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Abstract

Nowadays, oil and gas sources are found in deeper water depths and in more hostile environments. This results in the need for more advance technologies. Riser system is a key element in providing safety. Riser failure results in spillage or pollution and could endanger lives. Hence, it is important to establish a high degree of reliability for riser design.

Steel catenary risers (SCRs) have been a preferred riser solution for deep-water field developments due to its simple engineering concept, cost effective, flexibility in using different host platform and flexibility in geographical and environmental conditions. Flexible riser, on the other hand, is limited by technical and economical reasons when it comes to deep water field. Larger diameter is required in deep water to increase collapse resistance due to high hydrostatic pressure. Consequently, increase in cost and limit the option of host platform. Alternatively, Hybrid riser is a robust design for deepwater and harsh environments. It is insensitive to motion induced fatigue. However, hybrid riser is considered to be an expensive solution because it comprises a number of complex components (buoyancy can, riser bundle, flex joint, etc).

A number of SCRs have been installed worldwide over the past years and more to come in the future oil and gas explorations. However, there is no SCR that has been installed in deepwater with harsh environments to date. It is mainly because SCRs in harsh environments experience a great challenge due to large motions from host platform such as semi-submersibles and FPSOs. Therefore, significant design effort is required to prove that the SCRs could safely withstand environmental loads in harsh environments and the effects of deep water.

The study investigates the feasibility of 10 inch production SCR for Offshore Norway in a 1000m water depth with SCR attached to a semi-submersible vessel. Conventional SCR was analyzed and found difficulty in meeting strength design criteria at the touch down point (TDP) and at the riser hang off location. From previous industry work, the weight variation along the riser length has demonstrated a remarkable improvement to SCR response, particularly at TDP.

This study concentrates on fundamental aspects related to improvement from conventional SCR to weight distributed SCR. A number of insightful sensitivity analyses were performed in order to understand the correlation between the peak response and some fundamental parameters such as displacement, velocity and acceleration. Feasibility enhancement of present weight distributed SCR concept was also studied to provide more applicable SCR configuration solution. The study addresses global design considerations including analysis of strength and fatigue. Deepwater SCR Installation scheme was also discussed.

The study concludes that there is significant improvement in SCR response from conventional SCR to weight distributed SCR concept. It also proves that even though the design of SCR in harsh environments and deep water is technically challenging, innovative solutions can be developed.

Keywords: Steel Catenary Riser, Deepwater, Offshore Norway, Weight Distributed, Strength, Fatigue and Installation Design, RIFLEX

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Lastly, and most importantly, I wish to thank my parents whose encouragement, guidance and support enabled me to finish this thesis. To them I dedicate this thesis.

Stavanger, 9th June 2009

M.Iqbal Ruswandi

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Nomenclature

Greek Characters

α_c	parameter accounting for strain hardening and wall thinning
α_{fab}	fabrication factor
σ_e	Von Mises equivalent stress
σ_1, σ_2, σ_3	Principal stresses
σ_a	Basic allowable combined stress
σ_y	Material minimum yield strength
ρ_i	density of the internal fluid
γ_A	load effect factor for accidental
γ_E	load effect factor for environmental
γ_F	load effect factor for functional
$\Delta\sigma$	stress range

Symbol

A_e	external cross-sectional area
A_i	internal cross-sectional area
C_a	allowable stress factor
C_d	drag coefficient
C_f	design case factor
C_m	inertia coefficient
D_f	design factor
D_{fat}	Accumulated fatigue damage (Palmgren-Miner rule)
DFF	Design fatigue factor
D_i	the fatigue damage ratio for each phase of loading
E	Steel Young's modulus
f_0	Out-of-roundness tolerance
g	acceleration of gravity
h	height different between the actual location and the internal pressure reference point
H_s	Significant wave height
k	thickness exponent on fatigue strength
KC	Keulegan Carpenter number
M_A	Bending moment from accidental loads
M_d	design bending moment
M_E	Bending moment from environmental
M_F	Bending moment from functional
M_k	(plastic) bending moment resistance
N	the number of stress cycles to failure
P_a	Net allowable external design pressure
p_b	burst resistance
P_c	Predicted collapse pressure
P_d	design pressure differential
p_e	External pressure
p_{el}	elastic collapse pressure (instability) of a pipe
p_{ld}	local internal design pressure
p_{li}	Local incidental pressure
p_{min}	minimum internal pressure
P_p	predicted propagation pressure
p_{pr}	resistance against buckling propagation
Re	Reynold number
SF_i	associated safety factor
t	thickness through which a crack will most likely grow

t_1	the minimum wall thickness and is relevant for design checks where failure is likely to occur in connection with a low capacity.
t_2	used for design checks governed by the external loading and failure is likely to occur in connection with an extreme load effect at a location with average thickness.
t_{corr}	Internal and external corrosion allowance
t_{fab}	Absolute value of the negative tolerance taken from the material standard/specification of the pipe
t_{nom}	Nominal wall thickness of pipe (uncorroded)
t_{ref}	reference thickness
T_{ed}	Design effective tension
T_{eA}	Effective tension from accidental loads
T_{eE}	Effective tension from environmental
T_{eF}	Effective tension from functional
T_k	Plastic axial force resistance
T_p	Peak period
T_w	true wall tension

Abbreviations

ALS	Accidental Limit State
API	American Petroleum Institute
BHR	Bundle Hybrid Riser
DNV	Det Norske Veritas
FE	Finite Element
FLS	Fatigue Limit State
FPS	Floating Production System
FPSO	Floating Production Storage Offloading
JONSWAP	Joint North Sea Wave Project
LF	Low Frequency
LRFD	Load Resistance Factor Design
MSV	Multipurpose Support Vessel
RAO	Response Amplitude Operation
ROV	Remotely Operated Vehicle
SCF	Stress Concentration Factor
SCR	Steel Catenary Riser
SHR	Single Hybrid Riser
SLS	Serviceability Limit State
SLOR	Single Line Offset Riser
SMYS	Specified Minimum Yield Strength
TDA	Touch Down Area
TDP	Touch Down Point
TLP	Tension Leg Platform
TTR	Top Tensioned Riser
ULS	Ultimate limit State
VIV	Vortex Induced Vibration
WF	Wave Frequency
WSD	Working Stress Design

CHAPTER 1 INTRODUCTION

1.1 Background

The growing global demand for hydrocarbon energy sources has put oil and gas exploration into more advance technology. In addition, the new sources are being found in deeper water depths and in more hostile environments.

In offshore Gulf of Mexico, explorations of oil and gas have reached more than 2000m water depth. Independence Hub and Blind faith are some projects that operate in water depth beyond 2000m. The environmental conditions for offshore Gulf of Mexico and Brazil are rather calm to mild. Typical harsh environmental conditions can be observed in Norwegian Sea or North Sea. Deepwater and harsh environments become the most challenging combination for engineers. However, the experience and technology for field development in deepwater and harsh environment are still limited to date.

Advance riser technologies are one of important key elements for future oil and gas field development. Engineers are still trying to produce the most economical design and friendly technical solution of risers. There are a number of riser configurations that have been used in deepwater field such as flexible riser, steel catenary riser and hybrid riser.

Flexible riser has served good performance for typical mid water depth. The ability to accommodate high curvature and dynamic motions results in well performance to cope with harsh environment. Flexible riser is also easy to install. Nevertheless, when it comes to deepwater harsh environment, flexible riser is limited by technical and economical reasons. In deepwater, large diameter are required to increase collapse resistance due to high hydrostatic pressure. Increase in weight will have impact on load to host platform and hence reduce the options for host platform. Consequently, alternatives to flexible risers have been eagerly pursued.

Hybrid riser is one of alternative solution to flexible riser. The combination of vertical rigid tower from seabed to below wave action zone and flexible jumper that connects rigid tower to host platform makes hybrid riser a robust engineering solution. Hybrid riser is also insensitive to motion induced fatigue. However, hybrid riser is an expensive solution because it comprises a number of complex components (riser buncle, buoyancy can, flex joint, fexible jumper, etc).

Steel catenary riser (SCR) is another alternative solution to flexible riser. Steel catenary riser which composed only from simple steel pipe is cheaper than flexible and may be used in greater water depth without disproportionate increase in cost. Lighter weight reduces of vessel payload and increases the options for host platform. SCR concept allows the use of large diameter, which is suitable for deepwater and high pressure and high temperature (HPHT) field development. However, dynamic performance of steel catenary riser is rather limited. Significant heave and surge motions from host platform will have impact on excessive bending stress at touch down point (TDP). In time, cyclic stress caused by wave loading and vessel motion result in low performance to fatigue damage.

In deepwater and harsh environments, SCR is considered to be the simplest engineering concept. Therefore, in this present study, improvement of present SCR concept will be performed in order to establish more robust SCR design.

1.2 Problem Statement

In this present study, SCR concept in deepwater field will be considered. It is important to mention some challenges for deep water field development:

- Increase in water depth will increase the length of riser system i.e. increase vessel host payload.
- Collapse resistance riser becomes important due to high external hydrostatic pressure. Hence, it requires thicker wall pipe.
- Deepwater riser requires large riser spread at sea bottom. For steel catenary riser, typical radial spread of 1 to 1.5 times of water depth is required [Howells and Hatton, 1997].

In addition, typical harsh environment such as in offshore Norway increases the complexity of SCR system design, because [Karunakaran et al, 2005]:

- Large motions of the vessel due to waves and large vessel offsets due to wind, current and slow-drift wave motions will limit host platform options.
- Large heave and surge motions from host platform result in riser buckling issues at TDP.
- Fatigue problems due to vessel motions and soil interaction.

Due to the challenges from deepwater field and harsh environments, the cost of the riser system has significant proportion to the total field development cost. Therefore, it is important to establish economical design of SCR system. In addition, there is no SCRs that have been operated in deepwater and harsh environments. This limited experience will give difficulty to engineers to establish workable SCR configuration.

1.3 Purpose and Scope

The purpose of this study is to improve the solutions for steel catenary riser in deepwater field and harsh environmentals. Quantitative analysis of strength and fatigue design analysis and qualitative analysis of installation aspect will be the main focus for this study.

Chapter 2 describes the marine riser systems with the main focus on riser solutions for deepwater field and harsh environments. The challenges from deepwater and harsh environments are discussed.

Chapter 3 provides an understanding of deepwater steel catenary riser system. The strength, fatigue and installation design challenges are discussed in this chapter.

Chapter 4 discusses the codes checks that are used in riser design. DNV-OS-F201 Dynamic Riser and API RP 2RD Design of Risers for Floating Production Systems and Tension-Leg Platforms are used as design codes to design riser system.

Chapter 5 provides strength design analysis for conventional Steel Catenary Riser (SCR). Static analysis and dynamic non-linear time domain analysis are considered to analyze the SCR. The results from static and dynamic analysis will be checked against limit state check according to Load Resistance Factor Design - LRFD method (DNV-OS-F201) and Working Stress Design – WSD (API RP 2RD).

Chapter 6 provides strength design analysis for weight distributed SCR as a solution to conventional SCR design. There are two weight distributed SCR that are analysed in this chapter: weight distributed SCR by external coating and weight distributed SCR by clump weights.

Chapter 7 discusses the comparison study between conventional SCR and weight distributed SCR. The result from this study will be used to propose an improvement to weight distributed SCR in order to have a feasible and economical SCR application in deepwater field and harsh environments.

Chapter 8 provides fatigue analyses check for weight distributed SCR concept in order to verify requirement from fatigue limit state.

Chapter 9 provides deepwater installation scheme of SCR. All possible installation method will be discussed. The most suitable installation method will be chosed. Some installation issues are also discussed.

Chapter 10 provides the conclusions and recommendations from the study.

CHAPTER 2 DEEPWATER MARINE RISER SYSTEM DITIONS

2.1 Introduction

Riser system is a key element in providing safety in all phases from drilling, completion/workover, production/injection to export. Main function of riser is to transport fluids or gas from seabed to a host platform. Additional functions of riser according to area of application are provided as follows [API, 1998]:

- Conveys fluid between the wells and the floater for production and injection risers.
- Export fluid from floater to pipeline for export riser.
- Guide drilling or workover tools and tubulars to and into the wells for drilling and workover riser.

Applications of riser system vary according to water depth and environmental conditions. The design of riser system for deepwater field is obviously more challenging than shallow water. Deepwater riser systems have been extensively applied at Gulf of Mexico, Brazil and West of Africa. In terms of environmental conditions, those locations are considered as benign to mild environmental condition. When it comes to North Sea, Norwegian Sea or Barent Sea, the environmental condition becomes harsh. It is predicted that the future oil and gas development will move to deepwater and harsh environments. Therefore, this study is focused on riser system solutions for deepwater field and harsh environments.

In this chapter, the challenges from deepwater and harsh environments are discussed. To start with, an understanding to marine riser system is discussed as a basis for deepwater applications.

2.2 Marine Riser System

Typical elements of a riser system are [API, 1998]:
- Riser body: metal pipe or flexible pipe
- System Interfaces : top interface and bottom interface

The riser system is in the interface between a static structure at the bottom interface and the dynamic floater structure at the top interface. The dynamic behaviour of floater at the surface is the main challenge for riser system design. This is the main reason for next categorizing of riser system according to the ability of riser system to cope with floater motion [DnV, 2001]:
- Top tensioned riser
- Compliant riser

Hybrid riser is the combination of tensioned and compliant risers.

2.2.1 Top Tensioned Riser

The riser in Top Tensioned Risers (TTRs) concept is supported in the floater by providing top tension force in order to maintain acceptable vertical movement. The horizontal motions of the floater induce stresses in the riser base and at the top end near the flex/keel joints. Typical TTRs applications can be seen from Figure 2.1.

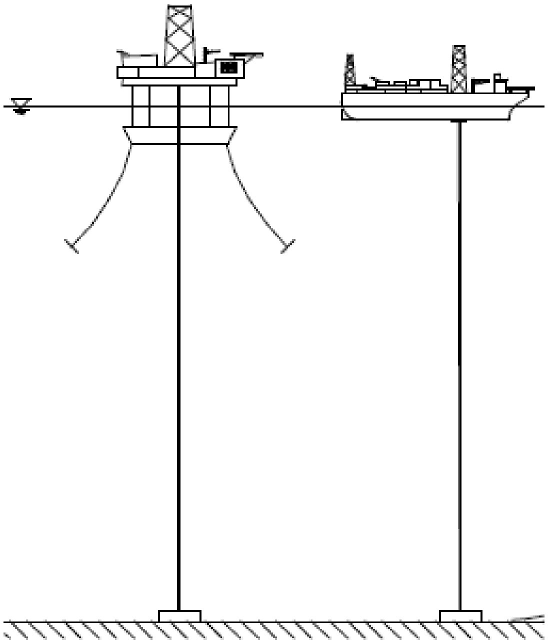


Figure 2-1 Top Tensioned Riser [DnV, 2001]

TTRs are applied for dry tree production facilities such as SPARs or tension leg platforms (TLPs). SPARs and TLPs have small heave motion which is desirable for TTR concept. To some extent, semi-submersibles can also be considered as host platform for TTRs by incorporating separate heavy compensation system to account for the floater motions. Generally, TTR can be used for drilling, production, injection and export riser.

For deepwater application, the riser top tension requirements become significant to support riser weight and prevent bottom compression. The increase in riser tension affects the size of the tensioning system, the buoyancy requirements, as well as the size of the flex-joints or stress joints. In addition, harsh environments will give significant movement on the floaters and TTR itself. Therefore, at some level of combination between water depth and environmental conditions, TTR becomes technically unfeasible and uneconomical.

2.2.2 Compliant Riser

Compliant riser provides flexibility to cope with floater motions. Configurations of compliant riser are formed such that it could absorb floater motions without having additional equipment e.g. heave compensation system. The design flexibility to have high dynamic resistance allows compliant riser to work on deeper water depth and harsher environments. The system flexibility is achieved by arranging the pipe in one of the compliant riser configurations as shown in Figure 2.2: Steep S, Lazy S, Steep wave, Lazy Wave, pliant Wave or Free Hanging [DnV, 2001].

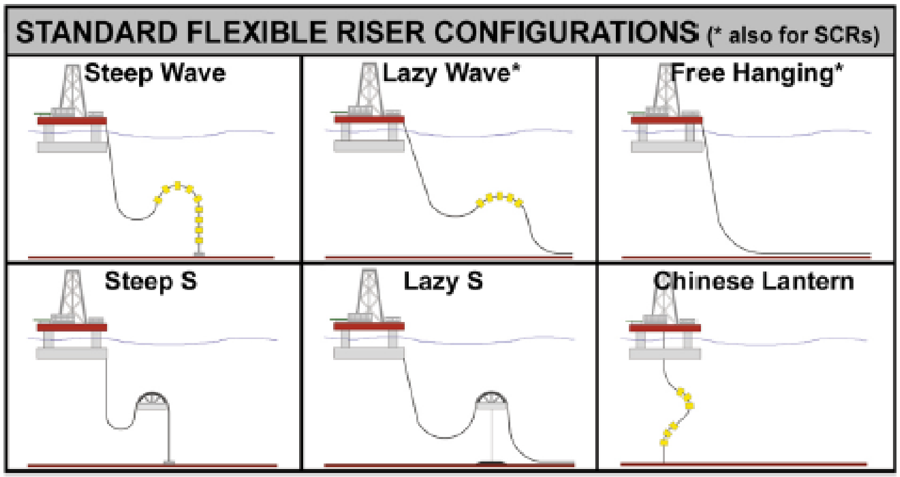


Figure 2-2 Standard Compliant Riser Configurations [Offshore Magazine, May 2001]

Compliant risers are mainly applied as production, export and injection risers. It can be applied to wide variations of floater such as TLPs, Semi-submersibles, and Ships.

According to material selection, compliant risers can be divided into:

- Rigid riser
- Flexible riser

Rigid riser consists primarily of a steel pipe string. Typical material grades are X60, X65 or X70. As an alternative to steel pipe, titanium offers a promising solution due to higher degree of flexibility, higher yield stress and lighter weight.

Flexible riser is built up from a number of independent spiral laid steel and thermoplastic layers and has been used for many years for riser applications worldwide. Typical flexible pipe can be seen in Figure 2.3. Flexible riser could accommodate high curvature, allowing ease of installation and accommodation of dynamic motions.

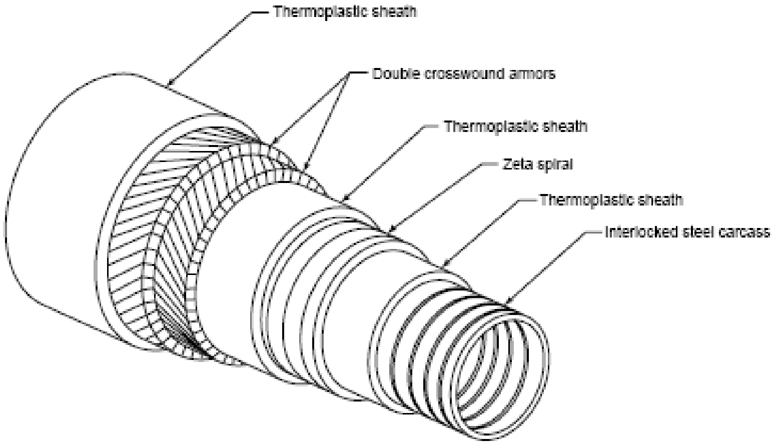


Figure 2-3 Typical Flexible Pipe Structure [API, 1998]

2.2.3 Hybrid Riser

Hybrid riser is the combination of tensioned and compliant risers. The hybrid riser consists of a vertical steel pipe tensioned by a near surface buoyancy can with a flexible jumper connecting the top of the riser and the floater. The foundation is drilled and grouted pile. The hybrid riser arrangement is shown in figure 2.4 below.

