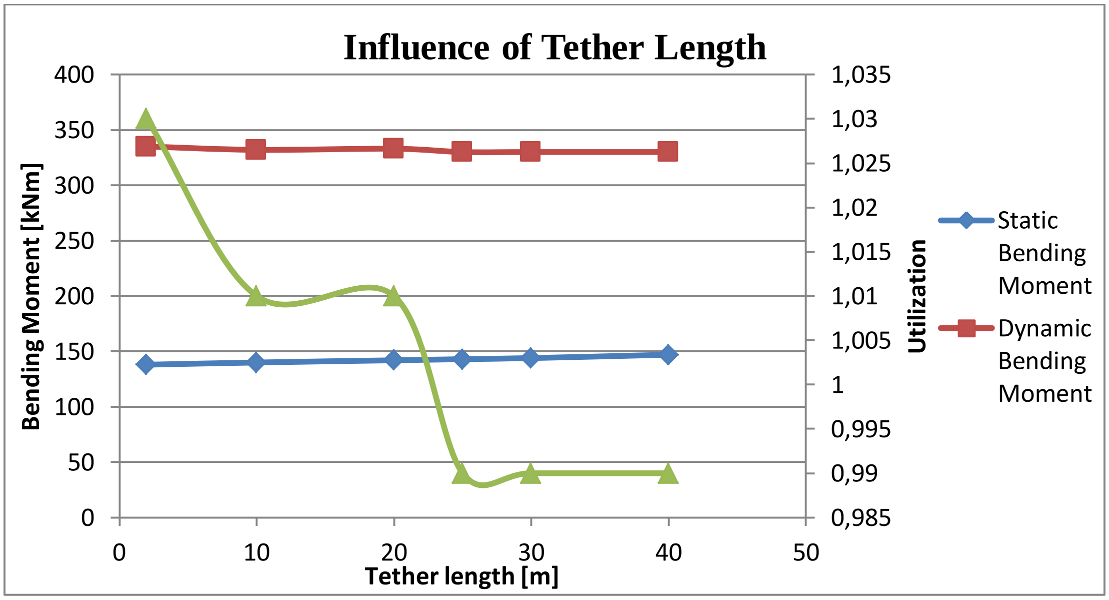

Figure 7.18 Sensitivity Study of Tether Length

Table 7.11 summarizes the bending moment and Utilization factor for various tether length. The static moment is larger with longer tether. This might be because of the effect of varying current profile with depth. The dynamic bending moment and consequently the pipe utilization at sagbend increases with the reduction in the tether length. This might be due to the interaction of the added mass of buoyancy unit with the pipeline as the buoyancy module is brought closer to the pipeline due to a shorter tether.

As shown in Figure 7.18, a tether length of 20-25 m seems optimum with respect to ease of deployment and pipe utilization. Anything longer than that has very little influence on utilization. However very small tether length of 5 m and below has adverse effect and should be avoided. The corresponding utilization results are presented in Table E.15.

7.9 OPTIMIZATION PROCEDURE FOR BUOYANCY CONFIGURATION

Sagbend utilization is primarily controlled by bending moment at sagbend. Hence the variation of bending moment in each critical step is studied to establish a procedure for the determination of optimal buoyancy configuration.

A thorough optimization process requires hundreds of scenarios to be analyzed and it is very time consuming. Also the dynamic behavior is often unpredictable and makes the identification of the most optimal configuration difficult. The procedures presented in Table 7.12 attempts to stream line the process and minimize the iterations required.

Table 7.12 Procedure for determining the Optimal Buoyancy Configuration

Step	Description
1	Prepare the step by step Initiation Lay Table.
2	Perform the analysis for the different steps of the initiation. This should include the top and sagbend utilization for the critical wave incident direction and time periods for the specific vessel.
3	Identify the critical steps with respect to sagbend utilization.
4	Identify the exact critical payout of the pipe that yields the worst utilization. This can be determined by increasing the pipe length in steps of 5 m to either side of critical step identified earlier.
5	Attach a buoyancy module on the structure at zero offset with net buoyancy equal to submerged mass of the structure. Determine the utilization for the critical step.
6	Determine the utilization for 2 steps on either side of the critical step. Compare them with the critical step identified in step 3. Verify if the critical step has shifted to adjacent steps.
7	Offset the buoyancy module to the position where the maximum bending moment occurred for the critical step determined in step 5. Determine the utilization. Also determine the utilization for other offset positions in steps of 2 m from the structure. Compare the utilizations to determine the offset that yields the best utilization.
8	Perform a similar analysis as done in step 7 by offset of buoyancy module at the adjacent critical step. Verify if the optimal offset determined in step 7 provides a better result at the adjacent step as well. If not, ascertain the optimal offset by comparing the utilization results from step 7 and 8.
9	If the structure is very heavy, perform a similar analysis as step 7 and 8 with 2 buoyancy modules – one on the structure and the other offset at a distance.

8. CONCLUSION AND RECOMMENDATIONS

8.1 SUMMARY

Installation of inline structures can be challenging due to the additional weight of the structure in the catenary and the increased dynamic loading. The limiting sea state for the initiation is drastically reduced with the inline structure. Buoyancy modules are used to reduce the submerged weight of the structure and improve the installation sea state. Extensive analysis work has to be performed to identify the optimal buoyancy module configuration to improve the limiting sea state. Net buoyancy, geometry of the module, attachment position on the catenary with respect to the structure and number of buoyancy modules are the primary parameters analyzed during the process of optimal buoyancy identification.

The initiation phase is divided into 32 steps of pay out as presented in Table E.1 is Appendix E. The highest dynamic response is experienced by the catenary when the structure is at the sagbend of the catenary. The pipeline experiences very high bending moment with a maximum utilization of 1.6 without buoyancy module at a significant wave height of 2 m during step 26 of the initiation phase. Hence Step 26 is the most critical step of the initiation and is used as the base case for the optimization process.

The use of the buoyancy module connected to the structure at step 26 has decreased the bending moment from 422 kNm to 332 kNm, a reduction of 21%, resulting in an acceptable utilization factor of 1 for a wave height of 2 m as shown in Table 7.1 in section 7.2. The optimal configuration for the case studied is a single buoyancy unit connected at an offset of 10 m from the structure with a net buoyancy of around 780 kg. With this configuration, the limiting sea state is increased from 1.4 m of significant wave height to 1.8 m as shown in section 7.6. A summary of the general analysis and the optimization process is described here.

1. The catenary during the initiation phase is governed by the weight of the pipeline and structure, the ramp angle and the water depth. While a J lay ramp can typically provide ramp angle between 20 and 90, the optimal ramp angle at the depth of 200 m is 60 or 65. This provides sufficient pipe length on the seabed for the J tube Pull in and an optimal catenary and vessel lay back distance.

2. The critical step of the initiation is step 26 which corresponds to the structure at sagbend. The bending moment is 422 kNm and the utilization is 1.6 which is the maximum for all the steps of the initiation with a wave height of 2 m.

3. The inclusion of the buoyancy module into the system reduces the bending moment to 332 kNm and utilization to an acceptable value of 1 for step 26. However the critical step has shifted to step 25 as shown in section 7.2.

4. The offset of the buoyancy module away from the structure produces better results. During steps 24 and 25, an offset brings the buoyancy closer to the sagbend and utilization is improved. An offset of 10 m provides optimum result across all steps as shown in section 7.6.

5. Net buoyancy to submerged structure mass ratio of 1 provides the most favorable result amongst all the ratios tried. Bending moment in the lower part of the sagbend away from the connection point of the buoyancy module is high if the net buoyancy is large (Section 7.3).

6. The geometry of the buoyancy module affects the bending moment by influencing the associated added mass introduced into the system. Sensitivity study shows that the results are favorable with an added mass of around 4000 kg for the buoyancy module for the current configuration and the case analyzed. Also cylindrical cross section of larger diameter is slightly better than a square cross section. (Refer section 7.5.1).

7. For an inline structure like J tube with relatively low mass, the use of two buoyancy modules yields an adverse result. With 10 m and 20 m offset of a dual buoyancy system, the bending moment values are very high at 438 kNm and 389 kNm respectively for step 25 as shown in section 7.7.

8. Tether length has very little influence. However, very short tether length should be avoided.

8.2 CONCLUSION

The analysis shows that to obtain a reasonable limiting sea state for operation, the use of buoyancy module is required for inline structure installation.

Buoyancy module configuration with net buoyancy to submerged structure mass ratio of approximately 1 when attached to the pipeline catenary at an offset of around 10 m from the structure yields the most optimal result for the case analyzed. A buoyancy module offset position that balances the bending moment at the structure and the bending moment at the critical section in the lower part of the sagbend below the structure for all the critical steps of the initiation phase is the most optimal offset position.

Sensitivity analysis on the added mass and drag of the buoyancy module shows that better utilization results are achieved when there is a large added mass associated with the buoyancy module due to the out-of-phase dynamic response of this added mass with the dynamic response of the pipeline catenary. Analysis on various geometries of the buoyancy module shows only marginal difference in utilization and no conclusive results could be established.

The use of dual buoyancy modules is not recommended in the present case. The results are adverse. In general the sagbend bending moment is the governing factor and negates the effect of additional buoyancy modules irrespective of the number of modules and net buoyancy or the offset distance.

The analysis performed is limited. A heavy structure might require a different configuration and net ratio and the use of dual buoyancy modules. In general the determination of the optimal configuration does not follow a set of established rules. It is very case specific. Water depth, the type and weight of the structure, current and ramp angle together determine the final configuration of the buoyancy module required.

However the procedure discussed can be used in general to understand the behavior of the system and to minimize the number of iterations required to determine the optimal configuration.

8.3 RECOMMENDATION FOR FURTHER WORK

The following analyses are recommended to reach a definite conclusion:

A comprehensive analysis of the net buoyancy to submerged structure mass ratio should be performed by varying the weight of the inline structure and the position of the inline structure with respect to the critical section of sagbend. In other words the influence of the ratio has to be analyzed at all the critical steps of the initiation phase. This study should also take into consideration the offset of the buoyancy module from the structure.