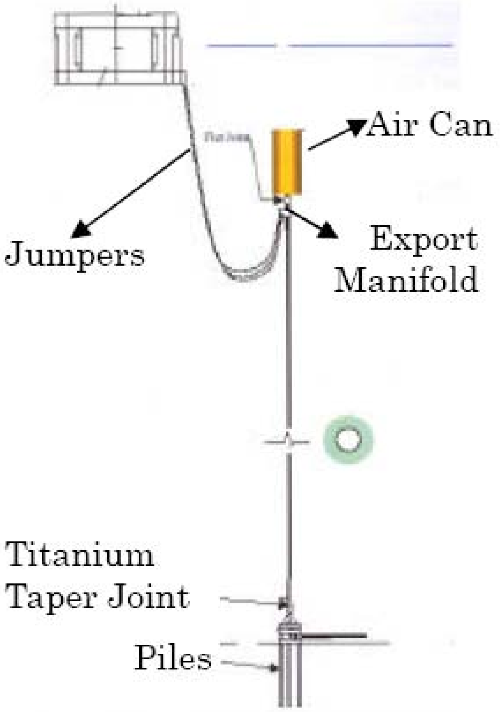


Figure 2-4 Buoyant Free Standing Riser [DnV, 2005]

The vertical riser section is positioned at a distance below the water surface to minimize the effect of wave and current loading. The riser is offset from the host platform such that a suitable length of flexible pipe jumper joining the top of the steel riser to the vessel can be fitted to accommodate the vessel motions. Free Standing Hybrid Riser can therefore be used with a wide range of host platforms and is suitable for deepwater and ultra-deepwater application in all environments.

According to cross sectional lay-out of the riser tower, free standing hybrid risers can be divided into:

- *Bundle hybrid riser (BHR)*

  Bundle hybrid riser consists of a number of smaller diameter steel pipe strings and umbilicals that are grouped together, usually around a buoyant structural core pipe.

- *Single hybrid riser (SHR)*

  Single hybrid riser consists of a concentric pipe-in-pipe vertical steel riser section. For typical offset hybrid riser system, SHR is also known as Single Line Offset Risers (SLORs). Further development from SLOR is Grouped-SLOR which consists of aligned group of single riser. This collectively constrains riser movement and eliminates the risk of clashing.

2.3 Deepwater and Harsh Environmental Challenges

In designing riser system, there are many key issues such as water depth, pressure, temperature, environmental condition, thermal management, installation requirements, etc. In this study, deep water depth and harsh environmental conditions are the primary focus. The combination of deepwater and harsh environmental conditions is considered to be the most challenging for riser system design.

2.3.1 Deepwater Challenges

As deep water developments are being pursued in various parts of the world such as West of Africa, Gulf of Mexico, Brazil, and North of North Sea, risers are one of the components of a floating production system (FPS) that affected by depth. The challenges related to deepwater riser applications are discussed as follows:

- *Increase riser weight*

  The main issue related to increase in riser weight is increase in top-tension force. This affects in different area of riser system:

  - During installation of the pipe in deep water field, the pipe lay system shall accommodate high top-tension which consequently will limit the number of suitable vessels.
  - It is similar situation during service life of riser where heavy riser weight will increase vessel payload. It is observed that the vessel payload may be 10 to 30% larger in nominal conditions and 50 to 100% larger in extreme storm conditions than the riser weight [Howells and Hatton, 1997].
  - Increase the riser development cost. For flexible pipe which has significantly more expensive than rigid pipe, increase in riser weight may result in uneconomical development cost.

- *High hydrostatic pressure*

  External hydrostatic pressure increases with water depth. Excessive external pressure on the pipe results in collapse failure. Hence, thicker riser section is required to resist collapse failure. Therefore, deepwater field development increases the complexity of riser system design.

- *Increase riser spread*

  This is the case for steel catenary riser where generally 1 to 1.5 radial spread is required [Howells and Hatton, 1997]. For the case of field development in 1000m water depth, this would result in a total spread between diametrically opposed risers of 2 km to 3 km. Production system arrangement and positioning will become a problem especially for typical concentric wells.

- *Current influence becomes significant*

  In many deepwater applications, large currents speed may be observed. Riser becomes vulnerable to vortex induced vibration (VIV) for large currents speed. This leads to requirement for strakes along the critical area of riser which will, on the other hand, increase drag forces.

2.3.2 Harsh Environmental Challenges

In addition to deep water, harsh environments increase the complexity of riser design [Karunakaran et al, 2005].

- *large vessel motions*

  As riser system has to absorb vessel motions, large vessel motions will have direct impact on the riser behaviour. As vessel offset increases due to harsh environment, options for riser configuration become limited. Top tensioned riser may not be applied, or conventional free hanging steel catenary riser will experience high bending moment at touch down point.

- *Significant dynamic behaviour*

  One of the potential problems from significant dynamic behaviour is high lateral displacement. For small submerged weight of riser under extreme currents, potential clashing with adjacent riser is high. Another potential problem is risk of compression at touch down area (TDA).

- *Critical in fatigue performance*

  The fatigue loading due to high cyclic stresses is high in some of riser connections. The upper section of riser and TDA are considered to be the most susceptible to fatigue loading.

2.4 Riser Solutions for Deepwater and Harsh Environments

A number of riser concepts offer technical and commercial advantages for deepwater and harsh environments solutions. The riser concepts that have been developed for these situations are:

- Flexible riser
- Steel Catenary riser
- Hybrid Riser

2.4.1 Flexible Riser

Most of floating production fields around the world is combined with flexible risers. This leads to flexible riser as a proven technology especially for shallow to mid water depth. Flexible riser has ability to accommodate high curvature and dynamic motions which result in good performance for harsh environments such as Offshore Norway. It is easy to install, retrieve, corrosion resistance and reusable.

However, as many fields are being progressed to deeper water, flexible riser has technical and economical limitation mainly caused by development cost. Flexible pipe cost is significantly higher than rigid steel pipe. The necessity of having strong layers to resist the radial loads represents a limitation in relation to the available manufacturing processes and equipment. Furthermore, in the future, the need for high number of risers, large diameter, high depth, long life and coupled with harsh environment combined with production system is predicted [Howells and Hatton, 1996]. These developments push the current flexible pipe technology to the limit. Consequently, alternatives to flexible risers have been eagerly pursued.

Development of flexible pipe technology comprises study on reducing weight (by employing composite tensile armor), increasing the diameter envelopes for deeper water (targeting 12” in 2,500 meter depths), and improving flow assurance properties (by heating, advance insulation materials) [Clausen, T and Souza, R, 2001]. These developments will increase the competition of flexible riser with other configurations such as Steel catenary riser and hybrid riser.

2.4.2 Steel Catenary Riser

Steel Catenary Riser (SCR) is one of direct alternative to flexible riser. It may be used at larger diameters, higher pressures and temperatures and may be produced more easily. SCR can be suspended in longer lengths, removing the need for mid-depth buoys. Steel lines are cheaper than flexible and may be used in greater water depths without a disproportionate increase in cost. At the seabed, the need of riser base, stress joint or flex joint have been eliminated. This reduces the complexity of riser system and cost savings are made as a result of simplified riser system.

However, SCRs are very sensitive to environmental loading. Large heave and surge motion from host platform due to harsh environment results in buckling issues at touch down point. As the host platform moves, the lengths of pipe between the supports change. This makes the seabed touchdown point shift, hence moving the point of maximum curvature up and down along the length of pipe at the seabed. As a result, at touch down area, pipe is subject to maximum and almost zero curvature, making the region highly sensitive to fatigue damage. Vortex induced vibration due to current in deepwater application is another issue for SCR design.

These issues push the industry to develop new SCR solutions such that it could cope in deepwater and harsh environments. There are many studies have been done by the industry with regards to SCR optimisation design.

Some of SCR optimisation studies are:

- Lazy wave steel catenary riser
- Weight optimized SCRs by varying coating weight and riser wall thickness along the riser [Karunakaran et al, 2005]
- Weight optimized SCRs by attaching clump weight on the necessary region of riser [Foyt et al, 2007]

2.4.3 Hybrid Riser

Hybrid riser appears to be a promising concept for deepwater and harsh environments. It has the lowest vessel payload than flexible and steel catenary riser, excellent dynamic behaviour, low fatigue sensitivity, can be used with a wide range of host platforms. Hybrid riser arrangement allows a very compact subsea arrangement, while SCR is relatively coverage of the seabed.

However, hybrid riser is an expensive solution due to its many and complex components (buoyancy can, riser bundle, flex joint, etc). Additionaly, hybrid riser is installed as a single pre fabricated item, i.e. there is always the risk during tow and installation. In comparison, SCRs are installed as individual lines, i.e. the effect of failure is less significant.

2.5 Conclusion

In deepwater and harsh environmental application, both steel catenary riser and hybrid riser offer a promising alternative to flexible riser. Without a doubt, hybrid riser offers a robust engineering concept. It is suitable for deepwater and ultra-deepwater applications in all environments. However, its expensive solution gives problem for oil and gas developer.

Steel catenary riser, on the other hand, is a simple engineering concept and cost effective. It only consists of string of pipe free hanging from surface to sea floor which makes SCR outwardly simple. Even though SCR is not a robust engineering concept for deepwater and harsh environments, the studies on optimising SCR performance have been extensively produced. Therefore, in this study, steel catenary riser will be the main focus as a solution to deepwater and harsh environments condition. Different SCR configurations will be performed in order to study the driver parameters in designing SCR.

CHAPTER 3 AN UNDERSTANDING OF DEEPWATER STEEL CATENARY RISER

Steel catenary riser (SCR) concept is a promising solution for future deepwater applications. The design and installation challenges are discussed in this current study. The development of SCR concept for deepwater application is also discussed in this section.

To start with, following section will discuss about components in steel catenary riser.

3.1 SCR Components

SCR components can be categorized into:
- Components for fluid transfer
- Components for stability and external load control

3.1.1 Components for Fluid Transfer

According to its behaviour, SCR segment can be divided into:
- *Static flowline section*: the horizontal section that extends from termination structure until touch down area. It generally behaves statically due to the low effect of environmental loading.
- *Dynamic riser section*: the vertical section that connects static flowline section and flex joint at the top of host platform. It behaves dynamically due to environmental loading and host platform motions.

Metal-pipe SCR segments are joined together to make up a complete riser. This results in some connections on riser string from the seabed to the surface. According to location, the connections on the SCR can be divided into:
- *Riser coupling*: connection between riser sections
- *End connectors*: connection at top-end of riser to surface equipment and connection at bottom-end to seabed

The main purpose of riser coupling is to provide a seal between mating segments such that it could maintain its integrity under all external and internal loading conditions [API, 1998]. Additionally, the ability to produce well controlled connection details offers improvement to fatigue performance by reducing stress concentrations and improved fatigue classification.

Top end-connector of SCR provides fluid containment seal in the connection to the surface production equipment. Meanwhile, bottom connector provides the fluid containment seal between the riser and sea-floor equipment. The bottom connector shall have adequate capacity and rigidity to withstand any loading from SCR motions and environmental loading.

3.1.2 Components for Stability and External Load Control

There are many components that have ability to form adequate stability to withstand external load. SCR concept relies on its weight to provide tension. On the sea floor, the riser is critical to bending moment due to long suspended length all the way from host platform. In order to reduce high tension force and high bending moment, one solution is to provide supplemental buoyancies that attach externally to riser system.

The idea of providing buoyancy components is to form acceptable configuration in order to avoid excessive tension force and bending moment. However, in this study, this concept is not applied because it requires high cost of buoyancy components. Simpler concept will be considered in order to achieve the most effective and efficient solution for SCR in deepwater and harsh environments.

Furthermore, some devices are incorporated to SCR in order to reduce riser bending moments or control curvature. Those devices are:

- *Flex joint*
  Flex joint is provided at the top region of SCR in order to minimize bending moment. Flex joint which consists of alternating layers of metal and elastomeric materials allows angular deflections at top connection of riser [API, 1998]. For deepwater application, the design of flex joint shall consider the effect of high top tension and tension ranges for fatigue design [Bai, 2005]. The description of flex joint is shown in figure 3.1.

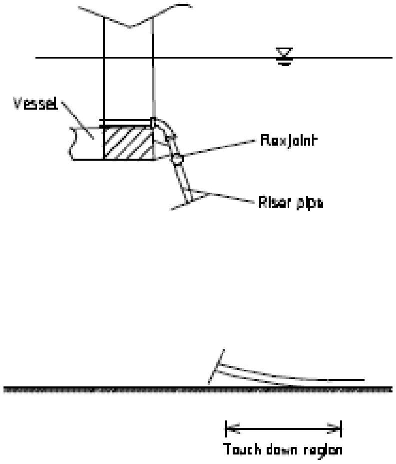


Figure 3-1 Flex Joint Description

- *Tapered stress joint*
  Taper stress joint is used to provide a transition member between rigidly fixed or stiffer sections of the production riser and less stiff sections of the production riser. This is used to reduce local bending stresses and to provide flexibility at the riser end.

There is also device that is used to reduce current effects. Helical strakes are used to reduce the VIV effects. Figure 3.2 shows a typical strake pattern and cross section on the riser.

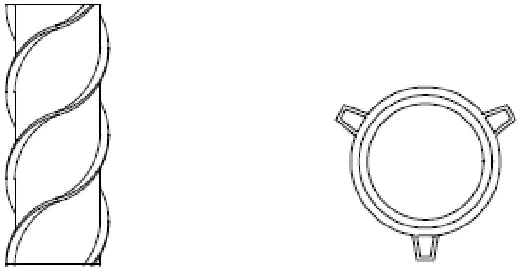


Figure 3-2 (a) Span Views of Helical Strakes (b) Section through riser

3.2 SCR Design Challenges

Critical locations on SCR are typically the wave zone, hog and sag-bends, touch down area at seafloor and at terminations to rigid structure. Figure 3.3 shows the schematic figure of steel catenary riser attached to floating production system (FPS).

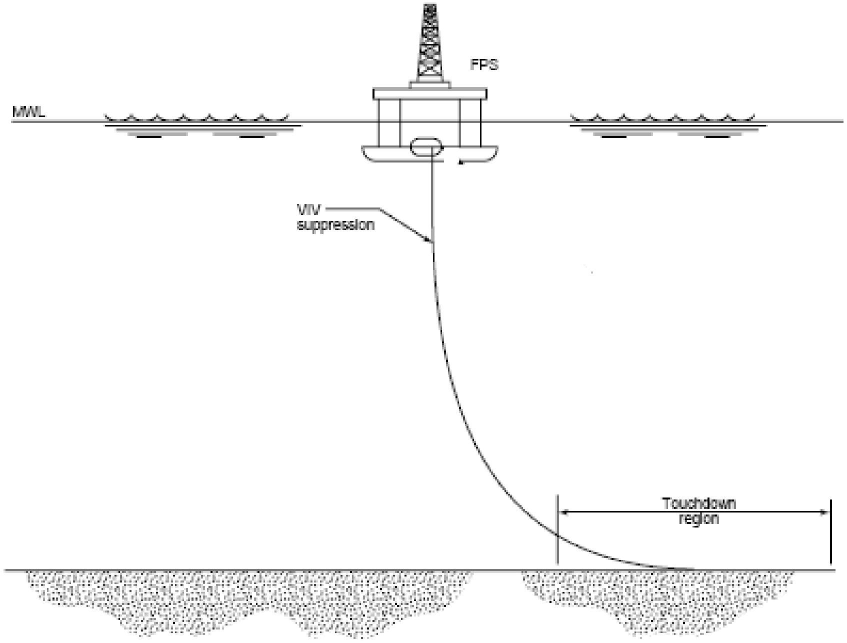


Figure 3-3 Schematic of Steel Catenary Riser

These are some parameters that contribute to complexity of SCR design:

1. *Water depth*

   Water depth is one of critical parameter for SCR design. Design for deepwater application will have completely different solution compared to shallow water application. One of the driving parameter is wall thickness requirement. Deepwater application requires thicker wall to resist high hydrostatic pressure. Thicker wall results in heavier steel weight and hence increase cost of development.

2. *Vessel motions*

   Differences between host vessel and riser in responding wave action can lead to high bending moment at attachment point to host vessel. This can be solved by providing flex joint that allows rotation of riser. At the touchdown area (TDA), large vessel motions (heave and surge motions) due to harsh environments may cause compression at TDA. The SCR design becomes more complex when the riser tension at the vessel becomes too great as the vessel drifts away from the touch down point (far case) or the bending moment becomes too great as the vessel drifts towards the touch down point (near case). This leads to challenging in either limiting the motion of floating structures such as TLPs or SPARs or improving the performance of SCR.

3. *Currents*

   In riser design, currents give two different considerations which are hydrodynamic drag effect and vortex induced vibration (VIV). The current together with wave has effect on moving the catenary riser at the touch down point due to low rigidity at this region. The vibration of structure will be critical if its period is close to natural period of the structure (resonance). In addition, VIV could result significant stress range on the pipe, i.e. fatigue problem.

4. *Field layout*

   Interference/clashing between risers is one of the issues for SCR design. The different dynamic behaviour for different riser sizes results in different displacements. Smaller pipe will move more than bigger pipe. Hence, it is important to have enough clearance between risers. However, enough clearance means reducing number of riser to be attached to host platform. For big field development where high number of risers is required, this complexity is an important challenge that needs to be solved.

5. *Impact on host platform payload*

   Deepwater SCR application has high top tension, and SCR concept does not have tensioning system. This has impact on host platform design to accommodate such high top tension force from SCRs.

6. *Fatigue*

   Experience from deepwater SCR applications shows that fatigue is one of the most challenging issue for SCR design. It is mainly because SCR designs are very sensitive to motion characteristics of the host platform. Fatigue damage caused by wave-induced motions is one of the main sources. Severe fatigue damage can also be observed when current velocities are high e.g. Gulf of Mexico, West of Africa or North Sea. Significant heave motions from host platform e.g semi-submersible make SCR sensitive to fatigue damage.

7. *High pressure and high temperature*

   High pressure and high temperature field lead to the need to have thicker section. Thicker section increases cost, challenging for offshore fabrication, higher riser tensions. Additionally, High temperature results in de-rating of material steel strength.

8. *Welding requirement*

   Riser segments which are joined together are normally constructed by welding. All welds may contain defects due to fabrication mistake or external dynamic loading. The propagation of weld defects may result in riser failure.

3.3 SCR Installation Challenges

For J-lay method with large SCR diameter in deepwater, installation requires high top tensioning system. This limits a number of vessels that capable to provide such high tensioning system. The current maximum tension limit is around 1000Te for high-end installation vessels, with several more vessels with capacities of over 500Te [Burgess and Lim].

For typical small to medium diameter, SCR can be installed by using reel lay vessel. It has a large number of reel lay vessel available around the world which reduces the challenge of SCR installation.

3.4 Development Studies on Optimizing SCR Performance

For typical deepwater applications and harsh environments where wave induced motions are significant and vessel motions are severe, it is difficult for simple conventional catenary riser configuration to meet both strength and fatigue design criteria, especially at the touch down point and hang-off location. On the other hand, the need for solutions to this issue is high due to the trend of oil and gas development in deeper water and harsher environment.

The challenges on SCR design can be successfully addressed by varying weight along the riser. One study from Karunakaran, et al (2005) shows that by varying heavy and light coating along the riser length, SCR strength and fatigue performance can be improved significantly. Figure 3.4 below shows the configuration of different weight applied to SCR.

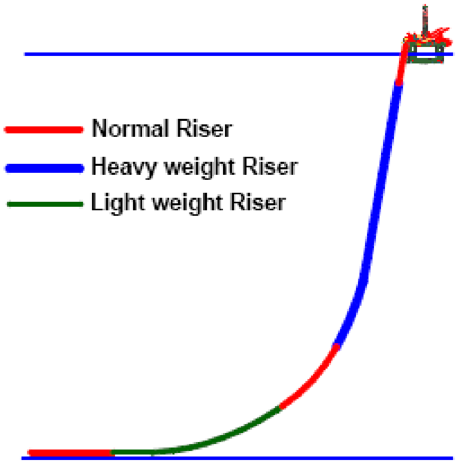


Figure 3-4 Weight Distributed SCR [Karunakaran et al, 2005]

Another study on weight distributed SCR was developed by Foyt et al (2007) for deepwater West Africa environments. A number of clump weights were attached above the sag-bend region, in order to provide heavy segment on the straight part of riser. The analysis results show that SCR strength and fatigue response are improved. Figure 3.5 shows the clump weight properties to be attached to riser section.

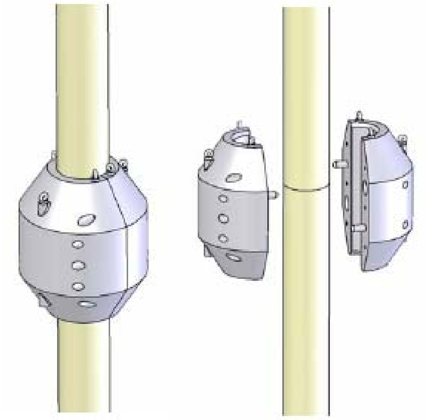


Figure 3-5 Clump Weight [Foyt et al, 2007]

In this current study, the observations will be done on both solutions to analyze why weighted sections can improve SCR response at the critical area. Driven parameters will be discussed to give an input for optimisation SCR design in deepwater applications and harsh environments.