A more detailed analysis of added mass of the buoyancy modules should be carried out by connecting it at various offset positions to understand its influence on the dynamic response of the catenary due to its out-of-phase interaction. This study should be extended to various geometries of the buoyancy.

The optimal buoyancy configuration for a heavier inline structure should be analyzed. The use of multiple buoyancy modules in this case has to be verified.

The behavior of the system and the veracity of the procedure with the variation of the water depth and current velocity should be analyzed.

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APPENDIX A: ORCAFLEX SOFTWARE AND MODELING

Description of Software Orcaflex:

Orcaflex is a marine dynamics program developed by Orcina for static and dynamic analysis of offshore systems, including all types of marine risers (rigid and flexible), global analysis, moorings, installation and towed systems. It provides a graphical interface for modeling the different objects and provision to view the simulation. Software description is based on reference [19].

OrcaFlex provides fast and accurate analysis of catenary systems such as flexible risers, umbilical cables and rigid pipelines under wave and current loads and externally imposed motions. OrcaFlex is a fully 3D non-linear time domain finite element program capable of dealing with arbitrarily large deflections from the initial configuration.

Coordinate System

OrcaFlex uses one global coordinate system GXYZ, where G is the global origin and GX, GY and GZ are the global axes directions. In addition, there are a number of local coordinate systems, generally one for each object in the model. In general we use Lxyz to denote a local coordinate system.

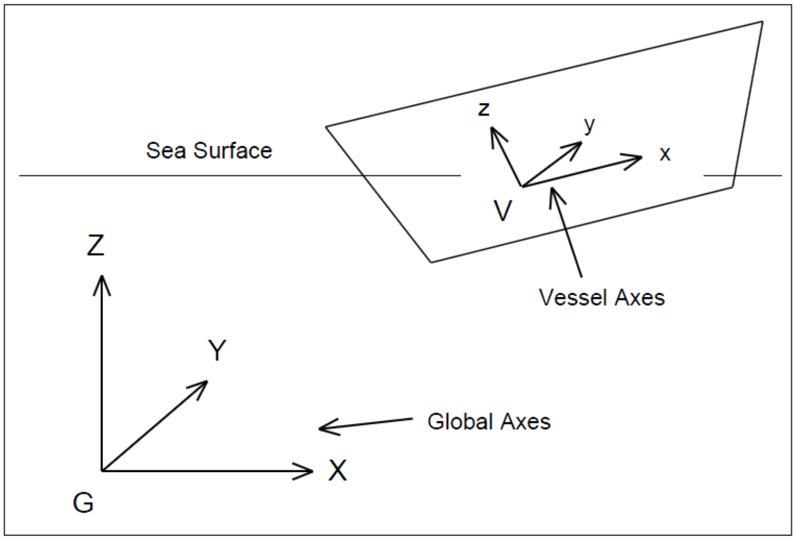


Figure A.1 Co-Ordinate system in Orcaflex

Directions and Headings

Directions and headings are specified in OrcaFlex by giving the azimuth angle of the direction, in degrees, measured positive from the x-axis towards the y-axis, as shown in the following figure.

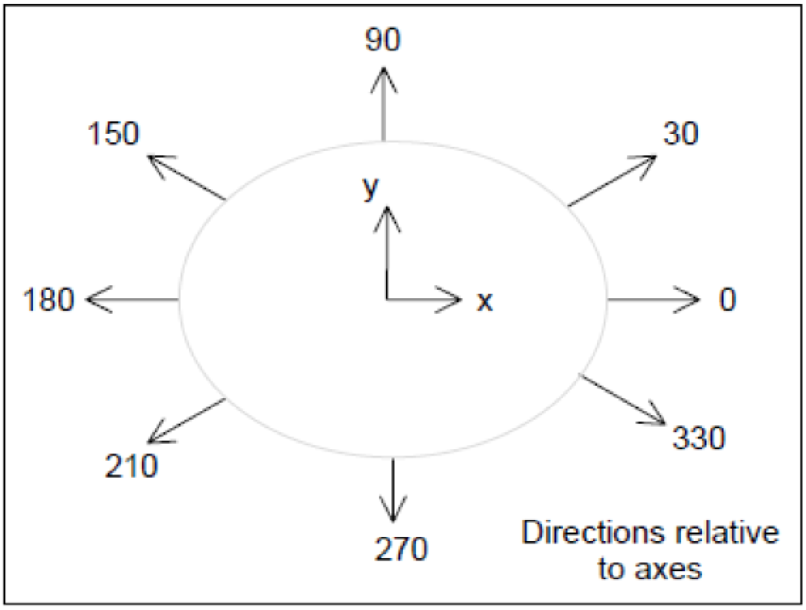


Figure A.2 Directions and Heading in Orcaflex

Directions for waves, current and wind are specified by giving the direction in which the wave (or current or wind) is progressing, relative to global axes. In other words for these directions the x and y-axes in the above figure are the global GX and GY axes. Vessel headings are specified as the direction in which the vessel Vx-axis is pointing, relative to global axes. So again, for vessel headings the x and y-axes in the figure A.2 are the global GX and GY axes.

Static Analysis

There are two objectives for a static analysis:

- To determine the equilibrium configuration of the system under weight, buoyancy, hydrodynamic drag, etc.
- To provide a starting configuration for dynamic simulation.

In most cases, the static equilibrium configuration is the best starting point for dynamic simulation and these two objectives become one.

Modeling

The J tube, sea bed and the vessel modeling reflect the project data. Figure A.3 shows the step 25 of the initiation process with dual buoyancy modules attached to the inline structure close to the sagbend.

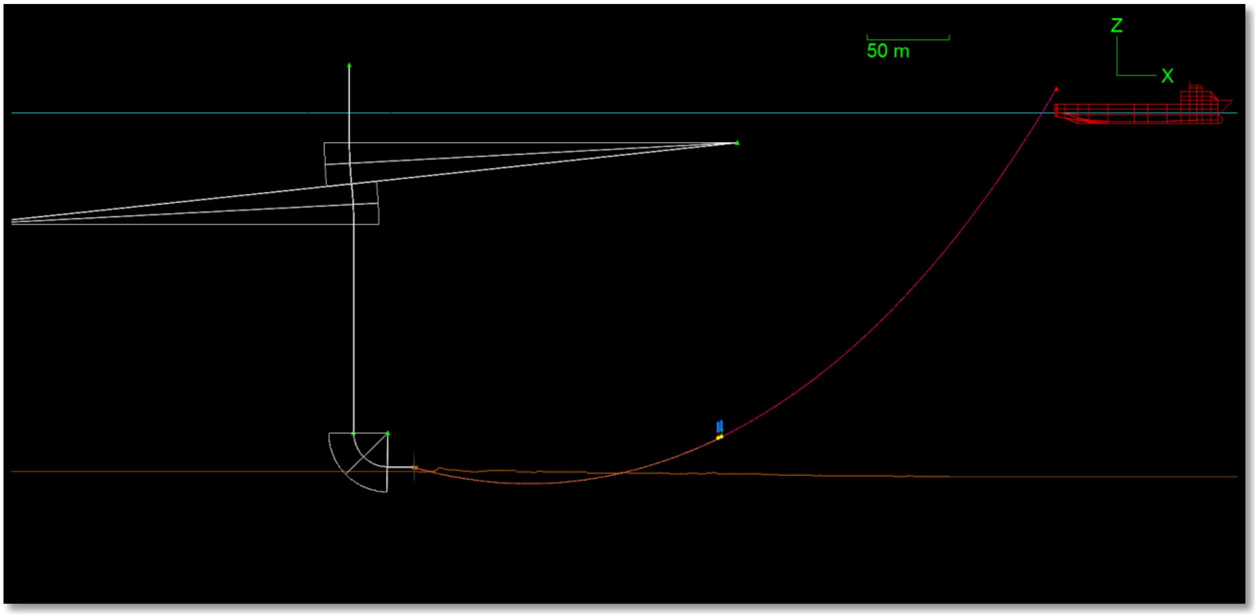


Figure A.3 Modeling in Orcaflex

Vessel: The reel vessel is modeled using the object 'Vessel' with wire frame drawing. Vessel motion is defined by a time history motion file.

Catenary: The pipeline and riser sections are modeled using 'Line' object with their corresponding geometry and material properties. The number of segments in the line is defined according to the accuracy of the result desired.

J Tube seal and clamp: J tube seal and clamp are defined by 'line' object as well.

Buoyancy unit: A 3-D buoy is used to represent buoyancy unit. 3-D buoys have only 3 degrees of freedom – movements in X,Y and Z directions. They do not rotate. While a buoyancy module might rotate in the sea, the rotation has very little impact and hence 3-D buoys are used. It saves computational time when compared to 6-D buoy.

Tether: Tether is modeled using 'Links' object of type 'Tether' with stiffness parameters defined.

Top end of the pipeline is fixed to the vessel and the bottom is anchored to the J tube extension at the seabed. The relative co-ordinates with respect to the vessel global co-ordinates are pre-determined based on the ramp angle for this vessel and is used as co-ordinates to clamp the pipe. The pipeline payout length for each step of the initiation phase is determined using 'line setup wizard'.

APPENDIX B: RIFLEX SOFTWARE AND MODELING

Description of Software

RIFLEX is a computer program developed for the analysis of flexible risers and other slender structures, such as mooring lines, umbilical, pipelines and conventional risers. RIFLEX is capable of performing static and dynamic analysis including time domain and frequency domain dynamic analysis. Software description is based on reference [20].

Figure B.1 shows the structure of the program and the different modules and file systems. A description of file systems used in the thesis is defined below:

INPMOD Module

The INPMOD module reads most input data and organizes a data base for use during subsequent analyses. Once the INPMOD module has been run, several analyses can be performed by the other modules without rerun of INPMOD.

STAMOD Module

The STAMOD module performs several types of static analyses. The results may be used directly in parameter studies etc., and are also used to define the initial configuration for a succeeding dynamic analysis. Element mesh, stress free configuration and key data for finite element analysis are also generated by STAMOD based on system data given as input to INPMOD.

DYNMOD Module

The DYNMOD module carries out time domain dynamic analyses based on the final static configuration, environment data and data to define motions applied as forced displacements in the analysis. It is possible to perform several dynamic analyses without rerun of INPMOD and STAMOD. Response time series are stored on file for further post processing by OUTMOD and PLOMOD. In addition to dynamic response, natural frequencies and mode shapes can be calculated.

FREMOD and OUTMOD are not used.

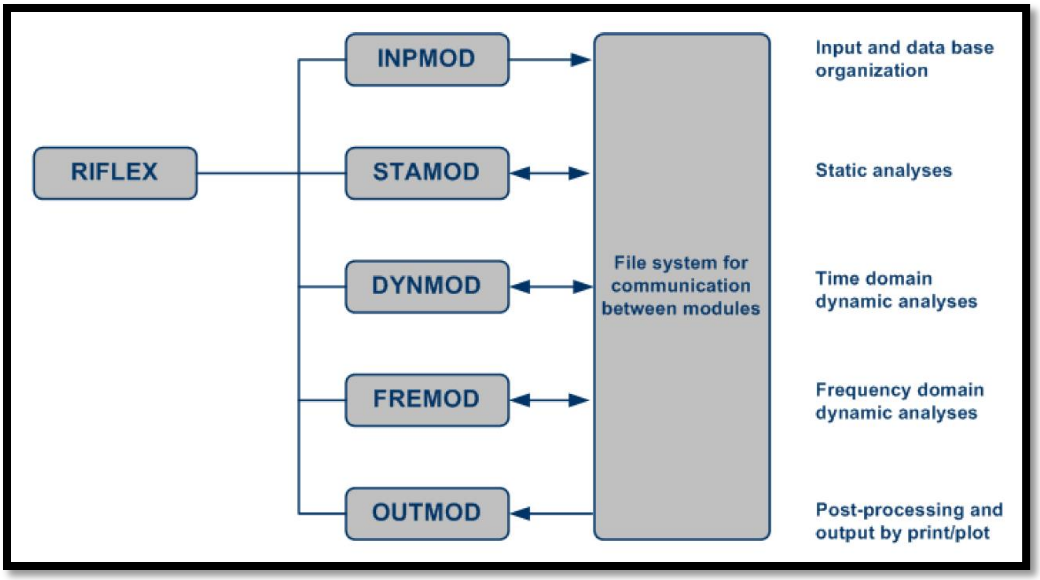


Figure B.1 Structure of RIFLEX program [20]

Static Analysis

The static configuration obtained from Orcaflex is used as the input in the stress free configuration to obtain the static configuration in Riflex. It serves as a good starting point and minimizes the iterations required to obtain static configuration in RIFLEX. The initial configuration of the catenary will be defined as a stress free configuration. This stress free configuration is transformed into the final static equilibrium configuration by application of various loads and boundary conditions in incremental steps. The results from the static analysis will determine the acceptable system layout for the catenary. This static configuration will be used as the input to the dynamic analysis.

Static Analysis comprises of:

- Equilibrium Configuration
- Parameter variation of tension or position parameters, current velocity and direction

Dynamic Analysis

After the static analysis, dynamic analysis will be carried out to analyze the global dynamic response of the catenary. This analysis will combine wave and current load with vessel dynamics to generate the bending moment and tension in the system. These values should be checked against the design limits in terms of pipe utilization.

Dynamic Analysis is carried out by using irregular wave theory defined by JONSWAP spectrum. Usually a 3 hour storm period analysis should be carried out. However it is very time consuming.

RIFLEX uses pseudo random numbers to generate the wave train. Prior sensitivity study has identified the random number that induces the most adverse response specific to the vessel. It has also identified the time step which induces the peak response from the vessel in a 3 hour wave train corresponding to this random number. The sensitivity study has also identified the wave period and heading that generates maximum response with respect to sagbend buckling utilization as shown in Table 6.8.

To reduce computation time, the simulation is run for only 100 seconds with this specific random number. The simulation start time is adjusted to coincide with the time step that induces the maximum response from the vessel and consequently generates the highest response in the catenary with respect to sagbend utilization.

Dynamic Analysis comprises of:

- Response to regular and irregular wave and motion excitation
- Response to harmonic motion
- Eigen value analysis, natural frequencies and mode shapes

Modeling

Catenary: Catenary is modeled using riser code type ‘AR’ which stands for ‘Arbitrary System’. This system defines the catenary configuration by defining its topology first and then defines its individual line and component details. The system topology is defined in terms of branching points and termination points by using ‘Super nodes’. Further these super nodes can be defined as free, fixed or prescribed based on the boundary conditions.

Without buoyancy unit, the entire catenary is defined as one single line with one super node fixed to the seabed and the other defined as prescribed by connecting it to the reel vessel. When a super node is defined as free, then all degrees of freedom are free. When the buoyancy unit is connected to the pipeline, additional lines are defined by introducing super nodes at the point of connection. The line connecting the buoyancy to the pipeline will be defined with super nodes that are free. More over the lines are divided into a number of elements defined by the user. When the number of elements is more, the results are more accurate.

Catenary Components:

The various components of the catenary such as the pipeline section, riser, J tube seal and clamp are defined using an individual component number with the component type ‘CRS1’ which is a Axi-Symmetrical Cross section component. Mass, diameter, thickness, stiffness parameters and hydro dynamic coefficients are defined for each of them.

Buoyancy Tether: It is defined by component type ‘CRS1’ as well.

Buoyancy Module: Buoyancy modules are defined by the component type ‘BODY’. Mass in air, displacement volume and hydrodynamic co-efficient values are the inputs. The calculation of hydrodynamic co-efficient is defined in Appendix: C.

Vessel: The vessel information is defined using a transfer function file which contains the RAO values for the vessel.

Current: A current profile with values from Table 6.6 pertaining to 1 Year extreme is used.

Wave Theory: Irregular wave theory with JONSWOP spectrum is used. The most sensitive wave heading and time period with respect to sagbend utilization as shown in Table 6.8 are used.

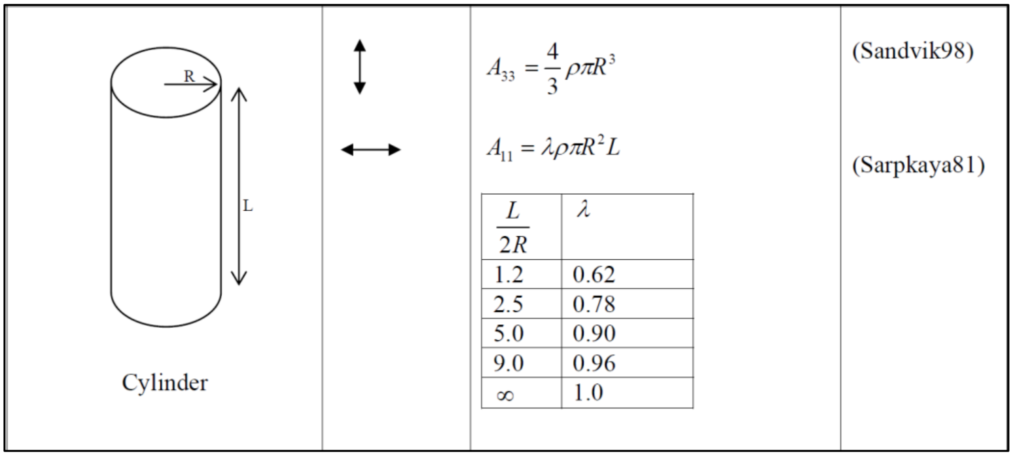
APPENDIX C: ADDED MASS AND DRAG COEFFICIENTS OF BUOYANCY

Description

This section contains MATHCAD calculations for determining added mass and drag force coefficients of the buoyancy module. It contains calculations for the general buoyancy unit with square cross section used throughout the thesis. It also contains the results for the buoyancy module with a cylindrical cross section and the module with a spherical geometry discussed in Section 7.5.1. The added mass and drag force coefficients are calculated from Subsea7 internal documents [33] and DNV-RP-H103 [34].

The formula to calculate the Drag force coefficient that is used as input in RIFLEX is from RIFLEX USER MANUAL. [20, C4.4, p. 89]

The Figures C.1 through C.5 shows the various added mass and drag force coefficients for the various geometries discussed.

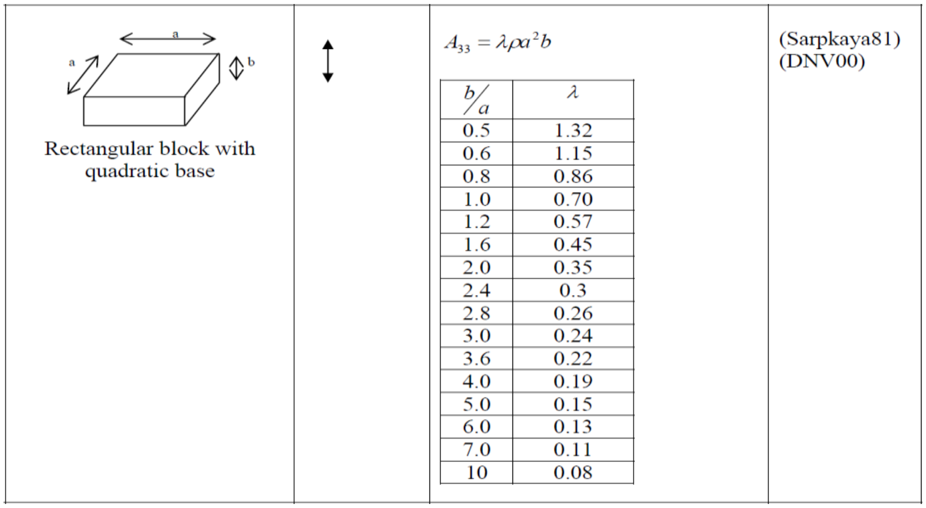


$$A_{33} = \frac{4}{3}\rho\pi R^3$$ (Sandvik98)

$$A_{11} = \lambda\rho\pi R^2 L$$ (Sarpkaya81)

$\frac{L}{2R}$	λ
1.2	0.62
2.5	0.78
5.0	0.90
9.0	0.96
∞	1.0

Figure C.1 Added Mass of a Cylinder [33]