CHAPTER 4 DESIGN CODES FOR STEEL CATENARY RISER

4.1 Introduction

Steel Catenary Risers are subjected to various types of loads and deformations that range from the routine to the extreme or accidental. The purpose of SCRs design is to design a riser system that can withstand load effects throughout its expected lifetime. The design is safe if the resistance is more than response and the ratio of response over resistance shall be less than acceptance criteria or allowable factor. Safety factor shall be incorporated in design check in order to account for various uncertainties due to natural variability, inaccuracy in analysis procedures and control of load effects and uncertainties in structural resistance.

There are two methods to establish acceptance criteria in structural design. One method is often referred to as Working Stress Design (WSD) where one central safety factor is used for each limit state to account for uncertainties from response and resistance. Another approach is referred to as Load and Resistance Factor Design (LRFD) where partial safety factor is applied for each load effect and resistance. In riser systems design, WSD is provided in API-RP-2RD; meanwhile LRFD is provided in DnV-OS-F201.

Traditionally, structural designs for riser systems were based on API-RP-2RD. The principles from DnV-OS-F201 offers more consistency riser design by allowing different riser design alternatives to take into account the environmental conditions.

In this chapter, WSD and LRFD structural design code are discussed to give a good understanding for basis evaluation to steel catenary riser design. At the end of this chapter, qualitative conclusions are provided for both WSD and LRFD code to give some guidance for quantitative design of steel catenary riser.

4.2 WSD code – API-RP-2RD

API has developed a Recommended Practice covering all aspects of riser design for floating production systems, emphasizing on working stress design. In this section, some design criteria with respect to pressure, functional loads, extreme storm loads and survival loads are discussed.

4.2.1 Stresses

In marine riser system, the pipe is considered to be plain pipe due to its axisymmetric geometry. The principal stresses for plain pipe are in the axial, hoop and radial directions [API, 1998]. Transverse shear and torsion are negligible for plain round pipe.

The three principal stresses are calculated to form a combined stress, called Von Mises equivalent stress and defined by the following equation:

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \tag{4.1}$$

Where,

σ_e = Von Mises equivalent stress
$\sigma_1, \sigma_2, \sigma_3$ = principal stresses

According to API, 1998 section 5.2.3, the design criteria of WSD for plain pipe is:

$$(\sigma_p)_e < C_f \sigma_a \tag{4.2}$$

Where,
$(\sigma_p)_e$ = Equivalent von Mises stress where the principal stresses consist of primary membrane stresses.
σ_a = Basic allowable combined stress, $\sigma_a = C_a \sigma_y$
C_a = allowable stress factor, $C_a = {}^{2}/_{3}$
σ_y = material minimum yield strength
C_f = design case factor
= 1.0 (normal operating)
= 1.2 (extreme)
= 1.5 (survival)

The usage factor which is calculated by considering allowable stress factor and design case factor are provided in table 4.1.

Table 4-1 Usage Factors in API RP 2RD

Load combination	Normal operating	Extreme	Survival
Functional plus environmental	0.67	0.8	1.0

4.2.2 Deflections

The purpose of limiting deflection is to prevent high bending stresses or large riser curvatures. Moreover, deflections shall be controlled to prevent clashing between risers.

4.2.3 Hydrostatic Collapse

In deepwater application, hydrostatic pressure is high. Excessive external pressure may result in collapse failure. Consequently, riser tubular shall have resistance to collapse during installation or operation. According to API, 1998 section 5.4.1.3, the design criteria for collapse pressure is given by the following equation:

$$P_a \leq D_f P_c \tag{4.3}$$

Where

P_a = Net allowable external design pressure
P_c = Predicted collapse pressure (refer to API, 1998 section 6.6.2.1)
D_f = design factor
= 0.75 for seamless or Electric Resistance Welded (ERW) API pipe
= 0.60 for (DSAW) internally cold expanded API pipe

4.2.4 Collapse Propagation

Impact or excessive bending due to tensioner failure is one of the sources that initiate the collapse at the pipe. The buckle will propagate and travel along the pipe until external pressure drops due to change in properties of pipe. Therefore, in order to prevent collapse initiation and propagation, thicker pipe shall be used or buckle arrestor is provided at some critical region.

The design criterion to prevent collapse propagation is provided in the following equation:

$$P_d \leq D_p P_p \quad (4.4)$$

Where

P_d = design pressure differential
P_p = predicted propagation pressure
$= 24\sigma_y \left(\frac{t}{D}\right)^{2.4}$
D_p = design factor
= 0.72

These criteria are applied to demonstrate metal tubular that used in FPS risers will not collapse under external hydrostatic pressure.

4.2.5 Fatigue

A design criterion for fatigue is provided in the following equation [API, 1998]:

$$\sum_i SF_i D_i < 1.0 \quad (4.5)$$

Where
D_i = the fatigue damage ratio for each phase of loading
SF_i = associated safety factor

4.3. LRFD code – DnV-OS-F201

The basis of this code is a limit state and partial safety factor methodology. The limit states are categorized into [DnV, 2001]:

- Serviceability Limit State (SLS): the riser shall remain fit to function during normal operation when subjected to operational loads.
- Ultimate limit State (ULS): riser shall remain intact and avoid rupture when subjected to the peak design load with 10^{-2} annual exceedence probability.
- Accidental Limit State (ALS): riser shall remain intact and avoid rupture when subjected to accidental loads such as dropped object, explosion, etc.
- Fatigue Limit State (FLS): riser shall remain fit to function during its service life due to accumulated excessive fatigue crack growth or damage under cycling loading.

4.3.1 Serviceability Limit State

In this limit state, riser is subject to operating loads and shall remain functional. For typical export or import riser, there are some limits that have to be satisfied:

- Risers do not deflect by more than certain limits
- During riser installation, a weather limitation shall be set to avoid riser interference [DnV, 2001]

- Out-of-roundness tolerance of the pipe shall be set to avoid premature local buckling. According to DnV, 2001, out-of-roundness tolerance from fabrication of the pipe shall be limited to 3.0%.

  $$f_o = \frac{D_{\max} - D_{\min}}{D_o} \leq 0.03$$

- Other serviceability limits may be determined to limit the degradation of riser coatings and attachments or for allowances due to wear and erosion [DnV, 2001]

In the case where SLS requirement are not satisfied, riser shall not fail structurally.

4.3.2 Ultimate Limit State

Load controlled conditions are emphasized on this design check. Pipe members subjected to pressure (collapse and bursting) and combined loading criteria (pressure and external loads) are the scope for ULS.

Bursting

Bursting failure of the pipe occurs due to internal overpressure. Along the riser, top-end is the critical area for bursting where the external hydrostatic pressure is minimal and there is internal fluid pressure.

According to DnV, 2001, a criterion for pipe resistance to bursting failure at all cross section is provided in the following equation:

$$(p_{li} - p_e) \leq \frac{p_b(t_1)}{\gamma_m \gamma_{sc}} \tag{4.6}$$

Where:

p_{li} = Local incidental pressure: the maximum expected internal pressure with a low annual exceedence probability. Normally the incidental surface pressure, p_{inc} is taken 10% higher than the design pressure, p_d:

$p_{li} = p_{ld} + 0.1.p_d$

Where:

p_{ld} = local internal design pressure
$p_{ld} = p_d + \rho_i .g.h$

Where:

p_d = design pressure; for riser type export/import riser from/to pipeline, design pressure is maximum export/import pressure during normal operations.
ρ_i = density of the internal fluid
h = height different between the actual location and the internal pressure reference point
g = acceleration of gravity

p_e = External pressure
$p_b(t)$ = burst resistance

$$p_b(t) = \frac{2}{\sqrt{3}}.\frac{2.t}{D-t}.\min(f_y;\frac{f_u}{1.15}) \tag{4.7}$$

The nominal wall thickness is given by:

$t_{nom} = t_1 + t_{corr} + t_{fab}$

The minimum required wall thickness for a straight pipe without allowances and tolerances is given by:

$$t_1 = \frac{D}{\frac{4}{\sqrt{3}}.\frac{\min(f_y;\frac{f_u}{1.15})}{\gamma_m \gamma_{sc}(p_{li} - p_e)} + 1} \tag{4.8}$$

System Hoop Buckling (Collapse)

Collapse failure of the pipe occurs due to external overpressure. Along the riser, lower part of riser is the critical area for collapse where external hydrostatic pressure is maxima.

According to DnV, 2001, a criterion for pipe resistance to collapse failure at all cross section is provided in the following equation:

$$(p_e - p_{\min}) \leq \frac{p_c(t_1)}{\gamma_{sc}\gamma_m} \tag{4.9}$$

Where:

p_{min} = minimum internal pressure; p_{min} is the local minimum internal pressure taken as the most unfavourable internal pressure plus static head of the internal fluid. For installation p_{min} equals zero. For installation with water-filled pipe, p_{min} equals p_e.

p_c = resistance for external pressure (hoop buckling)

$$\left(p_c(t) - p_{el}(t)\right)\left(p_c^2(t) - p_p^2(t)\right) = p_c(t).p_{el}(t).p_p(t).f_0.\frac{D}{t} \tag{4.10}$$

Where:

p_{el} = elastic collapse pressure (instability) of a pipe

$$p_{el}(t) = \frac{2.E.(\frac{t}{D})^3}{1-\upsilon^2} \tag{4.11}$$

p_p = plastic collapse pressure

$$p_p(t) = 2\frac{t}{D}f_y\alpha_{fab} \tag{4.12}$$

Where

α_{fab}: fabrication factor (Table 5-7 DnV, 2001)

f_0 = the initial ovality, i.e. the initial departure from circularity of pipe and pipe ends.

Propagating Buckling

Local buckle on the pipe may possibly occur due to system failure such as tensioner failure during installation. The local buckle will propagate until external pressure drops due to change in pipe properties. In order to design the local buckle will not propagate, following criterion shall be satisfied:

$$(p_e - p_{\min}) \leq \frac{p_{pr}}{\gamma_c\gamma_{sc}\gamma_m} \tag{4.13}$$

Where:

γ_c = 1.0 if no buckle propagation is allowed

= 0.9 if short distance buckle propagation is allowed.

p_{pr} = resistance against buckling propagation

$$p_{pr} = 35.f_y.\alpha_{fab}\cdot\left(\frac{t_2}{D}\right)^{2.5} \tag{4.14}$$

Where $t_2 = t_{nom} - t_{corr}$

Normally, propagating buckling criterion results in significantly thicker wall requirement compared to other criteria. Consequently, the design will be too conservative if this criterion has to be satisfied. In practice, designer would let the propagating limit to be exceeded and consequently, buckle arrestor shall be provided over the critical region. This method would save significant amount of riser weight and cost.

After riser system is designed to withstand both internal pressure and external pressure, riser is then checked for combination between axial load, bending moment, and pressure.

Combination Loading

Combination between *bending moment, effective tension* and *net internal overpressure* shall be designed to satisfy the following equation [DnV, 2001]:

$$\{\gamma_{SC}\cdot\gamma_m\}\left\{\left(\frac{|M_d|}{M_k}\cdot\sqrt{1-\left(\frac{p_{ld}-p_e}{p_b(t_2)}\right)^2}\right)+\left(\frac{T_{ed}}{T_k}\right)^2\right\}+\left(\frac{p_{ld}-p_e}{p_b(t_2)}\right)^2\leq 1 \tag{4.15}$$

Where:

M_d = design bending moment

$$M_d = \gamma_F\cdot M_F + \gamma_E\cdot M_E + \gamma_A\cdot M_A \tag{4.16}$$

Where:

M_F, M_E, M_A = Bending moment from functional, environmental, accidental loads respectively.

γ_F, γ_E, γ_A = load effect factor for functional, environmental, accidental respectively (Table 5.2 DNV-OS-F201).

M_k = the (plastic) bending moment resistance

$$M_k = f_y.\alpha_c.(D-t_2)^2.t_2 \tag{4.17}$$

Where α_c is a parameter accounting for strain hardening and wall thinning.

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

$$\beta = \begin{cases} (0.4 + q_h) & \text{for } D/t_2 < 15 \\ (0.4 + q_h)(60 - D/t_2)/45 & \text{for } 15 < D/t_2 < 60 \\ 0 & \text{for } D/t_2 > 60 \end{cases}$$

$$q_h = \begin{cases} \dfrac{(p_{ld} - p_e)}{p_b(t_2)} \dfrac{2}{\sqrt{3}} & \text{for } p_{ld} > p_e \\ 0 & \text{else} \end{cases}$$

T_{ed} = Design effective tension

$$T_{ed} = \gamma_F \cdot T_{eF} + \gamma_E \cdot T_{eE} + \gamma_A \cdot T_{eA} \tag{4.18}$$

T_{eF}, T_{eE}, T_{eA} = Effective tension from functional, environmental, accidental loads respectively.

Note: Normally A load is not considered simultaneously in global analyses.

The effective tension, Te:

$$T_e = T_W - p_i A_i + p_e A_e \tag{4.19}$$

Where:

T_w = true wall tension
p_i = internal (local) pressure
p_e = external (local) pressure
A_i = internal cross-sectional area
A_e = external cross-sectional area

T_k = the plastic axial force resistance

$$T_k = f_y . \alpha_c . \pi . (D - t_2) . t_2 \tag{4.20}$$

Combination between *bending moment, effective tension* and *net external overpressure* shall be designed to satisfy the following equation [DnV, 2001]:

$$\{\gamma_{SC} \cdot \gamma_m\}^2 \left\{ \left(\frac{|M_d|}{M_k} \right) + \left(\frac{T_{ed}}{T_k} \right)^2 \right\}^2 + \{\gamma_{SC} \cdot \gamma_m\}^2 \left(\frac{p_e - p_{min}}{p_c(t_2)} \right)^2 \leq 1 \tag{4.21}$$

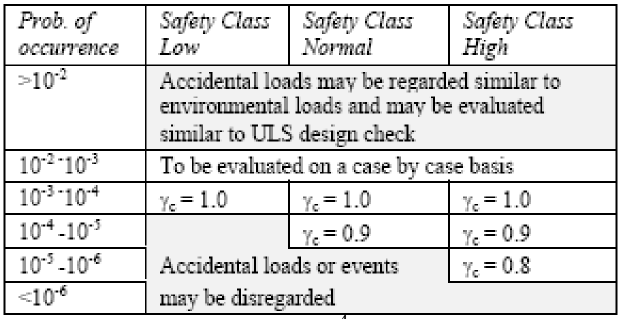
4.3.3 Accidental Limit State

ALS represents excessive structural damage as a consequence of accidents which affect the safety of the structure, environment and personnel. A design of riser shall maintain the structural integrity such that it will not be impaired during any accidental event or within a certain period of time after the accident. In SCR design, these are some sources that may lead to accidental event [DnV, 2001]:

- Fires and explosions
- Impact/collisions
- Hook/snag loads
- Loss of mooring line
- Earthquake, tsunamis, iceberg.

A simplified design check with respect to accidental load is shown in Table 4.2 below [DnV, 2001].

Table 4-2 Simplified Design Check for Accidental loads [DnV, 2001]



Prob. of occurrence	Safety Class Low	Safety Class Normal	Safety Class High
$>10^{-2}$	Accidental loads may be regarded similar to environmental loads and may be evaluated similar to ULS design check		
10^{-2}-10^{-3}	To be evaluated on a case by case basis		
10^{-3}-10^{-4}	$\gamma_c = 1.0$	$\gamma_c = 1.0$	$\gamma_c = 1.0$
10^{-4}-10^{-5}	Accidental loads or events may be disregarded	$\gamma_c = 0.9$	$\gamma_c = 0.9$
10^{-5}-10^{-6}			$\gamma_c = 0.8$
$<10^{-6}$			

For the case of probability of occurrence 10^{-4}, a total safety factor of 1.1 as standard practice industry suggested and consistent with safety class normal according to table 4.1.

4.3.4 Fatigue Limit State

The FLS design is carried out to ensure that the structure has an adequate fatigue life. The fatigue assessment methods may be categorized into [DnV, 2001]:

- Methods based on S-N curves
- Methods based on fatigue crack propagation

In this section, fatigue criterion according to S-N curves is discussed. The fatigue criterion in provided in the following equation [DnV, 2001]:

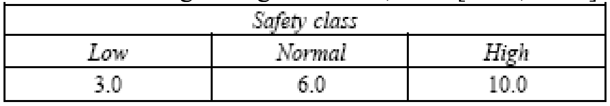
$$D_{fat}.DFF \leq 1.0$$

Where:

D_{fat} = Accumulated fatigue damage (Palmgren-Miner rule)

DFF = Design fatigue factor, see table 4.3

Table 4-3 Design Fatigue Factors, DFF [DnV, 2001]



Safety class		
Low	Normal	High
3.0	6.0	10.0

Reference is made to chapter 8 for more details with respect to fatigue design and analysis.

4.4 Conclusion

WSD method has been used in the most of riser system design. It is an easy-to-use method by having one central safety factor under certain condition e.g. operating, extreme or accidental. This approach has demonstrated the feasibility of steel catenary risers. However, this code can lead to overly conservative designs. As the riser system designs increase in complexity due to the trend of field development to deeper water and harsher environment, more economical riser design is being pursued. LRFD method provides more consistence design because it allows the loading uncertainty to be accounted for in the load factor and the uncertainty in yield stress to be accounted for in the material partial safety factor.

In this present study, both WSD and LRFD method will be applied in order to have quantitative results from different design code method.

CHAPTER 5 DEEPWATER SCR STRENGTH DESIGN AND ANALYSIS WITH CONVENTIONAL COATING

5.1 Introduction

SCRs have become a preferred riser concept in almost every new deepwater field development and have been designed and installed on TLP, SPAR, Semi-submersible and FPSO. SCRs have been installed in wide range of water depth from mid to ultra deepwater (e.g. Independence Hub: 8000ft water depth) and in wide range of environmental condition from benign environment (e.g. Offshore West Africa) to mild environment (e.g. Brazil, Gulf of Mexico). To date, there are no SCRs installed in deepwater and harsh environments. Hence, it is interesting to study the SCR concept for deepwater and harsh environments application.

To start with, conventional SCR configuration with uniform coating density is applied. The SCR design focuses on strength analysis and fatigue analysis. Installation analysis will be studied qualitatively.

5.2 SCR Strength Analysis Methods

According to DnV, 2001, the purpose of global riser system analyses is to describe the overall static and dynamic structural behaviour due to the system exposing to a stationary environmental loading conditions. The output of global riser system can be grouped into the following categories [DnV, 2001]:

- Resulting cross-sectional forces (effective tension, bending moments, torsional moment)
- Global riser deflections (curvature, elongation, angular orientation)
- Global riser position (co-ordinates, translations, distance to other structures, position of touch down point on seafloor, etc)
- Support forces at termination to rigid structures (resulting force and moments)

In order to derive all necessary output in global riser analyses, the following sections describe the stepwise analysis methods.

5.2.1 Initial Sizing

In initial design of riser system, minimum wall thickness is determined based on resistance to burst, collapse and the desired submerged weight. In normal industrial practice, resistance to propagation buckling is not necessarily satisfied as it can easily be prevented by providing buckle arrestor at some critical regions.

Water depth is one of important parameters in determining minimum wall thickness. The deeper the water depth is the higher requirement for collapse resistance because hydrostatic pressure increases linearly with water depth. It may require thick wall to resist the external overpressure. Requirement on thick wall can also come from burst resistance due to excessive internal pressure (High Pressure High Temperature reservoir). Riser internal fluid has significance on internal pressure. Gas has lower density than oil which results in lower internal pressure and makes the riser critical to collapse failure. Conversely, oil will result in higher internal pressure and makes the riser critical to burst failure.

Since there are a number of parameters that contribute to different failure mechanism, it is important to have a comprehensive and careful design in initial sizing of riser system.

5.2.2 Static Analysis

The main purpose of riser static analysis is to establish the equilibrium profile of riser under the combined effects of self-weight, buoyancy, extreme vessel offset and current. The basic loading components in static analysis are categorized into [DnV, 2001]:

1. volume forces (weight and buoyancy);
2. prescribed displacements (displacement of terminal points from stressfree to specified positions)
3. specified forces (e.g. applied top tension), and
4. displacement dependent forces (current loading)

Volume Forces

Volume forces of steel catenary riser are derived under the combined effect of self-weight, buoyancy, hydrostatic and internal fluid pressure. Figure 5.1 shows how the equilibrium of a segment of curved pipe under the combination of volume forces components can be equated to equilibrium under equivalent effective parameters by introducing equal and opposite pressures over the end faces of the segment.