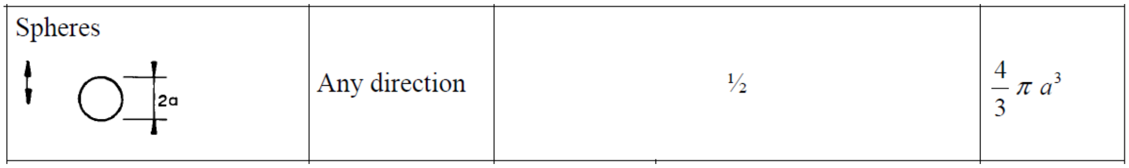


$$A_{33} = \lambda\rho a^2 b$$

(Sarpkaya81)
(DNV00)

b/a	λ
0.5	1.32
0.6	1.15
0.8	0.86
1.0	0.70
1.2	0.57
1.6	0.45
2.0	0.35
2.4	0.3
2.8	0.26
3.0	0.24
3.6	0.22
4.0	0.19
5.0	0.15
6.0	0.13
7.0	0.11
10	0.08

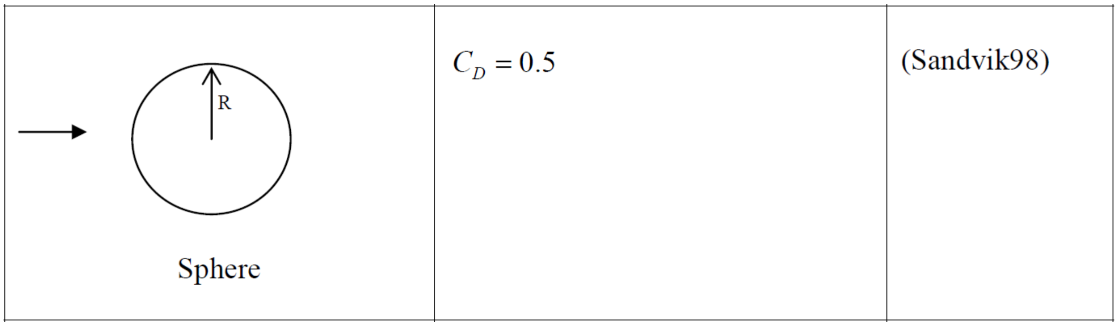
Figure C.2 Added Mass of a Rectangular Block [33]



Spheres	Any direction	½	$\frac{4}{3}\pi a^3$

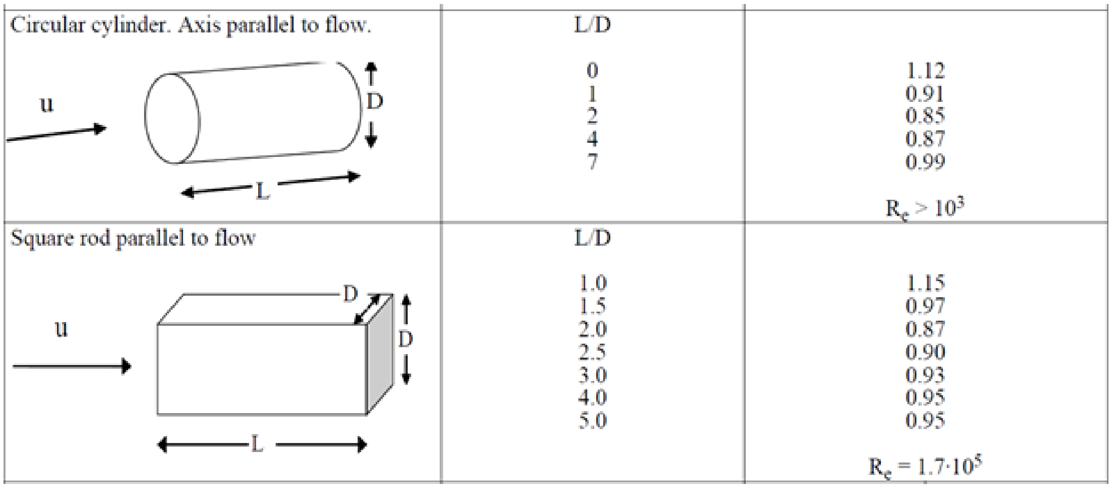
Figure C.3 Added Mass of a Sphere [34]

Drag Coefficient



Sphere	$C_D = 0.5$	(Sandvik98)

Figure C.4 Dimensionless Drag Coefficient for Sphere [33]



Circular cylinder. Axis parallel to flow.	L/D 0 1 2 4 7	1.12 0.91 0.85 0.87 0.99 $R_e > 10^3$
Square rod parallel to flow	L/D 1.0 1.5 2.0 2.5 3.0 4.0 5.0	1.15 0.97 0.87 0.90 0.93 0.95 0.95 $R_e = 1.7 \cdot 10^5$

Figure C.5 Dimensionless Drag Coefficients for Cylinder and Square Block [34]

Linear interpolation is used to arrive at the added mass and drag coefficient values from the ratio of height to side when the ratio is not available directly to calculate the added mass or drag coefficients. The calculation presented is performed for just one case of each type of geometry. Square cross section buoyancy calculations performed represents the buoyancy module used throughout the thesis and its properties are presented in Table 6.5. The results of cylindrical cross section (Diameter = 1 m) and spherical buoyancy are shown in Table 7.6. The calculations relating to other geometries analysed in Table 7.6 involving square cross section with side dimensions of 1 and 2 m and the cylindrical cross section buoyancy of diameter 2 m are not presented here.

Operational Parameters:

Density of Sea Water $\rho := 1025$ kg/m^3

General Buoyancy Data (Square Cross Section):

Net Buoyancy $NET\_B = 788$ kg

Mass of Buoyancy in Air $B\_MASS\_AIR = 1546$ kg

Buoyancy Base Dimensions $B\_DIM = 1.12$ m

Calculation of Added Mass and Drag Force Coefficient:

Buoyancy Volume $B\_VOL := \frac{(NET\_B + B\_MASS\_AIR)}{\rho} = 2.277\ m^3$

Buoyancy Height $B\_HT := \frac{B\_VOL}{B\_DIM^2} = 1.815\ m$

Ratio of Height to Side $RATIO\_H\_S := \frac{B\_HT}{B\_DIM} = 1.621$

Added Mass Coefficient in z Direction $\lambda = 0.45$

Added Mass $A\_MASS := \lambda \cdot \rho \cdot B\_DIM^2 \cdot B\_HT = 1.05 \times 10^3$ kg

Non Dimensional Drag Coefficient $D\_COF = 0.95$

Drag Force Coefficient $D\_F\_COF := 0.5 \rho \cdot B\_DIM^2 \cdot D\_COF = 610.736$ kg/m

Buoyancy Data (Cylindrical Cross Section):

Net Buoyancy $NET\_B = 788$ kg

Mass of Buoyancy in Air $B\_MASS\_AIR = 1546$ kg

Cylindrical Buoyancy Diameter $C\_DIA = 1$ m

Calculation of Added Mass and Drag Coefficient:

Buoyancy Volume $B\_VOL := \frac{(NET\_B + B\_MASS\_AIR)}{\rho} = 2.277\ m^3$

Cylindrical Buoyancy Height $C\_HT := \frac{B\_VOL}{\pi \cdot \left(\frac{C\_DIA}{2}\right)^2} = 2.899\ m$

Added Mass of Cylindrical Buoyancy $AM\_CYL := \frac{4 \cdot \pi \cdot \rho \cdot \left(\frac{C\_DIA}{2}\right)^3}{3} = 536.689\ kg$

Ratio of Height to Diameter $RATIO\_C := \frac{C\_HT}{C\_DIA} = 2.899$

Dimensionless Drag Coefficient $\lambda\_CYL = 0.86$

Drag Force Coefficient $D\_F\_COF\_CYL := 0.5\rho \cdot \pi \cdot \left(\frac{C\_DIA}{2}\right)^2 \cdot \lambda\_CYL = 346.164\ kg/m$

Buoyancy Data (Sphere):

Net Buoyancy $NET\_B = 788\ kg$

Mass of Buoyancy in Air $B\_MASS\_AIR = 1546\ kg$

Buoyancy Volume $B\_VOL := \frac{(NET\_B + B\_MASS\_AIR)}{\rho} = 2.277\ m^3$

Sphere Radius $S\_RAD := \left(\sqrt[3]{\frac{B\_VOL}{\frac{4 \cdot \pi}{3}}}\right) = 0.816\ m$

Added Mass of Sphere $AM\_SPHERE := \frac{4 \cdot \pi \cdot \rho (S\_RAD)^3 \cdot 0.5}{3} = 1.167 \times 10^3\ kg$

Dimensionless Drag Force Coefficient $S\_D\_COF = 0.5$

Drag Force Coefficient $S\_DF\_COF := \rho 0.5\pi \cdot S\_RAD^2 \cdot S\_D\_COF = 536.215\ kg/m$

APPENDIX D: CALCULATION OF UTILIZATION

DNV-OS- F101 provides the methodology to calculate buckling utilization for the pipeline. However it takes into account only the material properties of the backing steel of the pipe. Clad used in the pipeline has different material properties. A Joint Industry Project (JIP) between a number of oil companies, pipe manufacturers and offshore contractors including Subsea7 and Statoil has resulted in a methodology to calculate utilization taking into consideration the strength of the clad as well.

Figure D.1 and Figure D.2 show the parameters used by the subsea7 internal document that calculates the buckling utilization. Field parameters, pipeline design data, material properties (Backing steel and clad input separately) and Load factors are used as inputs as shown in Figure D.1. The rest of the parameters shown in Figure D.2 are calculated based on DNV-OS-F101 and JIP Report No.:2011-0467.

This section also presents a sample utilization calculation performed using MATHCAD. The utilization calculation is for Load case ‘b’ sagbend utilization for the step 26 base case presented in Table E.4 in Appendix E.