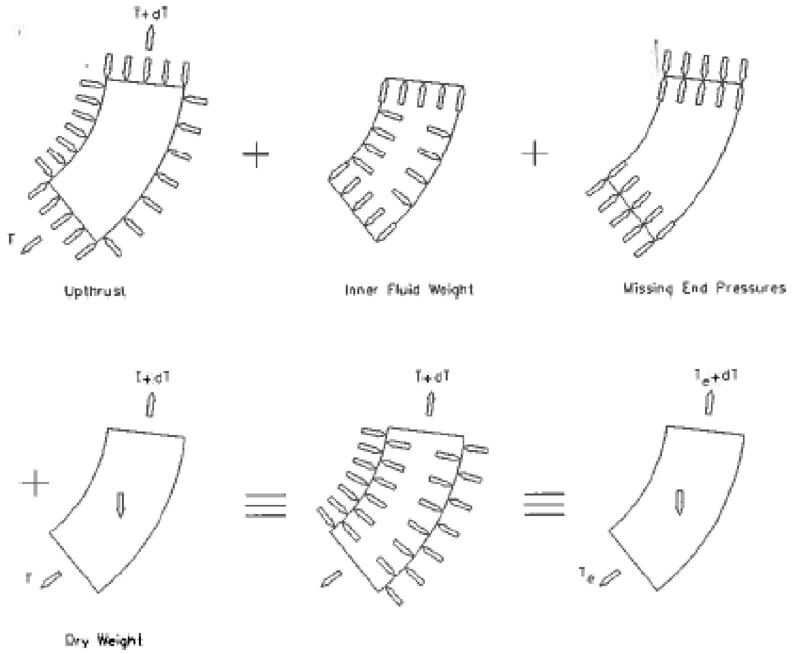


Figure 5-1 Effective weight and tension [Barltrop, 1998]

The formulae for effective weight and tension are:

$$W_{eff} = \gamma_s A_s + \gamma_i A_i - \gamma_o A_o \tag{5.1}$$

$$T_{eff} = T_t + P_o A_o - P_i A_i - \rho_i u_i^2 A_i \tag{5.2}$$

Where:

γ weight density
A area

P	pressure
T	tension
ρ	mass density

and subscripts:

i	internal
o	external
s	structural
t	true

Prescribed Displacement

Volume forces and specified displacement from stressfree to final position of terminal points are included in the catenary start solution. This iterative approach on boundary condition will give deviations between specified translating boundary condition i.e. x- and y- coordinate and boundary conditions computed by the catenary analysis.

Further, specified boundary conditions for rotations at the supports will not be satisfied by the catenary analysis due to neglection of bending stiffness. The final position is therefore found by application of prescribed displacements from catenary solution to specified positions.

Specified Forces (nodal point load)

Specified forces are used for the system where additional forces are applied to riser. One example is top tension force which is applied at the top end of riser in order to keep the riser in tension in any cases. It is normally applied for Top-tensioned riser system. In SCR system, tension force of riser relies on its submerged weight. No additional tensioner is applied to SCRs. Therefore, in this particular case, specified forces are not considered.

Displacement dependent forces (current loading)

For completion of equilibrium static configuration, steady current is applied in order to consider the relative magnitude of these forces in comparison to the effective weight.

In order to perform static riser analyses, a nonlinear finite element approach is normally performed. The FE approach for SCR static configuration are analysed in the order of volume forces (1)-prescribed displacement (2)-displacement dependent forces (4). Figure 5.2 below shows the sequence of establishing equilibrium static configuration.

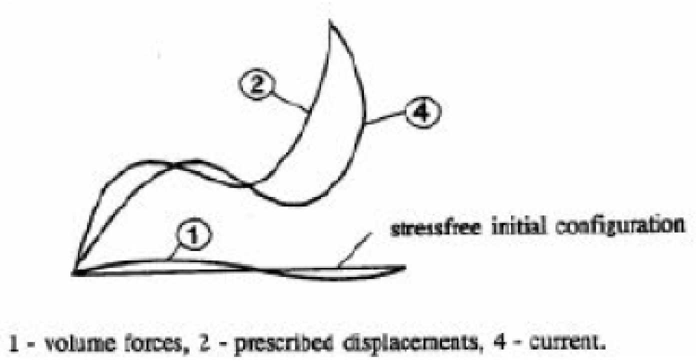


Figure 5-2 Default increment loading sequence [Riflex Theory Manual, 2005]

The static riser profiles are derived for near, mean, far locations of the host platform. The static profiles give an idea of the behaviour of riser under dynamic analysis. It is important to establish smooth transition at touch down area to prevent any excessive dynamic bending moment.

5.2.3 Dynamic Analysis

Steel Catenary Riser is the system that exposed to highly dynamic behaviour due to environmental loading from wind, waves and current. Actions induce loads in a SCR both directly through wave and current action on each segment of riser and indirectly through motion of suspension points on a floating vessel.

Furthermore, in slender marine structures such as riser, there are some nonlinear effects that must be considered in dynamic analyses [DnV, 2001]:

- Geometric stiffness (i.e. contribution from axial force to transverse stiffness).
- Nonlinear material properties.
- Hydrodynamic loading according to the generalized Morison equation expressed by relative velocities.
- Integration of loading to actual surface elevation.
- Contact problems (bottom contact, riser collision, vessel/riser,etc)

In addition, nonlinearities will be decisive for the statistical response characteristics for systems exposed to irregular loading [DnV, 2001]. Therefore, it is important to treat all the nonlinear effects in a correct way according to design criteria.

Table 5.1 below is the available techniques for dynamic finite element analysis:

Table 5-1 Dynamic Finite Element Analysis Techniques

Non-linear time domain	**Linearized time domain**	**Frequency domain**
non-linearities are evaluated at each time step and incorporated directly in the dynamic solution	Linearization of the dynamic equilibrium equations (stiffness, damping, inertia)-i.e. structural linearization	Linearization of stiffness, damping, inertia and external forces at static equilibrium position- i.e. structural and load linearization
Stiffness, damping, inertia and external forces are updated at each step	Stiffness, damping, inertia matrices are kept constant.	Stiffness, damping, inertia, and external forces matrices are kept constant
Give a good representation of a possible non-Gaussian response	Give a good representation if hydrodynamic loading is the major nonlinear contribution	Give a good representation of a possible Gaussian response
Application to the systems that undergo large displacements, rotations or tension variations or in situations where description of variable touch down location or material nonlinearities are important	Application to the tensioned risers with moderate transverse excursions	Not recommended for extreme response prediction. Main application to fatigue calculations and long-term response statistics to identify design conditions to be applied in time domain analyses

According to table comparison given above, for SCR strength analysis in deepwater field and harsh environmental conditions where large displacement, rotations and sensitivity in touch down area, non-linear time domain is best suited. Extremely time consuming in this method can be reduced by varying length of segment along different region of riser and time step.

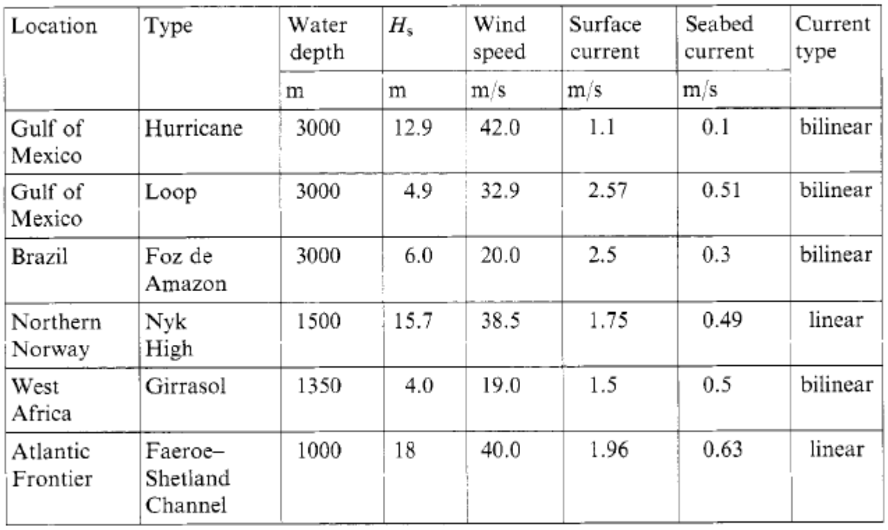
5.3 SCR Design Conditions

There are some important parameters for SCR design.

5.3.1 Environmental Conditions

The environmental conditions vary all over the world. The design of offshore structures may be significantly different from one location to another. Examples of wave, wind and current data for a few offshore deepwater sites worldwide are presented in table 5.2.

Table 5-2 Extreme environment criteria for various locations [Moros and Fairhust, 1999]



Location	Type	Water depth	H_s	Wind speed	Surface current	Seabed current	Current type
		m	m	m/s	m/s	m/s	
Gulf of Mexico	Hurricane	3000	12.9	42.0	1.1	0.1	bilinear
Gulf of Mexico	Loop	3000	4.9	32.9	2.57	0.51	bilinear
Brazil	Foz de Amazon	3000	6.0	20.0	2.5	0.3	bilinear
Northern Norway	Nyk High	1500	15.7	38.5	1.75	0.49	linear
West Africa	Girrasol	1350	4.0	19.0	1.5	0.5	bilinear
Atlantic Frontier	Faeroe–Shetland Channel	1000	18	40.0	1.96	0.63	linear

According to table 5.2, Gulf of Mexico without considering hurricane, Brazil and West of Africa are considered to be mild environments. Northern Norway and Atlantic frontier are considered to be harsh environment with significant wave height reaches 15m and strong current speed more than 1 m/s. Therefore, in this study, typical **Northern Norway environment** criteria are used to simulate the most challenging Steel Catenary Riser design.

Sea water

The water depth considered in this study is 1000m, with sea water density, ρ_{sw}, is 1025 kg/m^3.

Current

In typical slender structures such as marine riser or mooring lines, currents are the sources of significant loads. There are a number of different currents including tidal currents (astronomical tides), circulation currents (oceanic-scale circulation patterns), storm generated currents, loop and eddy currents. The vector of these currents is the total currents.

In deep water, tidal currents and storm surge currents become proportionately less important. However, the total current may still be very significant, such as in certain geographic areas e.g. Norwegian water where strong surface current velocity of about 1 m/s can be observed due to a sudden outflow of brackish water from the Baltic into the North Sea [Barltrop, 1998].

The current velocities vary with depth being maxima at the surface and vary with directions. For simplicity, in this study, current velocities are considered to be identical with directions.

By considering above theories, the current velocities for 10-year return period to be used in global strength analysis are provided in table 5.3 below:

Table 5-3 Current Velocities

Depth (m)	Current velocities – 10 year storm (m/s)
0	0.93
-50	0.68
-300	0.47
-1000	0.00

Waves

For offshore structure, wind-driven waves are a major component of environmental forces. For marine riser system, where the structure is attached to floating vessel, waves have both direct impact to riser and indirect impact from floater motions due to wave induced.

In global strength analysis, design storm concept with probability of exceedance 10^{-2} is considered. An appropriate formulation of the design storm concept is to use the combinations of significant wave height (H_s) and peak period (T_p).

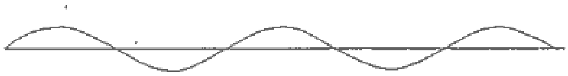
Typical Northern Norway wave parameters for 100-year return period are considered in this study and are given as follows:

- Significant wave height (H_s) : 15m
- Peak period (T_p) : 16s

When considering waves as loads to structure, there are two different approaches; regular waves and random waves (irregular waves).

Regular waves have the characteristics of having a period such that each cycle has exactly the same form. The simplest regular wave theory is linear or Airy waves where the ratio amplitude/length (known as steepness) is sufficiently small. The surface profile can then be well approximated by a sine wave. Due to small steepness, the applications of Airy waves are limited to low sea-states (1 yr storm), fatigue analysis or swell.

The higher wave heights resulting from larger storms require application of second-order theory or higher. Some theoretical wave profiles are shown in figure 5.3.



(a) Airy wave: deep water, small wave steepness

(b) Stokes wave: deep water, large wave steepness

(c) Cnoidal wave: shallow water

(d) Solitary wave : limit curve for cnoidal wave, when the period tends to infinity

Figure 5-3 Some theoretical wave profiles [Le Mehaute, 1976]

Furthermore, for deepwater with high waves, fifth-order Stokes wave theory is applied. These involve additional harmonics, which travel at the overall wave celerity and increase in order with steepness, typically up to 5th order. An example of the five components of the wave profile is shown in figure 5.4. The profile becomes vertically asymmetry with more peaked at the crests and flatter in the troughs.

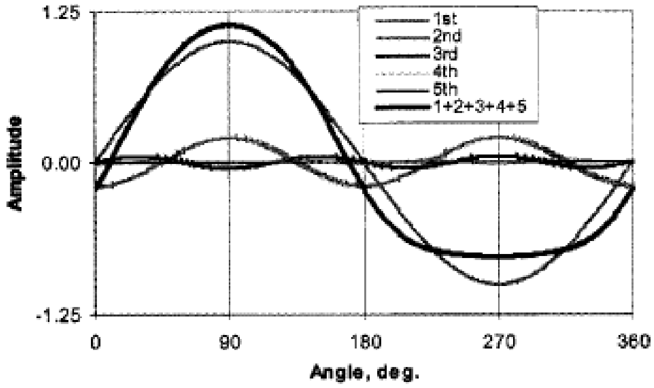


Figure 5-4 Example of five components of velocity for Stokes fifth-order theory

Some applications of fifth-order Stokes wave theory are storm waves, mooring and riser analysis.

In the real environment, wave does not posses a regular wave, but has an irregular form. The random ocean wave can be described by an energy density spectrum. The wave energy spectrum describes the energy content of an ocean wave and its distribution over a frequency range of the random sea. Therefore, for floating structure or slender structure, the random wave method of design is important.

It is decided that in order to accommodate the behaviour of steel catenary riser in high waves and deepwater, **irregular waves** are considered as representative model for wave loading.

The next step is to choose the most representative spectrum formula for typical Offshore Norway environments. There are several wave spectra that have been formulated to date. The most commonly used spectrum formulas are Pierson-Moskowitz model, Bretschneider model, ISSC model, JONSWAP model and Ochi-Hubble spectrum model. Detail description of each wave spectrum is provided in Appendix C. It is important to notice that the response of the structure for the same random wave energy (or equivalently, significant wave height) will be different if different spectrum models are used. It is important to choose the correct spectrum model for one particular location. Table 5.4 below shows the applicability of spectrum model in different offshore locations of the world. This could give an idea of choosing the appropriate spectrum model.

Table 5-4 Common form of spectral models applied to different regions

Location	Operational	Survival
Gulf of Mexico	P-M	P-M or JONSWAP
North Sea	JONSWAP	JONSWAP
Northern North Sea	JONSWAP	JONSWAP
Offshore Brazil	P-M	P-M or JONSWAP
West Africa	Ochi-Hubble	Ochi-Hubble

It is therefore decided to use **JONSWAP spectrum** for typical field development in Northern North Sea.

Table 5.5 below summarizes all the environmental parameters used in this study.

Table 5-5 Environmental parameters Data

No.	Environmental parameter	Description
1.	Offshore location	Northern Norway
2.	Water depth	1000m
3.	Surface current velocity (10-year)	0.93 m/s
4.	Significant wave height (100-year)	15m
5.	Peak period (100-year)	16s
6.	Wave load modeling	Irregular waves
7.	Wave spectrum	JONSWAP

5.3.2 Fluid Properties

Internal fluid properties considered in the analysis is dependent on the type of analysis. During installation of riser, empty pipe or water filled pipe may be considered. During service life of riser, gas or oil or combination of those may be considered.

In this present study, oil with density of 800kg/m^3 has been considered as internal fluid. In addition, the design head pressure of 200bar has been assumed.

5.3.3 Hydrodynamic Coefficients

Hydrodynamic coefficients which consist of drag coefficient (C_d) and inertia coefficient (C_m) are used for calculating wave and current forces impose to structure. The hydrodynamic coefficients are dependent on a number of parameters: body shape, Reynold number (Re), Keulegan Carpenter number (KC), roughness ratio, reduced velocity and relative current number. In common practice, the range of Cd is 0.7 –

0.8. However, the possibility of marine growth on the riser during its life time could change the surface profile to be rough. Therefore Cd of 0.9 is considered in this study. The inertia coefficient used in this analysis is 2.0.

5.3.4 Vessel Motion Characteristics

One of the most important design conditions is vessel motion characteristics. Floater, risers and mooring lines comprise an integrated dynamic system responding to environmental loading due to wind, waves and current in a complex way. In addition, the current loading and damping due to slender structures may significantly influence the low frequency floater motions of deep water mooring system. Therefore, there is a need to consistently consider the coupling effects for SCR design.

In order to consider coupled floater/slender structure dynamics on non-linear system, irregular wave frequency (WF) and low frequency (LF) environmental loading shall be considered [DnV, 2001]. The most direct way to incorporate this effect is called *coupled analysis* where the series of combined WF and LF floater motions computed by the floater motion analysis used as boundary conditions in the slender structure analyses. Another approach is to apply WF floater motions as dynamic excitation while LF floater motions are accounted for by an additional offset. This method is used by assuming the slender structure will respond quasi-statically to LF floater motions. Further, Response Amplitude Operations (RAOs) of floater are used to describe vessel response to wave-frequency excitation. This method is normally referred as de-coupled floater motion analysis.

The coupled analysis is considered to be a more accurate analysis and less conservative method [Rodrigues, M.V. et al, 2008]. However, it requires an excessive computational effort. Therefore, for simplicity purpose, the traditional **de-coupled floater motion analysis** is considered in this study.

Host platform selection

TLPs have served most of SCR applications for typical mid to deep water depth in offshore Gulf of Mexico and Brazil [Bai, 2005]. One of the reasons for having TLP as host platform of SCR is relatively low drift motions of up to 9% of water depth. In comparison, FPSO slow drift motions can be 20%-30% of water depth depending on mooring stiffness [Alderton and Thethi, 1998]. FPSOs production services have been used in several fields in offshore West Africa such as in Bonga, Erha and Dalia field. As the oil and gas explorations are moving into deeper water and harsher environment, the use of semi-submersibles as floating production unit have increased. The slow drift motion of Semi-submersible can be 10-15% of water depth. Relatively high vessel offset for semi-submersible results in challenge for SCR design because the riser tension at the vessel becomes too great as the vessel drifts away from the touch down point (far load case) or the bending stresses near the seabed become too great as the vessel drifts towards the touch down point (near load case).

As deep water and harsh environment have been selected in this study, and looking at the trend of using semi-submersibles as floating unit for future SCR applications, attention is focused on **SCRs attached to semi-submersible vessels**.

Vessel offsets

Vessel static offsets are applied due to the assumption of the slender structure will respond quasi-statically to LF floater motions. Offsets to near and far side are considered in this study. Offset to transverse direction is not considered because only one single riser is studied i.e. no interference issue. The following vessel offsets are used for strength analysis:

- Operational condition – Intact mooring : 10% water depth
- Accidental condition – One mooring line failure : 12% water depth

Vessel RAOs

In order to consider dynamic excitation from WF floater motions, RAOs of semi-submersibles are applied to all steps of design analyses.

5.3.5 Riser Data

Riser properties

In this study, production riser with inner diameter of 10 inch is considered. It is an X65 carbon steel pipe with density 7850 kg/m^3. The outer diameter and wall thickness vary along the riser.

Material properties for X65 carbon steel are provided as follows:

- Yield stress at 20^o C SMYS = 448 MPa
- Steel Young's modulus E = 207000 MPa

Riser coating

Riser coating is applied uniformly along the riser for conventional SCR configuration.

- Riser coating wall thickness : 100mm
- Riser coating density : 800 kg/m^3

In reeled lay installation technique, riser coating wall thickness is limited to 100mm in order to avoid any damage one the outer surface of coating [Karunakaran et al, 2005].

Riser configurations

The SCR is hanging from outside the pontoon as shown in figure 5.5.