Utilization Calculation:

Material factors:

Material Resistance Factor, ULS	$\gamma_m = 1.15$
Safety Class Resistance Factor, Low	$\gamma_{sc} = 1.04$
Conditional Load Effect Factor	$\gamma_C = 1$
Fabrication Factor	$\alpha_{fab} = 0.85$
Material Strength Factor	$\alpha_u = 0.96$
Ovality	$f_o = 0.03$

Load Case ‘b’ Factors:

Functional Load Factor	$\gamma_F = 1.1$
Environmental Load Factor	$\gamma_E = 1.3$

Pipe Data:

Outer Diameter	$D_o = 270.9$ mm
Wall Thickness (Backing Steel)	$t_{bs} = 13.3$ mm

Wall Thickness (Clad) $t_{cl} = 3$ mm

Wall Thickness (Total) $t_{total} := t_{bs} + t_{cl} = 16.3$ mm

Material Data for Backing Steel:

Young's Modulus $E_{bs} = 207000$ MPa

Specified Minimum Yield Strength $SMYS_{bs} = 456.2$ MPa

Specified Minimum Tensile Strength $SMTS_{bs} = 554.7$ MPa

De-rating of Yield Stress at High temperature $f_{ytempbs} = 0$ MPa

De-rating of Tensile Stress at High Temperature $f_{utempbs} = 0$ MPa

Characteristic yield Strength $f_{ybs} := \left(SMYS_{bs} - f_{ytempbs}\right)\cdot\alpha_u = 437.952$ MPa

Characteristic tensile Strength $f_{ubs} := \left(SMTS_{bs} - f_{utempbs}\right)\cdot\alpha_u = 532.512$ MPa

Plastic Moment resistance $M_{pbs} := \dfrac{f_{ybs}\cdot\left(D_o - t_{bs}\right)^2\cdot t_{bs}}{1000000} = 386.518$ kNm

Plastic Axial Force resistance $S_{pbs} := \dfrac{f_{ybs}\cdot\left(D_o - t_{bs}\right)\cdot t_{bs}\cdot\pi}{1000} = 4.714\times 10^3$ kN

Material Data for Clad:

Young's Modulus $E_{cl} = 200000$ MPa

Specified Minimum Yield Strength $SMYS_{cl} = 170$ MPa

Specified Minimum Tensile Strength $SMTS_{cl} = 485$ MPa

De-rating of Yield Stress at High temperature $f_{ytempcl} = 0$ MPa

De-rating of Tensile Stress at High Temperature $f_{utempcl} =$ MPa

Characteristic Yield Strength $f_{ycl} := \left(SMYS_{cl} - f_{ytempcl}\right)\cdot\alpha_u = 163.2$ MPa

Characteristic tensile strength $f_{ucl} := \left(SMTS_{cl} - f_{utempcl}\right)\cdot\alpha_u = 465.6$ MPa

Plastic Moment resistance $M_{pcl} := \dfrac{f_{ycl}\cdot\left[\left[\left[D_o - \left(2\cdot t_{bs}\right)\right] - t_{cl}\right]^2\cdot t_{cl}\right]}{1000000} = 28.507$ kNm

Plastic Axial Force Resistance $S_{pcl} := \dfrac{f_{ycl}\cdot\left[\left[D_o - \left(2\cdot t_{bs}\right)\right] - t_{cl}\right]\cdot t_{cl}\cdot\pi}{1000} = 371.149$ kN

<u>Flow Stress parameters</u>

$$\beta_{bs} := \begin{cases} 0.5 \text{ if } \dfrac{D_o}{t_{bs}} < 15 \\ \left(\left(\dfrac{60 - \dfrac{D_o}{t_{bs}}}{90}\right)\right) \text{ if } 15 < \dfrac{D_o}{t_{bs}} < 60 \\ 0 \text{ if } \dfrac{D_o}{t_{bs}} > 60 \end{cases} = 0.44$$

$$\beta_{cl} := \begin{cases} 0.5 \text{ if } \dfrac{\left(D_o - 2\cdot t_{bs}\right)}{t_{cl}} < 15 \\ \left[\left[\dfrac{60 - \dfrac{\left(D_o - 2\cdot t_{bs}\right)}{t_{cl}}}{90}\right]\right] \text{ if } 15 < \dfrac{\left(D_o - 2\cdot t_{bs}\right)}{t_{cl}} < 60 \\ 0 \text{ if } \dfrac{\left(D_o - 2\cdot t_{bs}\right)}{t_{cl}} > 60 \end{cases} = 0$$

$$\beta_{total} := \left| \begin{array}{l} 0.5 \text{ if } \frac{D_o}{t_{total}} < 15 \\ \left(\left(\frac{60 - \frac{D_o}{t_{total}}}{90}\right)\right) \text{ if } 15 < \frac{D_o}{t_{total}} < 60 \\ 0 \text{ if } \frac{D_o}{t_{total}} > 60 \end{array} \right. = 0.482$$

Flow Stress Parameter, backing Steel $\alpha_{cbs} := \left(1 - \beta_{bs}\right) + \beta_{bs} \cdot \left(\frac{f_{ubs}}{f_{ybs}}\right) = 1.095$

Flow Stress parameter, clad $\alpha_{ccl} := \left(1 - \beta_{cl}\right) + \left[\beta_{cl} \cdot \left(\frac{f_{ucl}}{f_{ycl}}\right)\right] + 1.1 = 2.1$

Material Properties (Backing Steel + Clad)

Plastic moment Resistance $M_{ptotal} := M_{pbs} \cdot \alpha_{cbs} + M_{pcl} \cdot \alpha_{ccl} = 483.133$ kNm

Plastic Axial Force resistance $S_{ptotal} := S_{pbs} \cdot \alpha_{cbs} + S_{pcl} \cdot \alpha_{ccl} = 5.941 \times 10^3$ kN

Pressure Data:

Minimum Internal Pressure sustainable $P_i = 0$ MPa

Density of Sea Water $\rho_{sea} = 1026\ kg/m^3$

Water Depth $W_d = -228$ m

External Pressure at Sagbend $P_e := \frac{-W_d \cdot 9.81 \cdot \rho_{sea}}{1000000} = 2.295$ MPa

Collapse Pressure:

Elastic Collapse Pressure $P_{el} := \left(\frac{2}{1 - \upsilon^2}\right) \cdot E_{bs} \cdot \left(\frac{t_{total}}{D_o}\right)^3 = 99.105$ MPa

Plastic Collapse Pressure $P_p := 2 \cdot f_{ybs} \cdot \alpha_{fab} \cdot \left(\frac{t_{total}}{D_o} \right) = 44.798\,\text{MPa}$

The characteristic collapse pressure, P_c is calculated from the equation Eq.(D.1) below according to Eq (5.11) in DNV-OS-F101 [3].

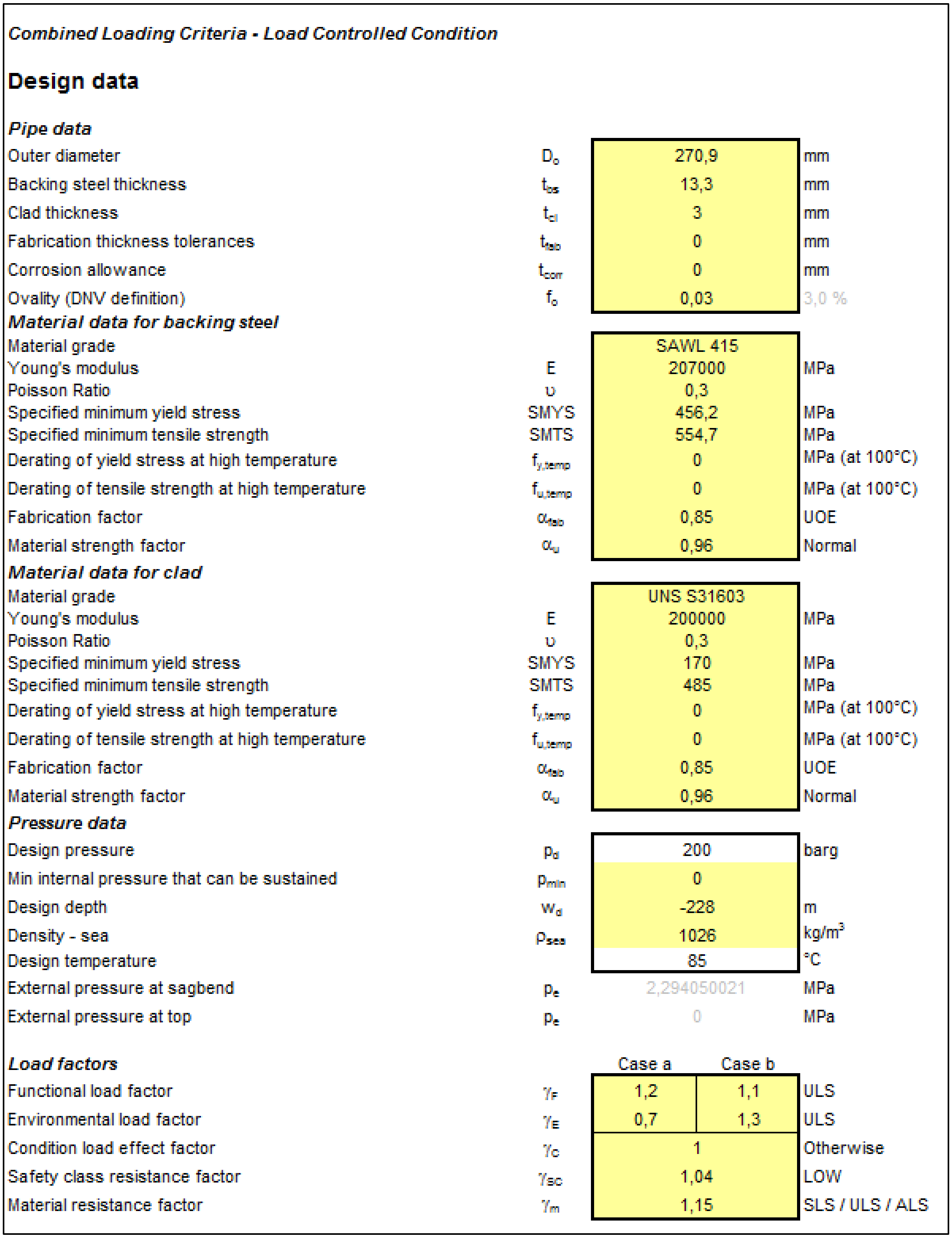
$$(P_c - P_{el})(P_c{}^2 - P_p{}^2) = P_c \cdot P_{el} \cdot P_p \cdot f_o \cdot \left(\frac{D_o}{t_{total}} \right) \qquad \text{Eq.(D.1)}$$