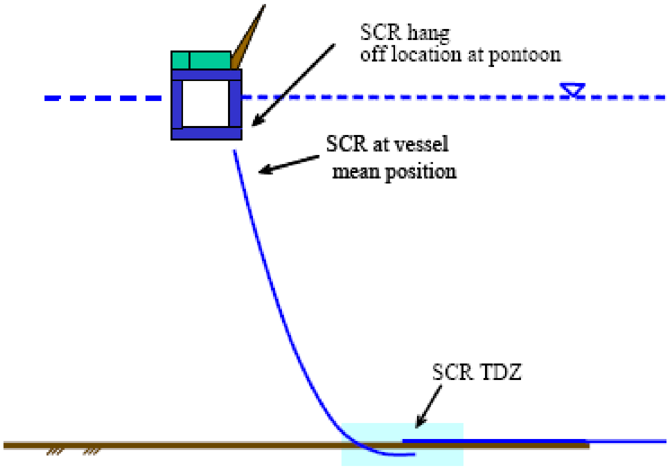


Figure 5-5 Riser Hang-off from Pontoon

Positioning of the riser on the host platform is important. In any offshore location, the most govern environmental loading occur from certain directions. It is also the case for offshore Norway where the most severe environment comes from North, North

West, West and Southwest. Therefore, in this study, SCR is placed in North western part of host platform in order to have the worst combination for SCR design. Figure 5.6 shows the riser orientation on the top connection to host platform.

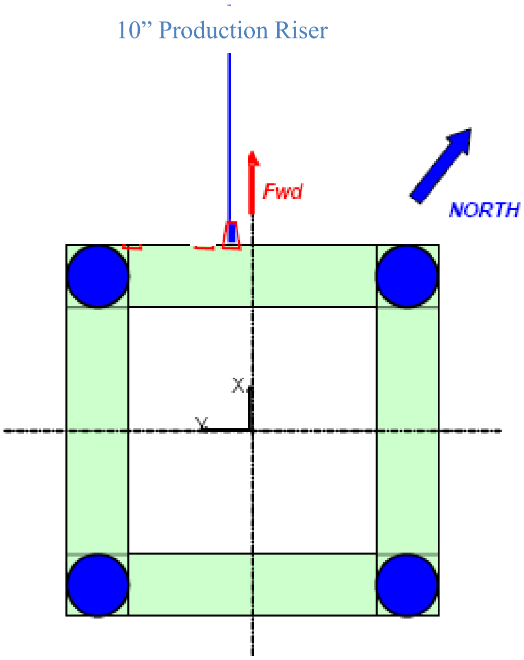


Figure 5-6 Riser Orientation

The production riser is placed 2m from the centre of the vessel and 20m below the mean sea level. Top angle of 15^{o} is defined in vessel mean position.

5.3.6 Soil-Riser interaction

Soil-riser interaction is important especially at touch down zone. The oscillatory motion of riser makes the interaction between soil and riser becomes complex. Further, the riser TDP locations move when the host platform changes its draft or moves between near and far positions. As a result, the interaction between riser and soil during riser's life time comprises over a wide range of region in a complex way.

The following soil parameters are used for strength analysis:

- Lateral friction coefficient : 0.5
- Lateral soil stiffness : 10 kN/m^2
- Vertical soil stiffness : 600 kN/m^2

5.4 SCR Wall Thickness Sizing

The wall-thickness for SCR is calculated in the first step of design. It shall be designed to withstand pressure containment (burst criteria) and collapse criteria. In addition, corrosion allowance shall be considered. For deep water field development, resistance to collapse is the major driver for deciding minimum wall thickness. Reference is made to chapter 4; section 4.2.3 for collapse resistance criteria according to API RP 2RD and section 4.3.2 for burst and collapse criteria according to DnV-OS-F201.

Table 5.6 below shows the minimum wall thickness requirement for 10” ID, X65 material steel grade and internal design pressure of 200bar. Detail calculation is provided in appendix B.

Table 5-6 Minimum Wall Thickness Requirement

API-RP 2RD		**DnV OS-F201**			
Hydrostatic collapse (mm)	**Collapse propagation (mm)**	**Burst – operation (mm)**	**Burst - system test (mm)**	**Collapse (mm)**	**Propagating buckling (mm)**
13.3	20.5	12	11	13.3	21.3

It is interesting to see that the result from API and DnV for minimum wall thickness required to resist hydrostatic collapse is shown to be equal (13.3mm). The highest requirement for wall thickness is given by propagating buckling (21.3mm). In order to keep local buckle remains local and does not lead to successive collapse of neighboring pipe section, relatively thick section is required. It is the reason why propagating buckling appears to be the driven criterion. In practice, it will not be economical to design the riser that can have ability to prevent propagating buckling by its own section, because it can easily be prevented by providing buckle arrestor at some critical regions. The same principal is used in this study; hence, minimum wall thickness of 14mm is used.

5.5 SCR Structural Modelling

In order to keep the SCR design as simple and economical as possible, a simple free hanging catenary shape is considered. The riser upper end is connected to a semi-submersible at 20m below mean sea level and the bottom end is connected to subsea flowline.

Riser boundary condition
At top-end of riser, flex-joint is incorporated to allow rotation of riser. Hence, pinned connection is defined at the connection to host platform. At the low far-end of the riser on the seabed, fixed connection is defined to model riser end termination.

Riser length
The total riser length is 2900m. The main concern in deciding total length of riser is to accommodate riser configuration for both near and far vessel offset.

Riser segment
Riser is segmented for finite element analysis. The purpose of this is to obtain an adequate representation of riser behaviour. Therefore, it is important to define sufficient riser segment at some critical regions such as at top-end, sag-bend and touch down area. Too long riser segment in highly dynamic region will cause instability results.

Critical region (top-end, sag-bend, TDA) : 2-3m riser segment long
Uncritical region (straight section, flat bottom end) : 5-10m riser segment long

Riser wall thickness
Two riser configurations are studied for conventional SCR. First configuration uses uniform wall thickness and uniform riser coating, meanwhile second configuration

uses varied wall thickness but uniform riser coating. Table 5.7 presents the detail of those two configurations.

Table 5-7 Riser Segment Definitions

Segment Name	Segment Length (m)	Wall Thickness (mm)	
		Configuration 1	Configuration 2
Up	200	25.4	25.4
Straight	950	25.4	25.4
Sag-bend Intermediate	25	25.4	22
Sag-bend light	300	25.4	19
TDA	250	25.4	19
Bottom	1175	25.4	25.4

5.6 SCR Strength Analysis

SCR strength analysis is performed to check the extreme response of SCR under static and dynamic structural behaviour to meet the design code limit. SCR is analyzed for operating extreme and accidental condition. The strength analyses are performed for both near and far position vessel offsets with 100-year wave and 10-year current. Only extreme storm case is discussed in this section as a starting point.

RIFLEX structural finite element analysis program developed by SINTEF is used as a tool for analyses and calculations. Detail description of RIFLEX program is provided in Appendix A.

5.6.1 Analysis Procedure

The SCR strength check is analysed by following some procedures as provided below:

- Three different models are prepared according to vessel offset: mean, near and far.
- Wave direction from 0 degree and 180 degree is respectively applied to simulate the worst combination for near and far load case. Lateral load case is not considered in this present analysis.
- The SCR is modeled by FEM principles using discrete beam elements.
- Static riser configuration is established by considering volume forces (weight and buoyancy), specified displacement and current forces.
- Nonlinear time domain analysis and irregular wave theory are applied for dynamic response analysis. Newton-Raphson approach is applied to establish dynamic equilibrium equations. The riser configuration and tension are calculated at each time step by an iterative procedure.
- The dynamic output results, e.g. axial and bending stress, Von Mises stress, displacements, are checked against the design limit from API-RP-2RD as well as DnV-OS-F201.

5.6.2 Static Analysis

In this section, riser configurations, static tension force and static bending moment for mean, near and far vessel offsets are discussed and presented in figure 5.7, 5.8, 5.10 respectively.

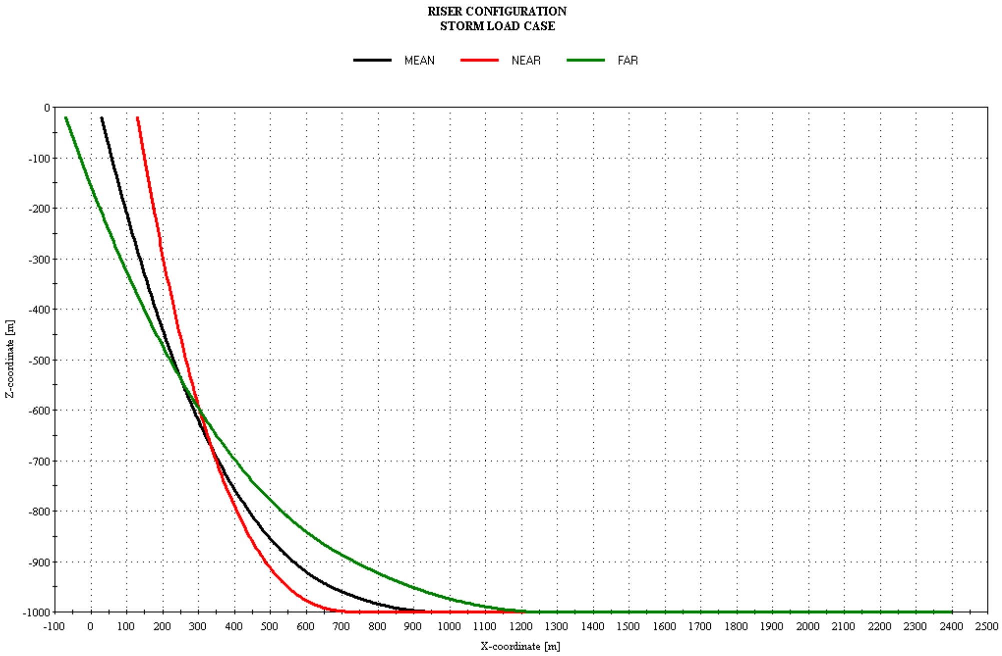


Figure 5-7 Riser configurations

It can be observed from the figure that vessel offsets have significant effect on riser configurations. An important design consideration with respect to SCR strength design is the significant change in location of TDP from near load case to far load case. This might result in significantly different dynamic behaviours. Further, it is important to notice that the higher the water depth is the more extreme the vessel offset which will be the problem for ultra deepwater development (>2000m WD).

The static effective tension for configuration 2 with variation in wall thickness is presented in Figure 5.8.

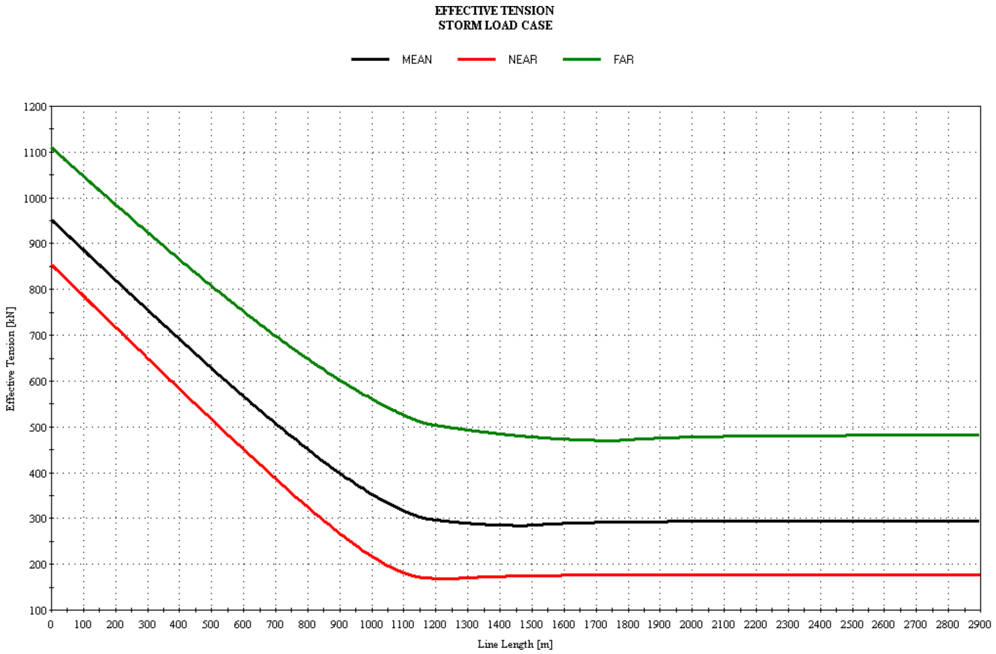


Figure 5-8 Static Axial tension forces – Configuration 2

Static tension force is simply a function of suspended riser length. Far load case has the highest static tension due to its longest suspended length compared to mean and near case.

Figure 5.9 presents the comparison of static axial tension forces between configuration 1 and configuration 2. Only mean load case is compared.

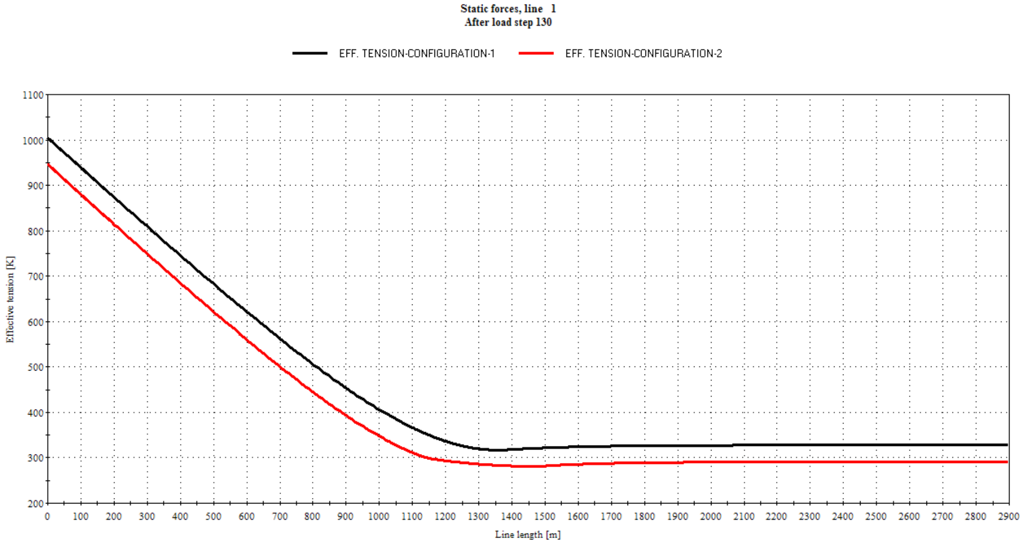


Figure 5-9 Static Effective Tensions – Configuration 1 and Configuration 2 (Mean Case)

Distribution of SCR's weight by varying wall thickness in configuration 2 results in lighter effective tension than uniform wall thickness along the riser in configuration 1. It is mainly because configuration 2 uses smaller thickness at some locations (see table 5.7).

Figure 5.10 presents static bending moment for configuration 2 for all load cases.

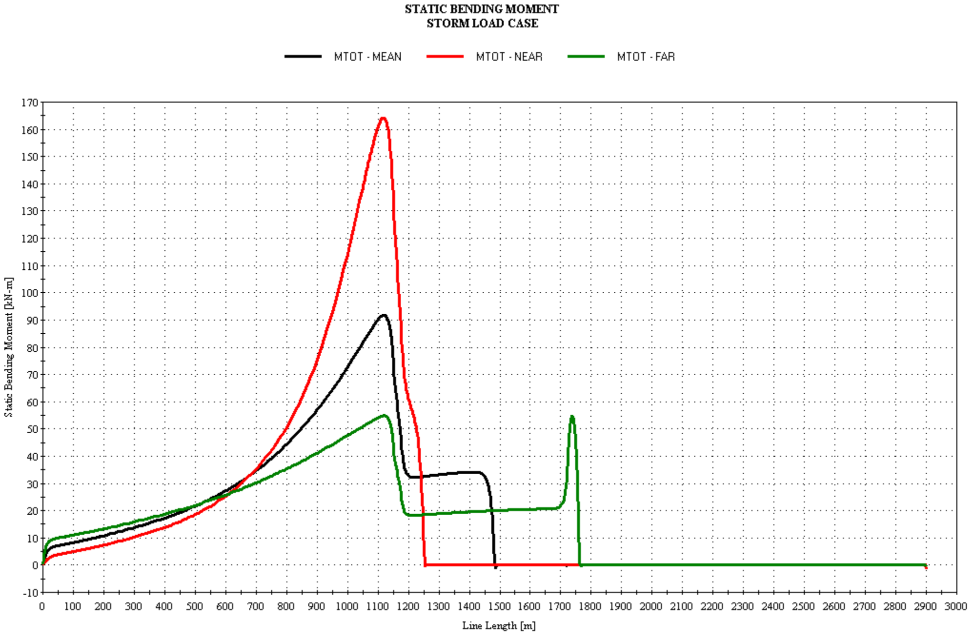


Figure 5-10 Static Bending Moment – Configuration 2

In near load case, the distance from host platform to TDP is the closest. This results in small sag-bend curvature i.e. high static bending moment as shown in figure 5.10. On the other hand, with high sag-bend curvature for far load case, the static bending moment is significantly low. In addition, due to its long suspended pipe, it allows the riser to have two peaks of bending moments; at the end of heavy segment and at TDP.

All riser configurations have static bending moment maximum at 1150m arc length. This is the location of transition from 25.4mm wall thickness (heavy segment) to 19mm wall thickness (light segment). This is a good indication in distributing the bending moment's peak i.e. not only concentrated at TDP.

Figure 5.11 presents the comparison of static bending moment between configuration 1 and 2. Only mean load case is compared.

Figure 5-11 Static Bending Moments – Configuration 1 & Configuration 2 (Mean Case)

It can be analyzed that configuration 2 has static bending moment peak at the end of heavy segment, a sudden drop to some level of bending moment and continues with constant bending moment for about 300m until touch down point. This indicates that there is distribution of bending moment for configuration-2. Meanwhile, configuration-1 has a sudden drop just after TDP. This indicates a concentrated bending moment.

5.6.3 Dynamic Analysis

Nonlinear time domain analysis with irregular waves is considered to analyze dynamic response of SCR. Three hour time simulations with time step of 0.11s have been applied in order to simulate extreme 100-year storm with sufficient computer simulation.

The results from dynamic analyses that have best interest for strength analysis are effective tension force and dynamic bending moment. For total effective tension, far load case given the highest force. It has already been identified from static effective tension (Figure 5.8). The envelope effective tension curve from configuration-2 for far load case is provided in Figure 5.12.

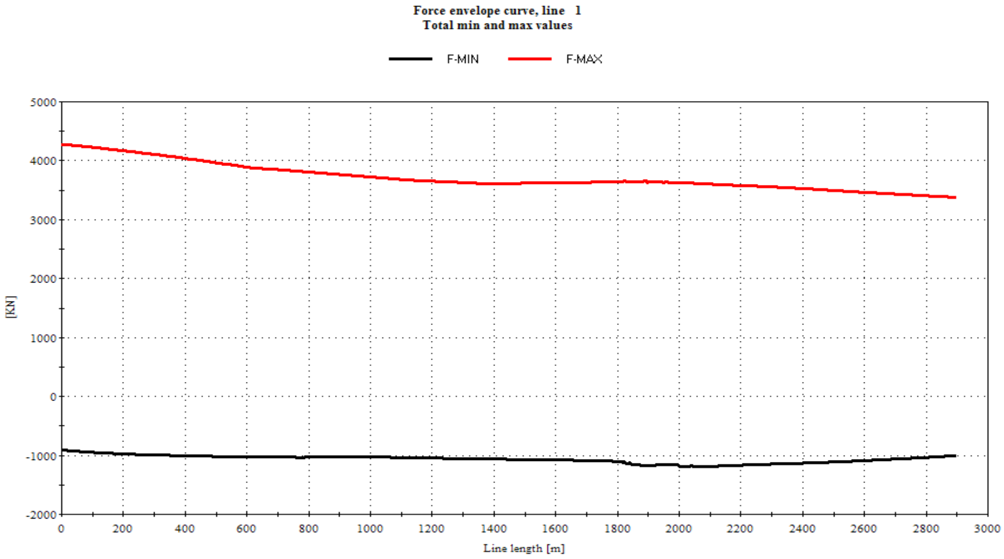
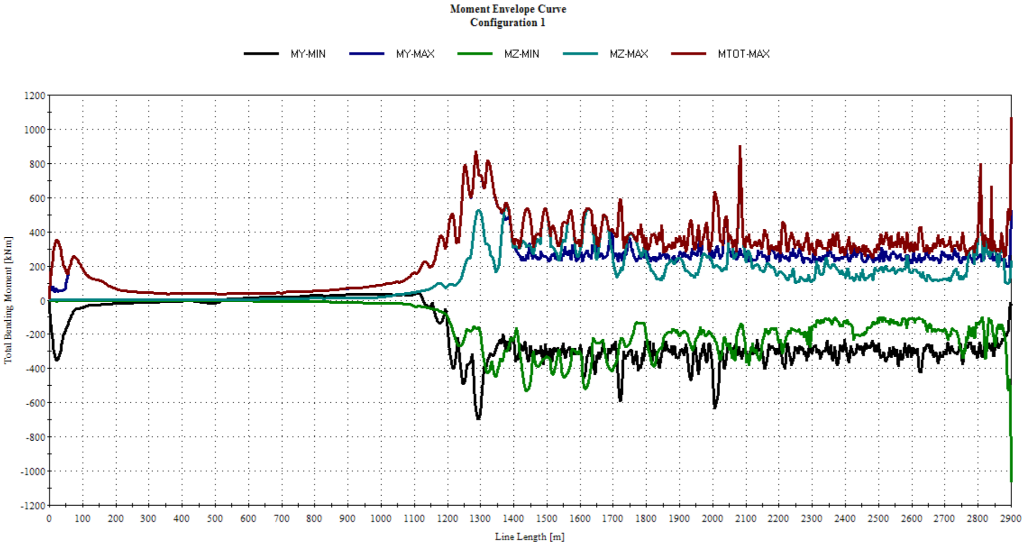


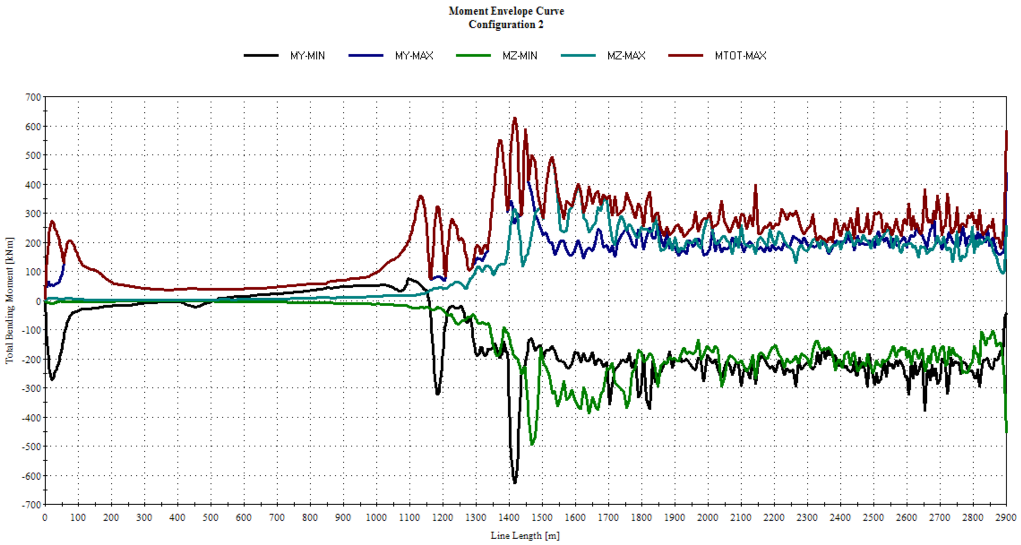
Figure 5-12 Dynamic Axial tension forces – Configuration 2 (Far Load Case)

From the figure, it can be observed that the minimum tension force is negative i.e. compression force. Compression force at TDP is not expected for SCR. Therefore, it is important to optimise the riser configuration and avoid any compression at TDP.

It is observed that near load case gives the highest bending moment than mean and far load case. Envelope bending moment curve from configuration 1 and configuration 2 for near load case are given in figure 5.13a and 5.13b respectively.



(a)



(b)

Figure 5-13 Dynamic Bending Moments (a) Configuration 1, (b) Configuration 2

In configuration-1, it can be analyzed that there is only one peak of bending moment, which is located at TDP. Meanwhile in configuration-2, there are two peaks which are located at the end of heavy segment and at TDP. The ability to distribute the bending moment in configuration 2 results in lower maximum bending moment, from 800 kNm in configuration-1 to 600 kNm in configuration-2. Furthermore, the pipe on the seafloor is unstable, indicated by the curly curve after TDP for both configurations.

5.6.4 Stress Check

LRFD and WSD codes are used to check the stresses acting on the riser. Table 5.8 and 5.9 present the stress check in storm condition for WSD code and LRFD respectively.

Table 5-8 SCR Strength Check - WSD

Load Case	**Configuration 1**		**Configuration 2**	
	VM Stress (MPa)	**Interaction Ratio**	**VM Stress (MPa)**	**Interaction Ratio**
Mean	674	1.88	635	1.77
Near	957	2.67	857	2.39
Far	1050	2.93	604	1.68

Table 5-9 SCR Strength Check - LRFD

Load Case	**Configuration 1**		**Configuration 2**	
	Utility – L.comb A	**Utility – L.comb B**	**Utility – L.comb A**	**Utility – L.comb B**
Mean	1.13	1.88	1.16	1.99
Near	1.62	2.65	1.46	2.47
Far	1.70	3.01	1.00	1.72

In configuration-1, far load case gives the highest Von Mises Stress compared to other load cases. This is mainly driven by long suspended length. Direct comparison to configuration-2 shows that far load case gives the lowest Von Mises stress. This is because thin wall thickness (19mm) was applied along the touch-down region. It can be concluded that providing light segment along touch-down region could improve the SCR response significantly.

Configuration-2 gives the indication that variation in wall thickness results in better riser performance than uniform riser wall thickness. However, the stress ratio from configuration-2 is still above the limit.

From table 5-9, there is significant difference in utility given by load combination A and load combination B. Load combination A uses factor of 1.2 for functional load and 0.7 for environmental load, meanwhile load combination B uses factor of 1.1 for functional load and 1.3 for environmental load. Since deepwater riser is highly dynamic with mostly affected by environmental load, the load due to environmental load is so much higher than functional load. This leads to load combination B as the most governing combination with the factor of 1.3 for environmental load.

The results from WSD code and LRFD code show small difference in utility, particularly for the structure that is highly governed by environmental load.

It is clearly observed that SCR with conventional uniform coating does not cope with deepwater and harsh environments. The stresses are too high above the material strength. As a result, significant solution to SCR design is required. Chapter 6 will provide a solution study to this issue and chapter 7 will focus on the study of optimisation SCR design in deepwater and harsh environments.

5.7 Discussion and Conclusion

Deepwater offshore Norway with harsh environments has been considered for conventional SCR design. Unrestricted motion from semi-submersible is applied as host platform for SCR in order to complete the worst design condition. Irregular waves with JONSWAP spectrum is applied for dynamic non-linear time domain analysis. Typical production SCR with 10” inner diameter, material grade of carbon steel X-65, 100mm riser coating with density of 800kg/m^3 are considered.

- The initial sizing of wall thickness is controlled by collapse pressure. It is the case for deepwater application because external hydrostatic pressure increases linearly with water depth. Further, the SCR wall thickness is not designed to withstand propagating buckling by its own properties because this issue can simply be solved by providing buckle arrestor at some critical locations. In addition, there are not much different results for calculating required wall thickness from API-RP 2RD and DnV-OS-F101 method
- There is not much difference in results given by WSD code and LRFD code, especially for for typical slender structure in active enviroments.
- The concept of applying heavy segment before sag bend region and light segment around touch-down region improves the SCR response. However, weight distributed concept by only varying wall thicknesses are not good enough. Therefore, conventional SCR design is hardly applied for deepwater and harsh environments. Significant solutions are required and provided in the following chapter.

CHAPTER 6 DEEPWATER WEIGHT DISTRIBUTED SCR STRENGTH DESIGN AND ANALYSIS

6.1 Introduction

The conventional SCR configuration shows inadequate performance to strength design. Highly dynamic movement of SCR due to extreme environments is one of major problems. Several enhancements to the conventional SCR configuration are required to improve SCR strength and fatigue performance.

As a matter of fact, there are two different approaches to reduce excessive bending moment around TDP. One alternative is by attaching some buoyancy modules on sag-bend area in order to provide near-bottom support as an addition to sea-bottom support. Another alternative is by adding more weight at sag-bend region and reducing weight at TDA. This method could reduce the bending moment by establishing smooth riser approach at TDP. There are two ways of varying the weight along the riser; (1) weight distributed by varying external coating density along the riser [Karunakaran et al, 2005], and (2) weight distributed by attaching a numbers of clump weights on the riser [Foyt et al, 2007].

In this present study, weight distributed solution is preferred due to simpler installation. Both weight distributed concepts are performed in this chapter.

6.2 Weight Distributed SCR – External Coating

Weight distributed SCR by coating is basically a simple principle by varying riser external coating densities along the riser. The idea of varying the weight along the riser is to reduce the riser's displacement at TDP. This is achieved by providing heavy segment along the straight line of riser and light segment around touch down region.

6.2.1 Riser External Coating

The coating systems are the primary barrier against the corrosion. Thick coatings are used to resist damage of pipe during transport and installation. The most common coating systems used in the oil and gas industry are:

- Multilayer polypropylene (PP) or polyethylene (PE)
- Polyuretane / syntactic polyurethane (PU)
- Rubber coating

Industry practice has used different types of external coating. Vikoweight coating from Trelleborg Viking is a rubber based weight coating with density of 3000 kg/m^3. This coating is considered to be heavy. In Bonga Project, PP coating with density of 680 kg/m^3 and coating thickness ranging from 34mm – 102mm was used. This coating is considered to be light. There is also limitation in coating thickness if reeled installation method is chosen. Maximum of 100mm coating thickness was identified to prevent damage on outer surface of riser coating. In Roncador project where reeled method was applied, 33mm to 66mm coating thicknesses were used for 8" risers. Full scale reeling test have also been successfully carried out for 12" pipes with 88.9mm coating thickness [Karunakaran et al, 2005].

In summary, a wide range of riser coating have been applied in offshore industry. This gives a flexible design variation for weight distributed SCR coating.

6.2.2 External Coating Application on Weight Distributed SCR

In order to achieve weight distributed SCR; there are four different external coating densities:

- Heavy coating (H) : 2800 kg/m^3
- Intermediate coating (I) : 1500 kg/m^3
- Normal coating (N) : 800 kg/m^3
- Light coating (L) : 670 kg/m^3

All defined riser coatings densities have been qualified for use. The riser external coating thickness is 100mm.

6.2.3 Riser Structural Modelling

Minimum wall thickness of 14mm that was calculated from chapter 5 is considered as lower limit. The riser segment is defined based on wall thickness and coating density. The defined segments are provided in Table 6.1 and figure 6.1.

Table 6-1 SCR Segment Definitions (Distributed Coating SCR)

Riser Segments	Segment Name	Wall thickness (mm)	Density Coating
Upper	Up-N	25.4	Normal
Straight	Straight-H	25.4	Heavy
Sag-bend	Sag-H	25.4	Heavy
TDZ-top	TDZ-I	25.4	Intermediate
TDZ-low	TDZ-L	19	Light
Bottom	Bottom-N	22	Normal

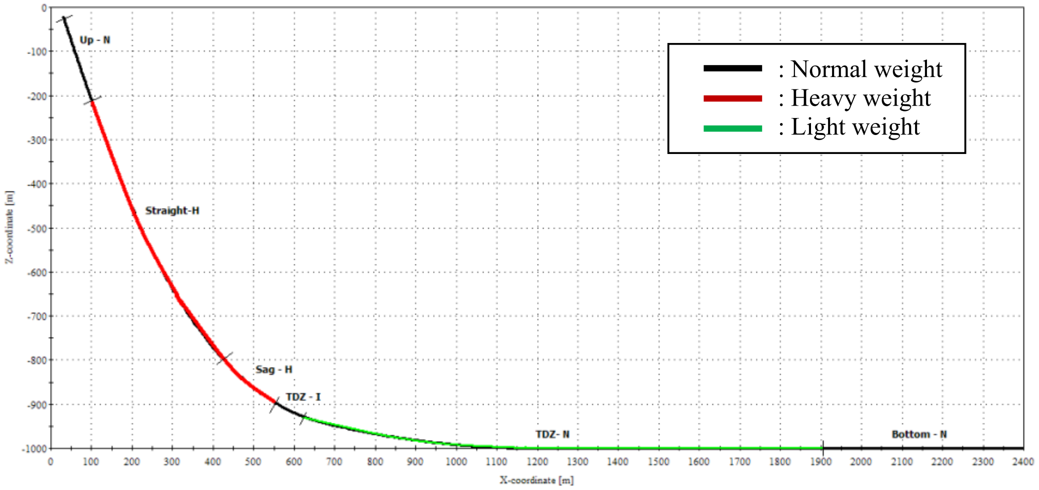


Figure 6-1 SCR Segments Definition

<u>Riser configurations</u>

Figure 6.2 shows riser configurations for mean, near and far vessel offsets.

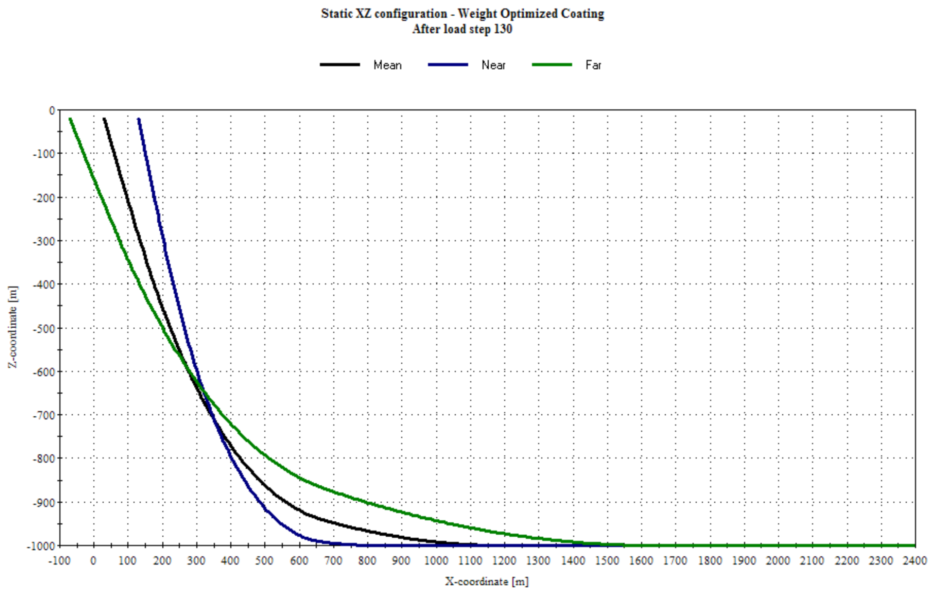


Figure 6-2 SCR Configurations – Weight Distributed SCR Coatings

6.2.4 Strength Design

Conventional SCR design from chapter 5 indicated that the driven parameter design is bending moment at TDP. Therefore, the study on weight distributed coating is started from near load case. Table 6.2 provides the different case studies for near load case.

Table 6-2 SCR Configuration Study Weight Distributed Coating (Near Case)

Case	Up-N	Straight-H	Sag-H	TDZ-I	TDZ-L	Bottom-N	VM Stress (MPa)	Interaction Ratio
A	600	200	100	200	750	1050	520.4	1.45
B	300	500	100	200	750	1050	505.9	1.41
C	300	750	100	15	700	1035	306.1	0.85
D	300	750	100	25	850	875	290.9	0.81

Increase in heavy segment length reduces maximum bending moment and hence reduces Von Mises stress. This can be observed from case A to case C where the heavy segment was increased from 300m to 850m. Furthermore, the Von Mises stress is reduced when intermediate segment length is increased (Case C to Case D). The purpose of having intermediate segment is to have smooth transition from heavy segment to light segment. SCR configuration given in case D is used for far load case check.

Table 6.3 gives results for far load case according to configuration D.

Table 6-3 SCR Configuration Study Weight Distributed Coating (Far Case)

Case	Up-N	Straight-H	Sag-H	TDZ-I	TDZ-L	Bottom-N	VM Stress (MPa)	Interaction Ratio
D	300	750	100	25	850	875	467	1.30

Configuration D is checked for far load case. The result shows that Von Mises stress is exceeded allowable stress. Detail observation is required for further optimisation.

Figure 6.3 and 6.4 show moment envelope curve and Von Mises envelope curve for configuration D respectively.

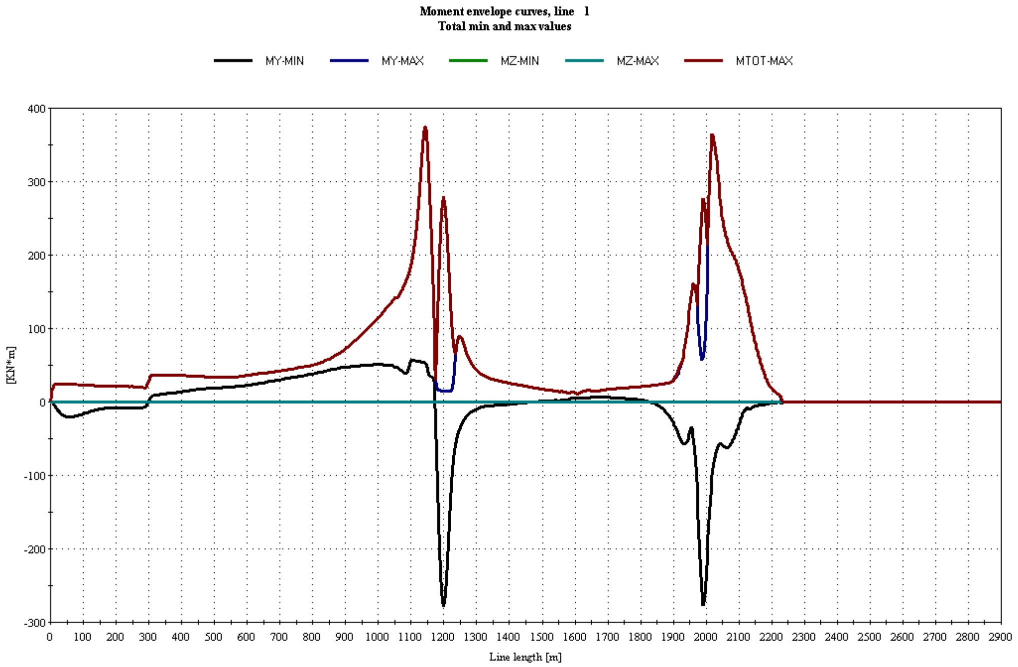


Figure 6-3 Moment Envelope Curve - Configuration D (Far Case)

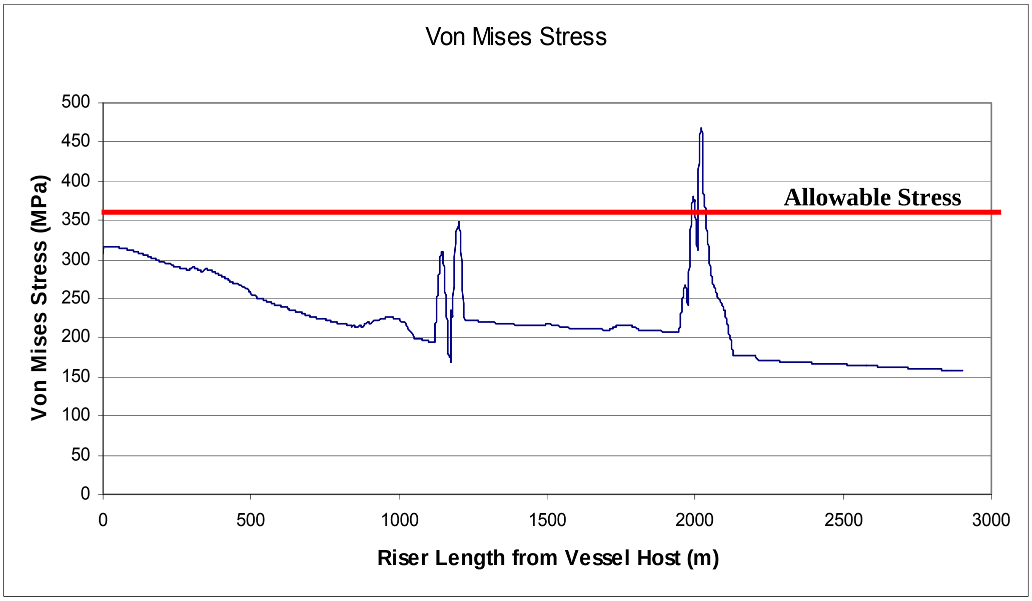


Figure 6-4 Von Mises Envelope Curve - Configuration D (Far Case)

Bending moment envelope curve and Von Mises curve show similar trend along the riser. From the curve, it can be observed that there are two peaks which are located at the end of heavy coating (1150m) and at touch down point (2020m). The transition from heavy segment to light segment is the cause for high bending moment at the end of heavy coating, meanwhile high bending moment at TDP is expected. Figure 6.4 shows excessive Von Mises stress at TDP. It is further observed that TDP falls in

Bottom-N segment with 22mm wall thickness and coating density 1500kg/m^3. Lighter segment is required to reduce bending moment at TDP as it is observed in near load case. Therefore, configuration E is proposed and results are provided for far, near and mean load case (Table 6.4).