$P_c = 31.348$ MPa

Utilization (sagbend utilization for Load case ‘b’):

Utilization calculated based on Eq (5.28) of DNV-OS-F101 [3] and the methodology described in section 4.2.2.3 of thesis.

$$\text{Utilization} = \left[\gamma_m \cdot \gamma_{sc} \cdot \frac{M_{sd}}{M_{ptotal}} + \left(\gamma_m \cdot \gamma_{sc} \cdot \frac{S_{sd}}{S_{ptotal}} \right)^2 \right]^2 + \left[\gamma_m \cdot \gamma_{sc} \cdot \frac{(P_e - P_i)}{P_c} \right]^2 = 1$$



Combined Loading Criteria - Load Controlled Condition

Design data

Pipe data

Outer diameter	D_o	270,9	mm
Backing steel thickness	t_{bs}	13,3	mm
Clad thickness	t_{cl}	3	mm
Fabrication thickness tolerances	t_{fab}	0	mm
Corrosion allowance	t_{corr}	0	mm
Ovality (DNV definition)	f_o	0,03	3,0 %

Material data for backing steel

Material grade		SAWL 415	
Young's modulus	E	207000	MPa
Poisson Ratio	υ	0,3	
Specified minimum yield stress	SMYS	456,2	MPa
Specified minimum tensile strength	SMTS	554,7	MPa
Derating of yield stress at high temperature	$f_{y,temp}$	0	MPa (at 100°C)
Derating of tensile strength at high temperature	$f_{u,temp}$	0	MPa (at 100°C)
Fabrication factor	α_{fab}	0,85	UOE
Material strength factor	α_u	0,96	Normal

Material data for clad

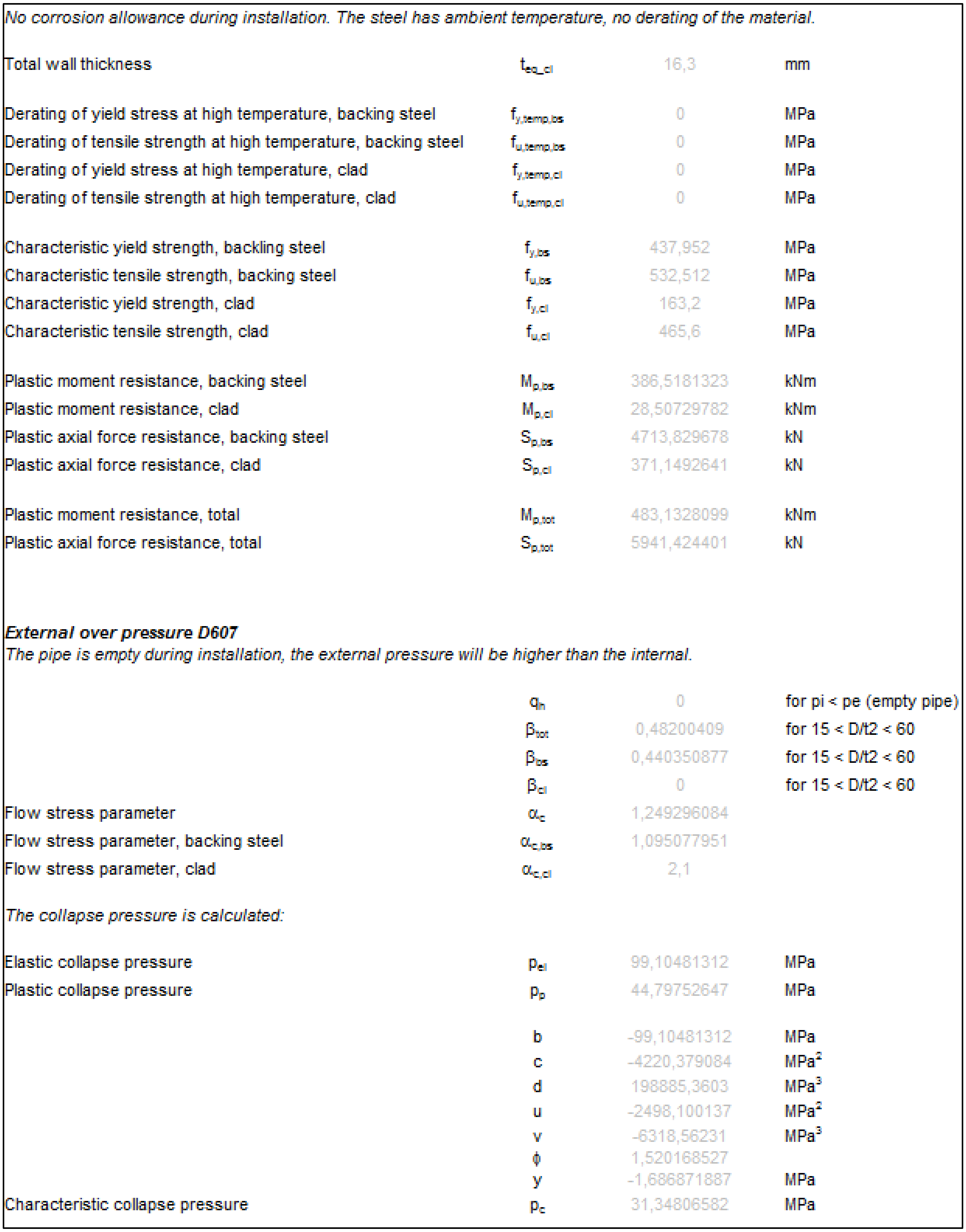
Material grade		UNS S31603	
Young's modulus	E	200000	MPa
Poisson Ratio	υ	0,3	
Specified minimum yield stress	SMYS	170	MPa
Specified minimum tensile strength	SMTS	485	MPa
Derating of yield stress at high temperature	$f_{y,temp}$	0	MPa (at 100°C)
Derating of tensile strength at high temperature	$f_{u,temp}$	0	MPa (at 100°C)
Fabrication factor	α_{fab}	0,85	UOE
Material strength factor	α_u	0,96	Normal

Pressure data

Design pressure	p_d	200	barg
Min internal pressure that can be sustained	p_{min}	0	
Design depth	w_d	-228	m
Density - sea	ρ_{sea}	1026	kg/m^3
Design temperature		85	°C
External pressure at sagbend	p_e	2,294050021	MPa
External pressure at top	p_e	0	MPa

Load factors		Case a	Case b	
Functional load factor	γ_F	1,2	1,1	ULS
Environmental load factor	γ_E	0,7	1,3	ULS
Condition load effect factor	γ_C	1		Otherwise
Safety class resistance factor	γ_{SC}	1,04		LOW
Material resistance factor	γ_m	1,15		SLS / ULS / ALS

Figure D.1 Buckling Utilization Document with Additional Analysis for Clad



No corrosion allowance during installation. The steel has ambient temperature, no derating of the material.

Total wall thickness	t_{eq_cl}	16,3	mm
Derating of yield stress at high temperature, backing steel	$f_{y,temp,bs}$	0	MPa
Derating of tensile strength at high temperature, backing steel	$f_{u,temp,bs}$	0	MPa
Derating of yield stress at high temperature, clad	$f_{y,temp,cl}$	0	MPa
Derating of tensile strength at high temperature, clad	$f_{u,temp,cl}$	0	MPa
Characteristic yield strength, backling steel	$f_{y,bs}$	437,952	MPa
Characteristic tensile strength, backing steel	$f_{u,bs}$	532,512	MPa
Characteristic yield strength, clad	$f_{y,cl}$	163,2	MPa
Characteristic tensile strength, clad	$f_{u,cl}$	465,6	MPa
Plastic moment resistance, backing steel	$M_{p,bs}$	386,5181323	kNm
Plastic moment resistance, clad	$M_{p,cl}$	28,50729782	kNm
Plastic axial force resistance, backing steel	$S_{p,bs}$	4713,829678	kN
Plastic axial force resistance, clad	$S_{p,cl}$	371,1492641	kN
Plastic moment resistance, total	$M_{p,tot}$	483,1328099	kNm
Plastic axial force resistance, total	$S_{p,tot}$	5941,424401	kN

External over pressure D607

The pipe is empty during installation, the external pressure will be higher than the internal.

	q_h	0	for pi < pe (empty pipe)
	β_{tot}	0,48200409	for 15 < D/t2 < 60
	β_{bs}	0,440350877	for 15 < D/t2 < 60
	β_{cl}	0	for 15 < D/t2 < 60
Flow stress parameter	α_c	1,249296084	
Flow stress parameter, backing steel	$\alpha_{c,bs}$	1,095077951	
Flow stress parameter, clad	$\alpha_{c,cl}$	2,1	

The collapse pressure is calculated:

Elastic collapse pressure	p_{el}	99,10481312	MPa
Plastic collapse pressure	p_p	44,79752647	MPa
	b	-99,10481312	MPa
	c	-4220,379084	MPa^2
	d	198885,3603	MPa^3
	u	-2498,100137	MPa^2
	v	-6318,56231	MPa^3
	ϕ	1,520168527	
	y	-1,686871887	MPa
Characteristic collapse pressure	p_c	31,34806582	MPa