Table 6-4 SCR Configuration E Weight Distributed Coating (All Cases)

Case	Up-N	Straight-H	Sag-H	TDZ-I	TDZ-L	Bottom-N	VM Stress (MPa)	Interaction Ratio
Extreme Storm Condition								
Far	300	750	100	25	1150	575	347	0.97
Near	300	750	100	25	1150	575	291	0.81
Mean	300	750	100	25	1150	575	349	0.97
Survival Condition								
Far	300	750	100	25	1150	575	433.1	0.99
Near	300	750	100	25	1150	575	741.7	1.65

Increasing light segment from 850m to 1150m reduces the Von Mises Stress for far load case such that it is within allowable stress. Check on near and mean load cases are also provided and show acceptable results. However, when it comes to survival load case with vessel offset 12% of water depth; highly overstress occurs for near load case. Figure 6.5 shows the comparison bending moment between near load case storm condition and survival condition.

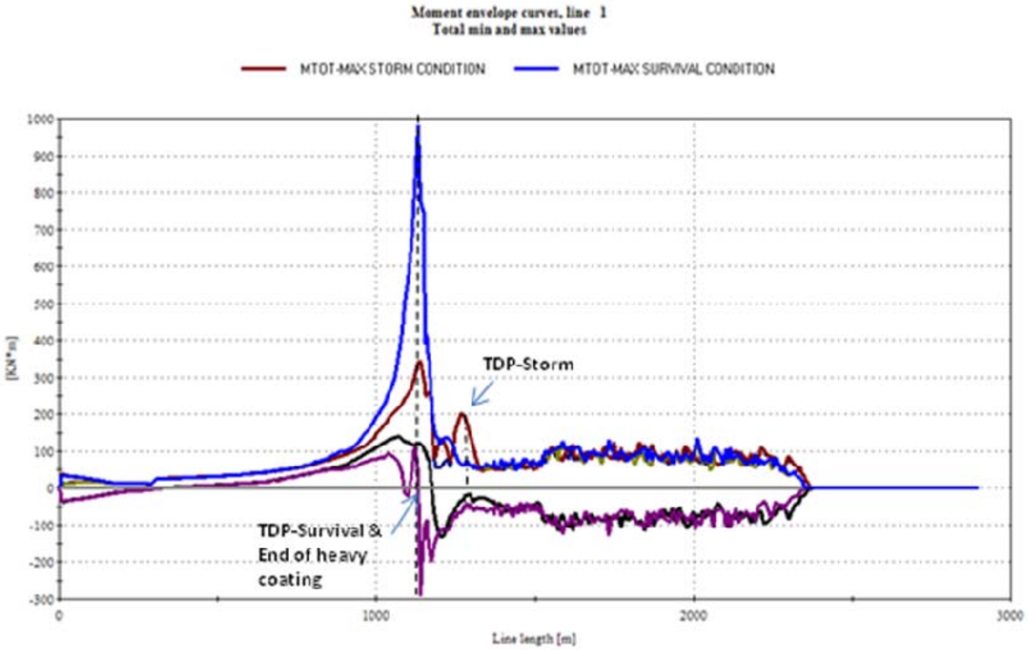


Figure 6-5 Moment Envelope Curve - Configuration E (Storm and Survival Condition)

Amplification in bending moment for survival case occurs because of too close distance between end of heavy coating and TDP. The 120m vessel offset to the near side for survival condition results in even closer distance from host platform to TDP compared to storm condition with 100m vessel offset. It shows from the figure that end of heavy segment is about in the same location as TDP for survival case. In comparison to extreme storm, there is about 100m distance between end of heavy coating and TDP. It is analyzed that over length of heavy segment amplifies the bending moment at TDP significantly.

Configurations in table 6.5 are then proposed with respect to the problem given in near survival case for configuration E.

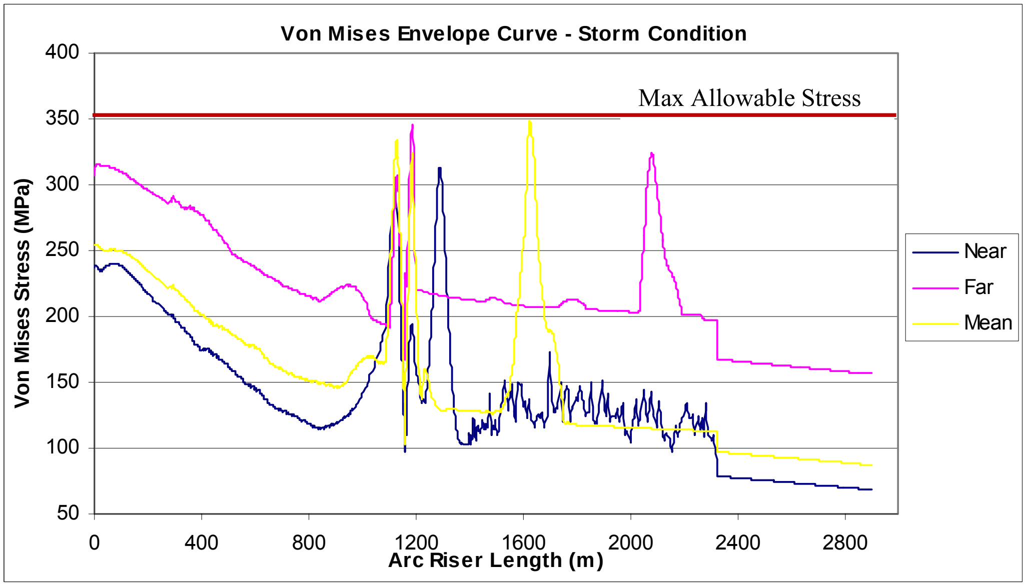
Table 6-5 SCR Configuration Study Weight Distributed Coating–Near Load Case (Survival)

Case	Up-N	Straight-H	Sag-H	TDZ-I	TDZ-L	Bottom-N	VM Stress (MPa)	Interaction Ratio
F	290	750	100	25	1160	575	514	1.15
G	285	750	100	25	1165	575	387	0.86

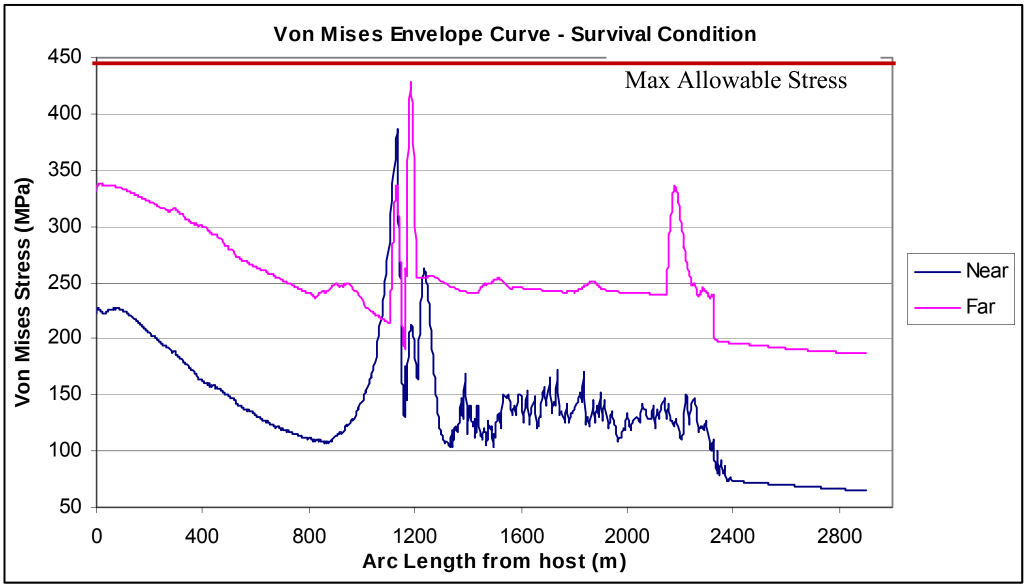
Shifting the heavy segment by 15m such that it has sufficient distance to TDP could reduce the Von Mises stress at TDP significantly. Hence, configuration G is checked for other load cases to complete the analysis.

Table 6-6 SCR Configuration G Weight Distributed Coating - All Cases

Case	Up-N	Straight-H	Sag-H	TDZ-I	TDZ-L	Bottom-N	VM Stress (MPa)	Interaction Ratio
Extreme Storm Condition								
Far	285	750	100	25	1165	575	345.9	0.96
Near	285	750	100	25	1165	575	312.3	0.87
Mean	285	750	100	25	1165	575	347.9	0.97
Survival Condition								
Far	285	750	100	25	1165	575	428.9	0.96
Near	285	750	100	25	1165	575	387	0.86



(a) Storm Condition



(b) Survival Condition

Figure 6-6 Von Mises Envelope Curve – Configuration G (a) Storm (b) Survival

The complete checks on all load cases have been performed and the results show acceptable Von Mises stress for both extreme storm condition and survival condition. Near case has only one peak because end of heavy segment is located close to TDP. Meanwhile, mean load case and far load case have two stress peaks; end of heavy coating and TDP (Figure 6.6a). For mean load case, maximum Von Mises is located at TDP, meanwhile for far load case, maximum Von Mises stress is located at the end of heavy coating. All these situations are very much depending on how the riser weight is distributed. It is proved that weight distributed coating has satisfied the strength design criteria.

6.3 Weight Distributed SCR - Clump Weight

As an alternative to weight distributed SCR by coating, a number of clump weights are attached on the riser as a replacement to heavy coating. This method was proposed by Foyt, E. et al 2007, for typical SCR configuration in conjunction with a turret moored FPSO for West African environment. The clump weights solution has been successfully applied for Mardi Gras Project in Gulf of Mexico [Foyt et al, 2007].

In this present study, application of clump weights will be used for SCR configuration in conjunction with Semi-submersible for Deepwater Offshore Norway environment. This obviously will give some challenges due to its extreme environment compared to West African environment.

The properties of clump weight shall be defined such that it has sufficient weight with relatively small buoyancy. Unlike buoyancy module that uses positive buoyancy to form a wavy shape, clump weight solution relies on its weight to provide heavy segment at straight part of the riser. It is still the same principle which is to avoid concentrated and excessive bending moment at TDP.

6.3.1 Clump Weight Properties

A simple clump weight as shown in Figure 6.7 is proposed [Foyt et al, 2007]. The properties given below used in the analysis:
Length : 1.5 m
Weight: 4 ton/m

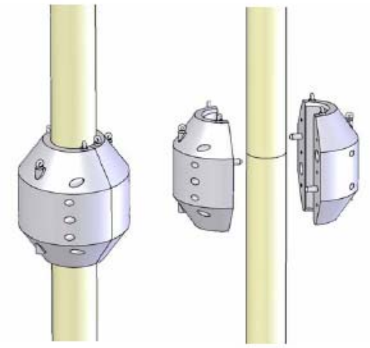


Figure 6-7 Description of Clump Weight [Foyt et al, 2007]

6.3.2 Clump Weight Modelling

One clump weight is required per joint (12m pipe joint) over the heavy segment. In RIFLEX software tool, clump weight is modelled as external wrapping as shown in figure 6.8.

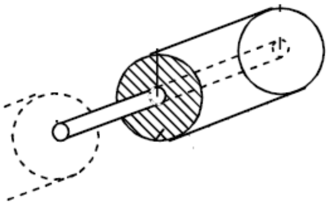


Figure 6-8 Clump Weight Model on SCR Analysis

Mass per unit length, buoyancy volume per unit length and ratio clump length over riser segment length are the inputs to model clump weight on SCR analysis. The clump weight is applied one every 12m riser segment. Numbers of clump weights will be decided according to SCR strength requirement.

6.3.3 Riser Structural Modelling

Initial riser base case configuration with clump weights is given in Table 6.7 below.

Table 6-7 SCR Segment Definitions (Clump Weight SCR)

Riser Segments	Segment Name	Wall thickness (mm)	Density Coating
Upper	Up-N	25.4	Normal
Straight	Straight-CL	25.4	Normal
Sag-bend	Sag-N	25.4	Normal
TDZ-top	TDZ-I	22	Normal
TDZ-low	TDZ-N	19	Normal
Bottom	Bottom-I	22	Normal

Riser normal coating density is 800 kg/m^3

6.3.4 Strength Design

Similar approach to weight distributed SCR coating where the riser configuration was initially derived from near load case is also applied for weight distributed clump weight. The study is started for extreme storm condition. Survival condition is checked when the extreme condition has been satisfied.

In this analysis, clump weights are basically used as replacement to heavy coating. In weight distributed coating, the length of heavy segment was 850m. Direct application to clump weight will require about 70 clump weights which appear to be unrealistic in terms of the numbers. Therefore, study is started from smaller number along with other optimisations. Table 6.8 shows different results from different riser configurations.

Table 6-8 SCR Configuration Study Weight Distributed Clump Weight (Near Case)

Case	Up-N	Straight-CL	Sag-N	TDZ-I	TDZ-N	Bottom-I	No. of clump weight	VM Stress (MPa)	Ratio
A	480	636	60	57	1092	575	53	338	0.94
B	624	492	60	57	1092	575	41	349.5	0.98

The main purpose of this analysis is to design clump weight as low number and light weight as possible. Reducing number of clump weight results in Von Mises Stress increment. It is obvious because it reduces the heavy segment weight. The lowest numbers of clump weight that can be achieved are 41 for near load case. This number can be reduced by modifying the clump weight heavier. However, it is not a good solution in this case since 4ton/m is already heavy. Case B is used for far load case check as presented in table 6.9.

Table 6-9 SCR Configuration Study Weight Distributed Clump Weight (Far Case)

Case	Up-N	Straight-CL	Sag-N	TDZ-I	TDZ-N	Bottom-I	No. of clump weight	VM Stress (MPa)	Ratio
B	624	492	60	57	1092	575	41	440	1.23
C	480	660	36	57	1092	575	55	375.6	1.05
Coating Density : 1000 kg/m^3									
C2	480	660	36	57	1092	575	55	342.2	0.95
D	504	612	60	57	1092	575	51	358	0.99

Similar configuration (case B) that works for near load case has been checked for far load case. The result however is not acceptable. Reference is made to figure 6.9 below where moment envelope curve of configuration B for far load case is provided. It can be analyzed that the first peak of bending moment which is located at the end of heavy segment is too high. The workable bending moment of typical X-65 steel grade shall be less than 400kNm for 25.4mm wall thickness.

Furthermore, configuration C is proposed with increasing in a number of clump weights from 41 to 55. Even though it reduces the Von Mises stress, but it is not good enough to meet the strength requirement. Another attempt to reduce the Von Mises stress is by increasing the coating density to 1000kg/m^3. This solution could reduce the Von Mises stress quite significantly such that it is within the allowable stress. However, numbers of clump weight used in configuration C2 is 55 which are too many to be employed on the riser. Therefore, configuration D is proposed with 51 numbers of clump weights and it is still within the allowable stress.

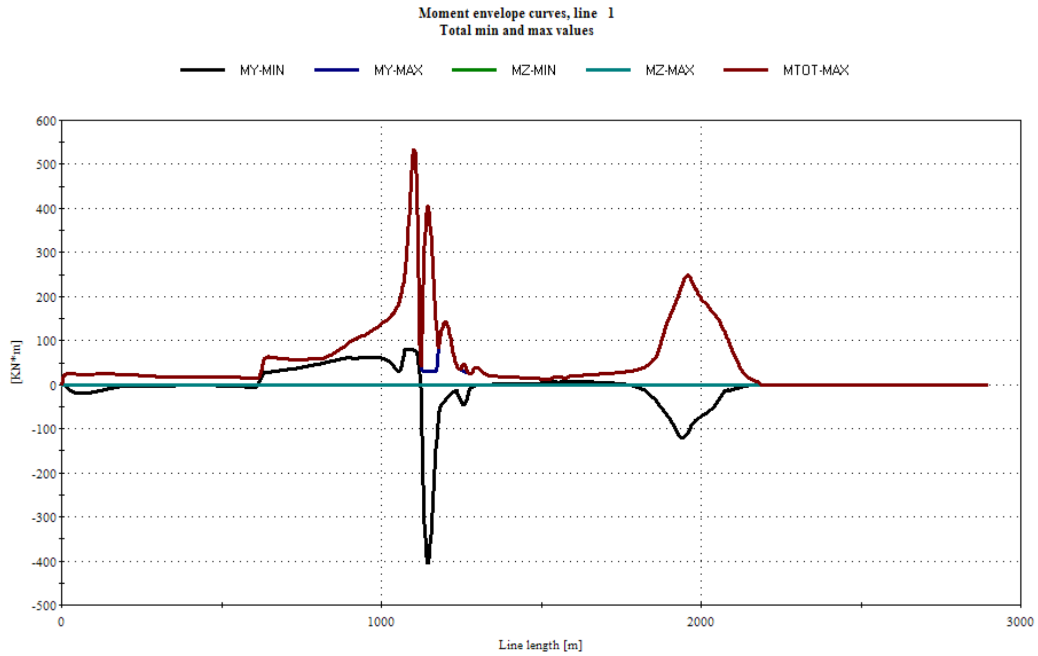


Figure 6-9 Moment Envelope Curve - Configuration B

Configuration D is checked for mean load case as present in table 6.10.

Table 6-10 SCR Configuration Study Weight Distributed Clump Weight (Mean Case)

Case	Up-N	Straight-CL	Sag-N	TDZ-I	TDZ-N	Bottom-I	No. of clump weight	VM Stress (MPa)	Ratio
D	504	612	60	57	1092	575	51	410.5	1.14
Normal coating: 1200 kg/m^3; Light coating: 800 kg/m^3									
E	456	696	24	57	1092	575	58	353.4	0.99

The check on mean load case for configuration D exceeds allowable stress. Figure 6.10 shows moment envelope curve that has excessive stresses at two locations; end of heavy segment and TDP. The cause of excessive bending moment at the end of heavy segment is insufficient heavy weight before sag-bend region. Increase numbers of clump weight will simply reduce the bending moment. Meanwhile, the cause of excessive bending moment at TDP is the relatively short distance from end of heavy segment to TDP. High bending moment at the end of heavy segment still affects the light segment at TDP.

Alternatively, configuration E is proposed. The result shows that by increasing numbers of clump weight and varying coating densities, Von Mises stress is within allowable stress. However, 58 numbers of clump weights are too many to be deployed during riser installation.

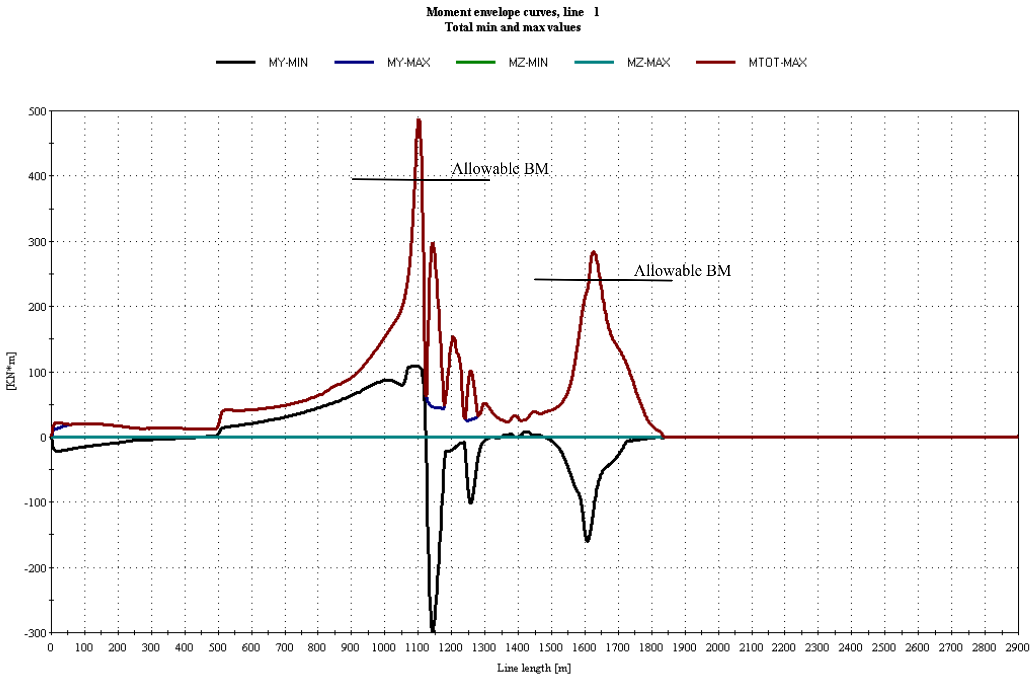


Figure 6-10 Moment Envelope Curve - Configuration D

A new riser configuration concept is proposed by combining heavy clump weight and light clump weight. The purpose of this concept is to establish smooth transition from heavy segment with heavy clump weight to intermediate segment with light clump weight. Heavy clump has weight of 4 ton/m and light clump has weight 2 ton/m with each length is 1.5m.