Figure D.2 Buckling Utilization Document with Additional Analysis for Clad

APPENDIX E: LIST OF TABLES WITH UTILIZATION RESULTS

Table E.1 Initiation Pay Out Steps

	Pipe		Platform Wire		Vessel		
Step No	Pay Out	Total Paid Out	Wire Pull in	Total Wire Pay Out	Move	Position	Ramp Angle
	[m]	[m]	[m]	[m]	[m]	[m]	[Deg]
1	0	4	0	730	0	369	60.55
2	7	11	8	722	0	369	60.55
3	10	21	10	712	0	369	60.55
4	21	42	20	692	0	369	60.55
5	38	80	40	652	0	369	60.55
6	39	119	40	612	0	369	60.55
7	40	159	40	572	0	369	60.55
8	51	210	50	522	0	369	60.55
9	41	251	40	482	0	369	60.55
10	21	272	20	462	0	369	60.55
11	8	280	8	454	0	369	60.55
12	2	282	2	452	0	369	60.55
13	18	300	20	432	0	369	60.55
14	36	336	30	402	0	369	60.55
15	30	366	30	372	0	369	60.55
16	14	380	14	358	0	369	60.55
17	20	400	0	358	20	389	60.55
18	20	420	20	338	0	389	60.55
19	29	449	30	308	0	389	60.55
20	15	464	15	293	0	389	60.55
21	10	474	10	283	0	389	60.55
22	10	484	10	273	0	389	60.55
23	22	506	22	251	0	389	60.55
24	39	545	39	212	0	389	60.55
25	29	574	29	183	0	389	60.55
26	24	598	24	159	0	389	60.55
27	45	643	45	114	0	389	60.55
28	0	643	30	84	-30	359	60.55
29	0	643	20	64	-20	339	60.55
30	19	662	19	45	0	339	60.55
31	30	692	30	14	0	339	60.55
32	19	711	19	0	0	339	60.55

Table E.2 Analysis of Initiation Steps without Buoyancy Module

Description: Comparison of Various Initiation Step Without Buoyancy Module
Wave Heading: 60
Wave Period: 9 s
Ramp Angle: 60.55^{o}

Description				Result Parameters						Buckling Interaction Check					
				Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Wave Height	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	m	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Step 24	2	0,73	Top	0	162	163	69	163	231	114,1	242,7	0,08	211,9	267,9	0,27
			Sag bend	140	62	145	53	285	115	269,5	111,5	0,45	342,5	137,1	0,72
Step 25	2	1,28	Top	0	157	153	74	153	231	107,1	240,2	0,071	198,9	268,9	0,24
			Sag bend	152	61	222	59	374	120	337,8	114,5	0,70	455,8	143,8	1,28
Step 26	2	1,60	Top	0	154	146	84	146	238	102,2	243,6	0,065	189,8	278,6	0,22
			Sag bend	198	61	224	60	422	121	394,4	115,2	0,961	509	145,1	1,59
Step 26	1,4	0,93	Top	0	154	107	52	107	206	74,9	221,2	0,035	139,1	237	0,12
			Sag bend	198	60	131	34	329	94	329,3	95,8	0,67	388,1	110,2	0,93
Step 27	2	0,93	Top	0	150	150	91	150	241	105	243,7	0,069	195	283,3	0,24
			Sagbend	125	58	193	65	318	123	285,1	115,1	0,507	388,4	148,3	0,93

Table E.3 Analysis of Various Catenary Component Configurations

Description: Analysis of various Catenary component configuration
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55°
Net Buoyancy: 788 Kg
Volume: 2.277 m3
Step : 26 (Structure at sagbend)

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
deg	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Pipe + Riser + Structure	1,60	Top	0	154	146	84	146	238	102,20	243,60	0,065	189,80	278,60	0,22
		Sag bend	198	61	224	60	422	121	394,40	115,20	0,962	509,00	145,10	1,60
Riser + Structure	0,88	Top	0	198	134	66	134	264	93,80	283,80	0,055	174,20	303,60	0,19
		Sag bend	167	88	149	50	316	138	304,70	140,60	0,578	377,40	161,80	0,88
Pipe + Structure	1,29	Top	0	153	150	84	150	237	105,00	242,40	0,069	195,00	277,50	0,24
		Sag bend	187	60	193	61	380	121	359,50	114,70	0,801	456,60	145,30	1,29
Only Pipe	0,74	Top	0	150	155	90	155	240	108,50	243,00	0,073	201,50	282,00	0,25
		Sag bend	118	58	165	62	283	120	257,10	113,00	0,413	344,30	144,40	0,74
Only Riser	0,56	Top	0	195	132	68	132	263	92,40	281,60	0,054	171,60	302,90	0,18
		Sag bend	110	86	138	50	248	136	228,60	138,20	0,329	300,40	159,60	0,56

Table E.4 Influence of Buoyancy Module attached to the Structure

Description: Comparison of Various Initiation Step With Buoyancy Module Attached on the Inline Structure
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^o
Net Buoyancy: 788 Kg
Volume: 2.277 m3

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Step 24	1,06	Top	0	156	151	87	151	243	105,70	248,10	0,070	196,30	284,70	0,24
		Sag bend	140	60	200	63	340	123	308,00	116,10	0,590	414,00	147,90	1,06
Step 25	1,50	Top	0	153	142	94	142	247	99,40	249,40	0,062	184,60	290,50	0,21
		Sag bend	145	62	257	59	402	121	353,90	115,70	0,776	493,60	144,90	1,50
Step 26	1,00	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	143	58	189	62	332	120	303,90	113,00	0,574	403,00	144,40	1,00

Table E.5 Influence of Net Buoyancy to Structure Weight Ratio

Description: Influence of Net Buoyancy to Structure Weight Ratio
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^{o}

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Ramp Angle	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
deg	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Ratio 1.18	1,18	Top	0	152	141	86	141	238	98,70	242,60	0,061	183,30	279,00	0,21
		Sag bend 302	164	58	198	62	362	120	335,40	113,00	0,698	437,80	144,40	1,18
Ratio 1	1,00	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend 302	143	58	189	62	332	120	303,90	113,00	0,574	403,00	144,40	1,00
Ratio 1.1	1,10	Top	0	150	152	90	152	240	106,40	243,00	0,071	197,60	282,00	0,24
		Sag bend 302	121	58	222	62	343	120	300,60	113,00	0,562	421,70	144,40	1,10
Ratio 1.44	1,44	Top	0	148	145	107	145	255	101,50	252,50	0,064	188,50	301,90	0,22
		Sag bend 302	100	58	287	66	387	124	320,90	115,80	0,640	483,10	149,60	1,44

Table E.6 Influence of Buoyancy Module Attachment position (Step 26)

Description: Influence of Buoyancy Module Attachment position for step 26
Wave Heading: 60 Wave Period: 9 s
Ramp Angle: 60.55 Wave Height: 2 m

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Position	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
m	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
20	1,16	Top	0	153	154	83	154	236	107,80	241,70	0,072	200,20	276,20	0,25
		Sag bend	184	59	177	60	361	119	344,70	112,80	0,737	432,50	142,90	1,16
10	1,00	Top	0	152	156	86	156	238	109,20	242,60	0,074	202,80	279,00	0,26
		Sag bend	168	58	167	61	335	119	318,50	112,30	0,630	401,90	143,10	1,00
5	0,94	Top	0	152	155	85	155	237	108,50	241,90	0,073	201,50	277,70	0,25
		Sag bend	158	58	166	61	324	119	305,80	112,30	0,581	389,60	143,10	0,94
2	0,93	Top	0	151	156	87	156	238	109,20	242,10	0,074	202,80	279,20	0,26
		Sag bend	149	58	172	61	321	119	299,20	112,30	0,557	387,50	143,10	0,93
1	0,94	Top	0	151	157	88	157	239	109,90	242,80	0,075	204,10	280,50	0,26
		Sag bend	146	58	176	62	322	120	298,40	113,00	0,554	389,40	144,40	0,94
0	1,00	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	143	58	189	62	332	120	303,90	113,00	0,574	403,00	144,40	1,00
-0.5	1,04	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	142	59	196	61	338	120	307,60	113,50	0,588	411,00	144,20	1,04
-1	1,08	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	143	59	200	62	343	121	311,60	114,20	0,603	417,30	145,50	1,08
-2	1,14	Top	0	151	155	89	155	240	108,50	243,50	0,073	201,50	281,80	0,25
		Sag bend	146	60	207	62	353	122	320,10	115,40	0,636	429,70	146,60	1,14
-3	1,22	Top	0	151	154	89	154	240	107,80	243,50	0,073	200,20	281,80	0,25
		Sag bend	148	61	216	61	364	122	328,80	115,90	0,671	443,60	146,40	1,22
-4	1,29	Top	0	151	153	90	153	241	107,10	244,20	0,072	198,90	283,10	0,25
		Sag bend	151	61	224	61	375	122	338,00	115,90	0,709	457,30	146,40	1,29

Table E.7 Influence of Buoyancy Module Attachment Position (Step 25)

Description: Influence of Buoyancy Module Attachment position for step 25
Wave Heading: 60 Wave Period: 9 s
Ramp Angle: 60.55^{o} Wave Height: 2 m

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Connection Point	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
m	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
0	1,50	Top	0	153	142	94	142	247	99,40	249,40	0,062	184,60	290,50	0,21
		Sag bend	145	62	257	59	402	121	353,90	115,70	0,776	493,60	144,90	1,50
1	1,47	Top	0	153	143	94	143	247	100,10	249,40	0,063	185,90	290,50	0,21
		Sag bend	144	59	254	61	398	120	350,60	113,50	0,762	488,60	144,20	1,47
2	1,45	Top	0	153	145	93	145	246	101,50	248,70	0,064	188,50	289,20	0,22
		Sag bend	143	59	252	61	395	120	348,00	113,50	0,751	484,90	144,20	1,45
5	1,35	Top	0	153	150	91	150	244	105,00	247,30	0,069	195,00	286,60	0,24
		Sag bend	140	60	241	60	381	120	336,70	114,00	0,703	467,30	144,00	1,35
10	1,14	Top	0	154	158	86	158	240	110,60	245,00	0,076	205,40	281,20	0,26
		Sag bend	135	60	216	58	351	118	313,20	112,60	0,610	429,30	141,40	1,14

Table E.8 Sensitivity Study on Added Mass of Buoyancy Module

Description: Sensitivity Study of Variation in Added Mass of Buoyancy Module
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^o

Description				**Result Parameters**						**Buckling Interaction Check**					
				Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Added Mass (Z Direction)	Utilization	Location	M_F	S_F	M_E	S_E	M_F + M_E	S_F + S_E	M_d	S_d	Utilization	M_d	S_d	Utilization
	[kg]	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
1	0	1,10	Top	0	151	152	88	152	239	106,40	242,80	0,071	197,60	280,50	0,24
			Sag bend	143	59	203	60	346	119	313,70	112,80	0,612	421,20	142,90	1,10
2	1000	1,07	Top	0	151	154	87	154	238	107,80	242,10	0,072	200,20	279,20	0,25
			Sag bend	143	59	199	60	342	119	310,90	112,80	0,601	416,00	142,90	1,07
3	2000	1,02	Top	0	151	155	91	155	242	108,50	244,90	0,073	201,50	284,40	0,25
			Sag bend	143	59	192	58	335	117	306,00	111,40	0,582	406,90	140,30	1,02
4	3000	0,95	Top	0	151	156	90	156	241	109,20	244,20	0,074	202,80	283,10	0,26
			Sag bend	143	59	181	63	324	122	298,30	114,90	0,554	392,60	146,80	0,95
5	4000	0,92	Top	0	151	157	91	157	242	109,90	244,90	0,075	204,10	284,40	0,26
			Sag bend	143	59	175	62	318	121	294,10	114,20	0,538	384,80	145,50	0,92
6	5000	0,90	Top	0	151	156	91	156	242	109,20	244,90	0,074	202,80	284,40	0,26
			Sag bend	143	59	173	62	316	121	292,70	114,20	0,533	382,20	145,50	0,90

Table E.9 Sensitivity Study on Drag Coefficient of Buoyancy Module

Description: Sensitivity Study of Variation in Drag Coefficient of Buoyancy Module
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^o

Description				Result Parameters						Buckling Interaction Check					
				Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Drag Coefficient	Utilization	Location	M_F	S_F	M_E	S_E	M_F + M_E	S_F + S_E	M_d	S_d	Utilization	M_d	S_d	Utilization
	[kg/m]	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
1	0	1,10	Top	0	151	152	88	152	239	106,40	242,80	0,071	197,60	280,50	0,24
			Sag bend	143	59	203	60	346	119	313,70	112,80	0,612	421,20	142,90	1,10
2	1000	1,03	Top	0	151	155	89	155	240	108,50	243,50	0,073	201,50	281,80	0,25
			Sag bend	143	59	193	61	336	120	306,70	113,50	0,585	408,20	144,20	1,03
3	2000	1,04	Top	0	151	158	89	158	240	110,60	243,50	0,076	205,40	281,80	0,26
			Sag bend	143	59	195	63	338	122	308,10	114,90	0,590	410,80	146,80	1,04
4	3000	1,07	Top	0	151	161	90	161	241	112,70	244,20	0,079	209,30	283,10	0,27
			Sag bend	143	59	199	63	342	122	310,90	114,90	0,601	416,00	146,80	1,07

Table E.10 Comparison of Buoyancy Module Geometry

Description: Comparison of Buoyancy Module Geometry
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55

Description									Result Parameters						Buckling Interaction Check					
									Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Shape	Diameter	Height	C_{DZ}	CD_Z	C_{AZ}	AM_Z	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	[m]	[m]	-	[kg/m]	-	[kg]	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Cylinder	1	2.899	0.86	346	0	536	1,02	Top	0	151	154	88	154	239	107,80	242,80	0,072	200,20	280,50	0,25
								Sag bend	143	59	192	60	335	119	306,00	112,80	0,582	406,90	142,90	1,02
Cylinder	2	0.724	1	1610	0	4293	0,98	Top	0	151	162	89	162	240	113,40	243,50	0,080	210,60	281,80	0,28
								Sag bend	143	59	185	61	328	120	301,10	113,50	0,564	397,80	144,20	0,98
Square	1	2.277	0.885	453	0.325	758	1,01	Top	0	151	155	88	155	239	108,50	242,80	0,073	201,50	280,50	0,25
								Sag bend	143	59	190	61	333	120	304,60	113,50	0,577	404,30	144,20	1,01
Square	2	0.569	1.161	2378	1.321	3079	1,02	Top	0	151	164	89	164	240	114,80	243,50	0,082	213,20	281,80	0,28
								Sag bend	143	59	191	63	334	122	305,30	114,90	0,580	405,60	146,80	1,02
Sphere	0.816	0	2	2,0	12	180	0,99	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
								Sag bend	143	59	187	59	330	118	302,50	112,10	0,569	400,40	141,60	0,99

Table E.11 Influence of 10 m Offset of Single buoyancy Module

Description: Influence of 10 m Offset of Single buoyancy Module
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^{o}

Description				Result Parameters						Buckling Interaction Check					
				Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Step No:	Wave Height	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	m	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Step 24	2	1,15	Top	0	156	148	91	148	247	103,6	250,9	0,067	192,4	289,9	0,23
			Sag bend	135	67	218	55	353	122	314,6	118,9	0,615	431,9	145,2	1,15
Step 25	2	1,14	Top	0	154	158	86	158	240	110,6	245,0	0,076	205,4	281,2	0,26
			Sag bend	135	60	216	58	351	118	313,2	112,6	0,610	429,3	141,4	1,14
Step 26	2	1,00	Top	0	152	156	86	156	238	109,2	242,6	0,074	202,8	279,0	0,26
			Sag bend	168	58	167	61	335	119	318,5	112,3	0,630	401,9	143,1	1,00
Step 24	1,8	0,88	Top	0	154	132	75	132	229	92,40	237,3	0,053	171,6	266,9	0,18
			Sag bend	135	60	176	48	311	108	285,2	105,6	0,507	377,3	128,4	0,88
Step 25	1,8	0,94	Top		156	127	79	127	235	88,90	242,5	0,049	165,1	274,3	0,17
			Sag bend	142	60	179	52	321	112	295	108,4	0,544	388,9	133,6	0,94

Table E.12 Influence of 20 m Offset of Single buoyancy Module

Description: Influence of 20 m Offset of Single buoyancy Module
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55^o

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
Step 24	1,16	Top	0	160	150	85	150	245	105,00	251,50	0,069	195,00	286,50	0,24
		Sag bend	137	60	217	61	354	121	316,30	114,70	0,622	432,80	145,30	1,16
Step 25	0,66	Top	0	154	161	81	161	235	112,70	241,50	0,079	209,30	274,70	0,27
		Sag bend	125	58	145	59	270	117	251,50	110,90	0,396	326,00	140,50	0,66
Step 26	1,16	Top	0	153	154	83	154	236	107,80	241,70	0,072	200,20	276,20	0,25
		Sag bend	184	59	177	60	361	119	344,70	112,80	0,737	432,50	142,90	1,16

Table E.13 Influence of 10 m Offset of Two buoyancy Module System

Description: Influence of two buoyancy units at 10 m Offset Wave Heading: 60 Wave Height: 2 m Wave Period: 9 s Ramp Angle: 60.55^{o}														
Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
STEP 24	1,42	Top	0	146	138	116	138	262	96,60	256,40	0,058	179,40	311,40	0,20
		Sag bend	153	52	239	93	392	145	350,90	127,50	0,763	479,00	178,10	1,42
STEP 25	1,79	Top	0	149	125	137	125	286	87,50	274,70	0,048	162,50	342,00	0,17
		Sag bend	137	56	299	99	436	155	373,70	136,50	0,865	539,40	190,30	1,79
STEP 26	0,95	Top	0	149	163	100	163	249	114,10	248,80	0,081	211,90	293,90	0,28
		Sag bend	118	55	201	66	319	121	282,30	112,20	0,497	391,10	146,30	0,95

Table E.14 Influence of 20 m Offset of Two buoyancy Module System

Description: Influence of two buoyancy units at 20 m Offset Wave Heading: 60 Wave Height: 2 m Wave Period: 9 s Ramp Angle: 60.55														
Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Scenario	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
STEP 24	1,51	Top	0	150	133	117	133	267	93,10	261,90	0,054	172,90	317,10	0,19
		Sag bend	143	53	259	93	402	146	352,90	128,70	0,772	494,00	179,20	1,51
STEP 25	1,42	Top	0	150	141	120	141	270	98,70	264,00	0,061	183,30	321,00	0,21
		Sag bend	130	53	259	81	389	134	337,30	120,30	0,706	479,70	163,60	1,42
STEP 26	0,51	Top	0	150	164	92	164	242	114,80	244,40	0,082	213,20	284,60	0,28
		Sag bend	168	58	77	62	245	120	255,50	113,00	0,408	284,90	144,40	0,51

Table E.15 Influence of Tether length

Description: Influence of Tether length
Wave Heading: 60
Wave Height: 2 m
Wave Period: 9 s
Ramp Angle: 60.55
Net Buoyancy 788 kg
Step 26 (structure at sagbend)

Description			Result Parameters						Buckling Interaction Check					
			Functional (Static)		Environmental		Total (Dynamic)		Load Combination a			Load Combination b		
Tether length	Utilization	Location	M_F	S_F	M_E	S_E	$M_F + M_E$	$S_F + S_E$	M_d	S_d	Utilization	M_d	S_d	Utilization
m	Max	-	kN.m	kN	kN.m	kN	kN.m	kN	kN.m	kN	-	kN.m	kN	-
40	0,99	Top	1	151	154	87	155	238	109,00	242,10	0,074	201,30	279,20	0,25
		Sag bend	147	58	183	61	330	119	304,50	112,30	0,577	399,60	143,10	0,99
30	0,99	Top	0	151	155	88	155	239	108,50	242,80	0,073	201,50	280,50	0,25
		Sag bend	144	58	186	62	330	120	303,00	113,00	0,571	400,20	144,40	0,99
25	0,99	Top	1	151	154	88	155	239	109,00	242,80	0,074	201,30	280,50	0,25
		Sag bend	143	58	187	62	330	120	302,50	113,00	0,569	400,40	144,40	0,99
20	1,01	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	142	58	191	62	333	120	304,10	113,00	0,575	404,50	144,40	1,01
10	1,01	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	140	58	192	62	332	120	302,40	113,00	0,569	403,60	144,40	1,01
2	1,03	Top	0	151	156	88	156	239	109,20	242,80	0,074	202,80	280,50	0,26
		Sag bend	138	58	197	62	335	120	303,50	113,00	0,573	407,90	144,40	1,03