Table 6.11 presents the complete check for configuration F.

Table 6-11 SCR Configuration F - Weight Distributed Clump Weight

Case	Up-N	Straight -CL-H	Straight -CL-L	TDZ -I	TDZ -N	Bottom-I	No.of clump weight	VM Stress (MPa)	Ratio
Extreme Storm Condition									
Mean	732	348	24	129	1172	495	31	358	0.99
Near	732	348	24	129	1172	495	31	321.6	0.90
Far	732	348	24	129	1172	495	31	354.6	0.99
Survival Condition									
Near	732	348	24	129	1172	495	31	318.5	0.71
Far	732	348	24	129	1172	495	31	443.6	0.99

By using this concept, the numbers of clump weight can be reduced from 58 to 31. In this configuration, far load case for survival condition gives the highest Von Mises stress. It is because far load case for survival condition with offset 120m gives the longest distance between host platform and TDP, meanwhile heavy segment length can not be extended due to limitation from near load case. This leaves far load case with insufficient heavy segment length. However, the result shows that the maximum Von Mises stress is still within acceptable allowable stress. Therefore, configuration F satisfies strength design requirement.

6.4 Discussion and Conclusion

- Some discussions on satisfying weight distributed SCR for near load case:
  - Provides heavy segment long enough could improve SCR response.
  - Heavy segment shall not exceed TDP, because it could amplify the bending moment significantly. Survival condition is the limit for providing heavy segment because of the closest distance between host platform and TDP.
  - Provides light segment at TDA could reduce improve SCR response.
- Some discussions on satisfying weight distributed SCR for far load case:

  In addition to discussion on near load case, light segment shall be provided long enough such that it still falls on TDP for far load case. It is important to notice that far load case has the longest distance from host platform to TDP.
- Some discussions on satisfying weight distributed SCR for mean load case:

  In addition to discussion on near and far load case, it is important to establish smooth transition from heavy segment to light segment in order to reduce concentrated stress at transition. This becomes important for mean load case due to close distance between end of heavy segment to TDP.
- Additional issues from weight distributed clump weight SCR:
  - Far load case requires more numbers of clump weights than near load case due to its longer suspended riser. In addition, mean load case requires even need more clump weights due to its close distance between end of heavy segment to TDP i.e. not much relaxation distance.
  - Fatigue analysis gives opposite requirement to strength design. Fatigue analysis requires as light segment as possible at TDA, meanwhile strength design requires high number of clump weights to restrain the SCR movement. As a solution to this conflicting requirement, light clump weights are applied in order to provide smoother transition from end of heavy segment to light segment, hence reducing excessive bending moment at the end of heavy segment and number of clump weights can be reduced.
- However, there are some drawbacks from the concept given by weight distributed SCR by coating and weight distributed SCR by clump weight when it comes to practical approach:
  - Maximum coating density used in this study is 2800 kg/m^3. It is considered to be difficult to find.
  - Maximum heavy clump weight used in this study is 4 ton/m. It is considered to be too heavy, especially during installation.
- Despite some drawbacks mentioned in previous point, weight distributed SCR is a promising solution to conventional SCR. The Von Mises stress could be reduced in about half than conventional SCR. Further optimisation will be provided in chapter 7 in order to present weight distributed SCR as promising as well as applicable solution.

CHAPTER 7 BEHAVIOUR OF WEIGHT DISTRIBUTED SCR AND SENSITIVITY STUDY

7.1 Introduction

Previous studies for SCR applications in deepwater field and harsh environments indicate that a heavy section in the sag-bend region and light section along the touch-down region improves response significantly. The heavy section was achieved by two methods; (a) apply heavy coating (b) apply a number of clump weights. Both methods have improved the SCR response and fatigue performance.

There are a number of parameters that drive the SCR response. It is important to understand the correlation between the peak response and the following parameters:

- Maximum upward displacement
- Maximum downward displacement
- Maximum upward velocity
- Maximum downward velocity
- Maximum upward acceleration
- Maximum downward acceleration

In this chapter, a number of insightful sensitivity analyses and innovative solutions to SCR performance for deepwater application are presented.

7.2 Comparison of Conventional SCR and Weight Distributed SCR

The study is started by comparing conventional coating SCR and weight distributed coating SCR. Table 7.1 presents the riser configurations for both cases.

Table 7-1 SCR Configurations – Conventional SCR and Weight Distributed SCR

Riser Segment	Segment Length (m)	Conventional SCR		Weight Distributed SCR	
		WT (mm)	Coating Density (kg/m^3)	WT (mm)	Coating Density (kg/m^3)
Upper	285	25.4	800	25.4	800
Straight	750	25.4	800	25.4	2800
Sag-bend	100	25.4	800	25.4	2800
TDZ-top	25	22	800	22	1500
TDZ-low	1165	19	800	19	670
Bottom	575	22	800	22	800

Riser configuration for conventional SCR is formed by uniform coating density and wall thickness variations. Meanwhile, weight distributed SCR has variation on both wall thickness and coating density. The riser response for conventional SCR is not able to satisfy the requirement for extreme storm condition as discussed in chapter 5. On the other hand, weight distributed SCR has satisfied the extreme storm and survival requirement as discussed in chapter 6. Therefore, the comparison study between these configurations will be studied in order to understand the improvement from conventional SCR to weight distributed SCR.

Figure 7-1 shows the riser configurations for both conventional SCR and weight distributed SCR.

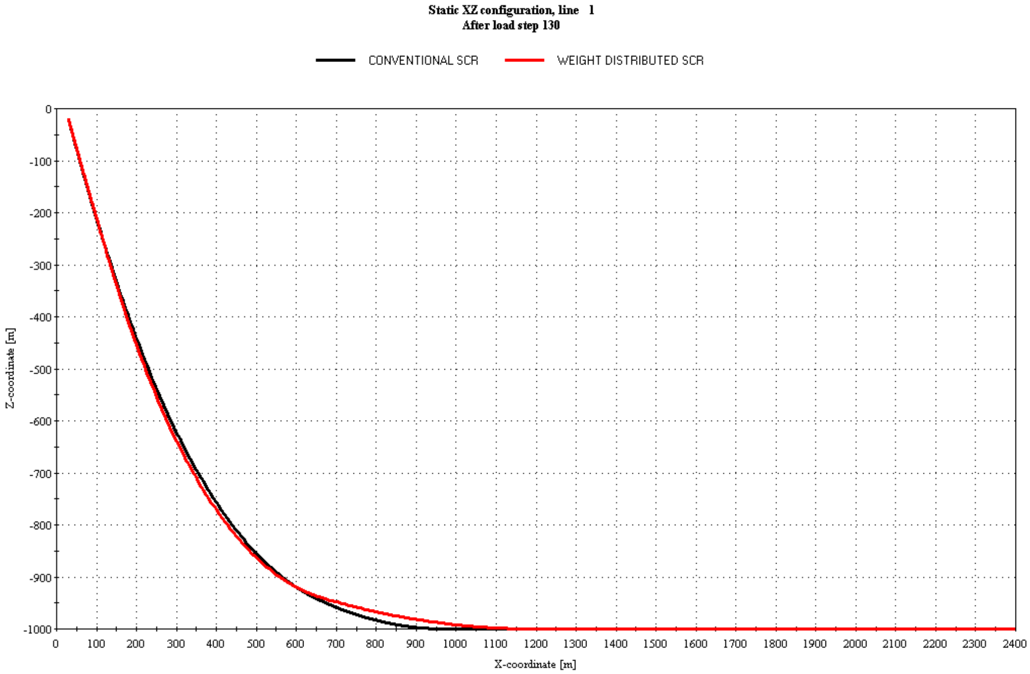


Figure 7-1 SCR Configurations - Conventional SCR and Weight Distributed SCR

It is clearly seen from the figure that the combination of heavy weight along the straight segment of riser and light weight along the TDA results in different riser configuration than uniform weight. Smoother approach to touch-down point is achieved by weight distributed SCR than conventional SCR. It is important to establish smooth approach of riser in order to avoid excessive bending moment at TDP.

Detail observations on how the weight distributed SCR could improve the riser performance is provided in the following sections.

7.2.1 Maximum Displacement

The study on displacement envelope curve for both conventional SCR and weight distributed SCR is presented in this section. Figure 7.2 shows the vertical displacement until riser length of 2000m.

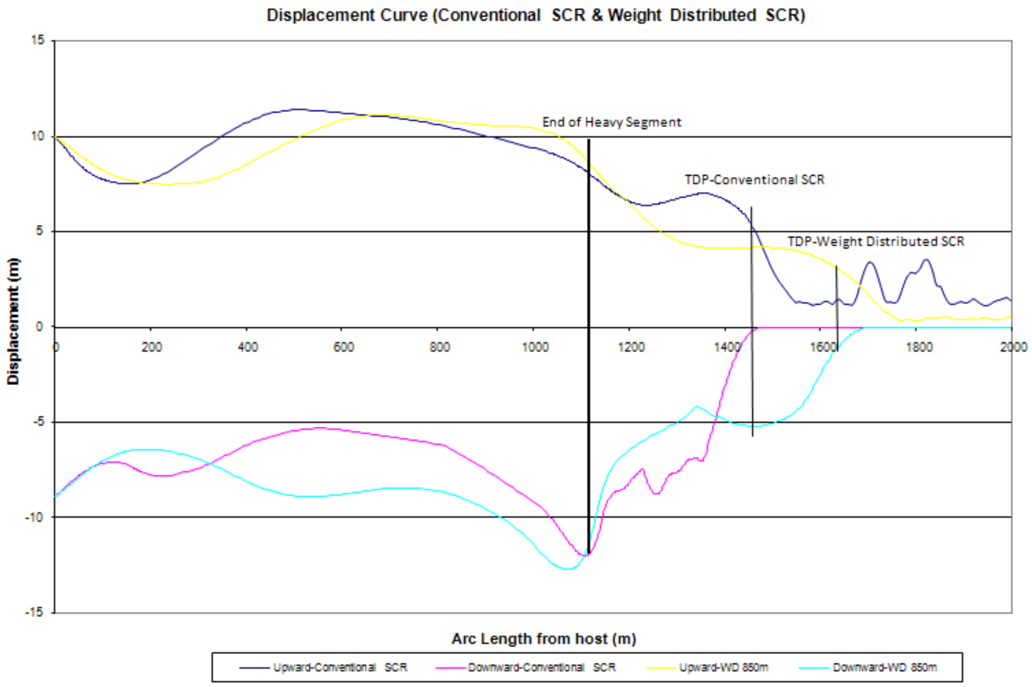


Figure 7-2 Comparison Displacement Curve–Conventional SCR & Weight Distributed SCR

From this envelope curve, it is interesting to see that there is a significant difference between conventional SCR and weight distributed SCR particularly around sag-bend and TDA. For conventional SCR, the curve decreases gradually from sag-bend to TDA and further decreases significantly when it approaches sea bottom (dark blue curve). For weight distributed SCR, significant decrease in displacement occurs around sag-bend and gradually decrease as it approaches sea bottom (yellow curve).

The relation between SCR displacement and SCR Von Mises is presented in table 7.2 and 7.3.

Table 7-2 Vertical Upward Displacement and Von Mises Stress

Location	Conventional SCR		Weight Distributed SCR	
	Displacement (m)	Von Mises Stress (MPa)	Displacement (m)	Von Mises Stress (MPa)
End of heavy segment	7.70	306	8.00	321
Z=-980m	6.50	227	4.15	129
Z=-996m	6.84	432.5	3.85	186
TDP	6.70	633	3.24	348

Table 7-3 Vertical Downward Displacement and Von Mises Stress

Location	Conventional SCR		Weight Distributed SCR	
	Displacement (m)	Von Mises Stress (MPa)	Displacement (m)	Von Mises Stress (MPa)
End of heavy segment	-11.00	306	-9.50	321
Z=-980m	-7.75	227	-4.83	129
Z=-996m	-3.90	432.5	-3.78	186
TDP	-2.70	633	-1.40	348

It is clearly understood that high displacement results in high Von Mises Stress, and vice versa. At end of heavy segment, the Von Mises Stresses between the two SCR configurations are not significantly different. However, at TDP, the Von Mises Stress from weight distributed SCR is reduced almost half from conventional SCR. It is a good indication that the weight distributed SCR improves SCR response.

7.2.2 Maximum velocity

Study on displacement has shown the relation between displacement and SCR response. Further study is performed by analyzing velocity of SCR at different locations. Table 7.4 and 7.5 show the comparison of velocities between conventional SCR and weight distributed SCR along with Von Mises Stress.

Table 7-4 Vertical Upward Velocity and Von Mises Stress

Location	Conventional SCR		Weight Distributed SCR	
	Velocity (m/s)	Von Mises Stress (MPa)	Velocity (m/s)	Von Mises Stress (MPa)
End of heavy segment	3.40	306	2.9	321
Z=-980m	2.75	227	1.68	129
Z=-996m	2.70	432.5	1.55	186
TDP	2.68	633	1.31	348

Table 7-5 Vertical Downward Velocity and Von Mises Stress

Location	Conventional SCR		Weight Distributed SCR	
	Velocity (m/s)	Von Mises Stress (MPa)	Velocity (m/s)	Von Mises Stress (MPa)
End of heavy segment	-3.25	306	-4.35	321
Z=-980m	-2.55	227	-1.74	129
Z=-996m	-3.30	432.5	-2.15	186
TDP	-3.40	633	-2.28	348

Vertical velocities have shown similar indication to displacements. Velocity of conventional SCR is generally about twice as high as velocity on weight distributed SCR. Figure 7.3 shows the velocity comparison curve between conventional SCR and weight distributed SCR.

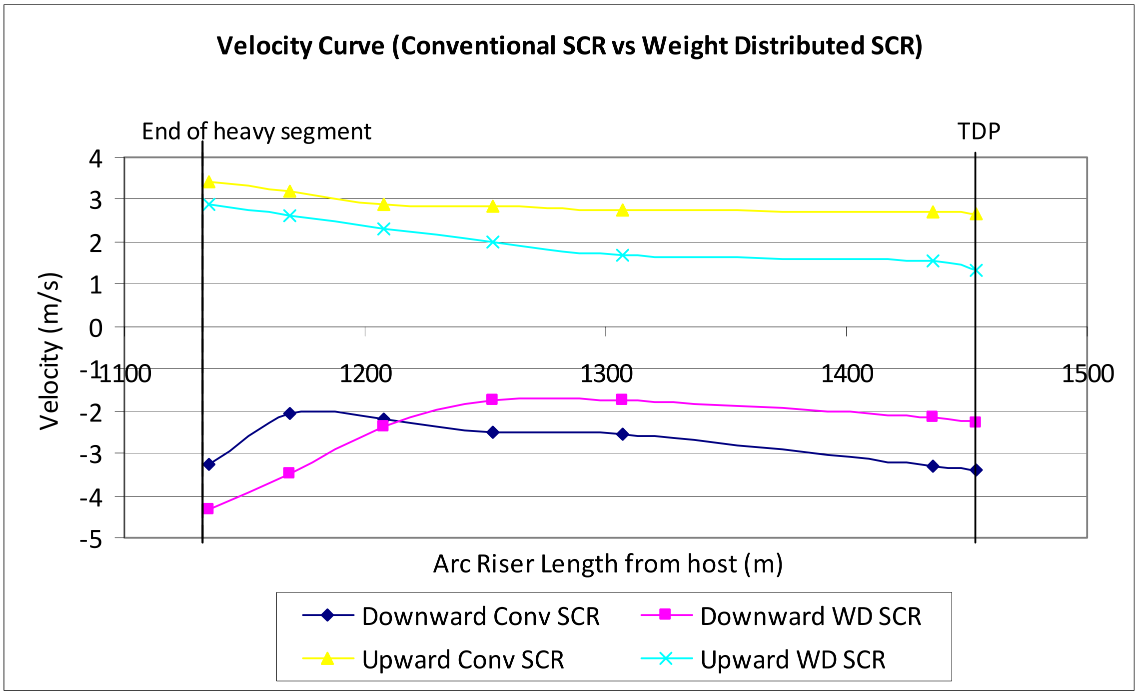


Figure 7-3 Comparison Velocity Curve – Conventional SCR and Weight Distributed SCR

Upward velocity curves (yellow and light blue curves) show obvious difference between the velocity of conventional SCR and weight distributed SCR. The difference between these two curves increases as the riser approaches TDP. Meanwhile, downward velocity curves (dark blue and pink curves) show two different patterns. At the end of heavy segment until some distances, velocities from weight distributed SCR give higher value than velocities from conventional SCR. As the riser approaches TDP, velocities from weight distributed SCR is lower than velocities from conventional SCR. It can be concluded that at TDP, for both upwards abd downwards velocity, weight distributed SCR has significantly lower velocity than conventional SCR.

7.2.3 Maximum Acceleration

Comparison study on riser's acceleration is also given to confirm the relationship between these parameters and riser response.

Table 7-6 Vertical Upward Acceleration and Von Mises Stress

Location	**Conventional SCR**		**Weight Distributed SCR**	
	Acceleration (m/s^2)	**Von Mises Stress (MPa)**	**Acceleration (m/s^2)**	**Von Mises Stress (MPa)**
End of heavy segment	3.45	306	1.80	321
Z=-980m	4.73	227	2.15	129
Z=-996m	6.73	432.5	2.70	186
TDP	4.60	633	4.40	348

Table 7-7 Vertical Downward Acceleration and Von Mises Stress

Location	Conventional SCR		Weight Distributed SCR	
	Acceleration (m/s^2)	Von Mises Stress (MPa)	Acceleration (m/s^2)	Von Mises Stress (MPa)
End of heavy segment	-3.65	306	-2.35	321
Z=-980m	-2.75	227	-1.05	129
Z=-996m	-3.10	432.5	-2.25	186
TDP	-2.55	633	-2.52	348

Typical observation as displacement and velocity is found for acceleration.

7.2.4 Maximum Bending moment

SCR behaviour in deepwater and harsh environments is highly dynamic movement. This results in high bending moment at touch-down region. Bending moment is the most driver parameter for SCR. Table 7.8 provides comparison of bending moments for both riser configurations along with Von Mises stress at each location.

Table 7-8 Maximum Bending Moment and Von Mises Stress

Location	Conventional SCR		Weight Distributed SCR	
	Bending Moment (kNm)	Von Mises Stress (MPa)	Bending Moment (kNm)	Von Mises Stress (MPa)
End of heavy segment	358	306	388	321
Z=-980m	262.5	227	33	129
Z=-996m	350	432.5	105	186
TDP	563	633	250	348

Both SCR configurations experience two peaks of bending moment which located at the end of heavy segment and at TDP. At TDP, bending moment for conventional SCR is more than twice of bending moment for weight distributed SCR. This is a result of highly movement from conventional SCR which was observed from high values of displacement, velocity and acceleration.

The study on displacement, velocity and acceleration has shown that low values of these parameters result in low Von Mises stress. Therefore, it is important to design riser such that displacement, velocity and acceleration have significantly low values.

7.3 Sensitivity Study

According to study on previous section, it can be observed that riser response has strong relation to displacement, velocity and acceleration. In this section, sensitivity study will be performed in order to derive the maximum allowable velocity that results in acceptable Von Mises stress.

7.3.1 Sensitivity in Heavy Segment Length

From analysis on weight distributed SCR by varying riser density coating, the length of heavy segment was 850m. The sensitivity study will be performed by varying heavy segment length into:

a. Base case : 850m
b. Sensitivity 1 : 650m
c. Sensitivity 2 : 450m

Figure 7.4 presents the riser configurations for base case, sensitivity 1 and sensitivity 2.

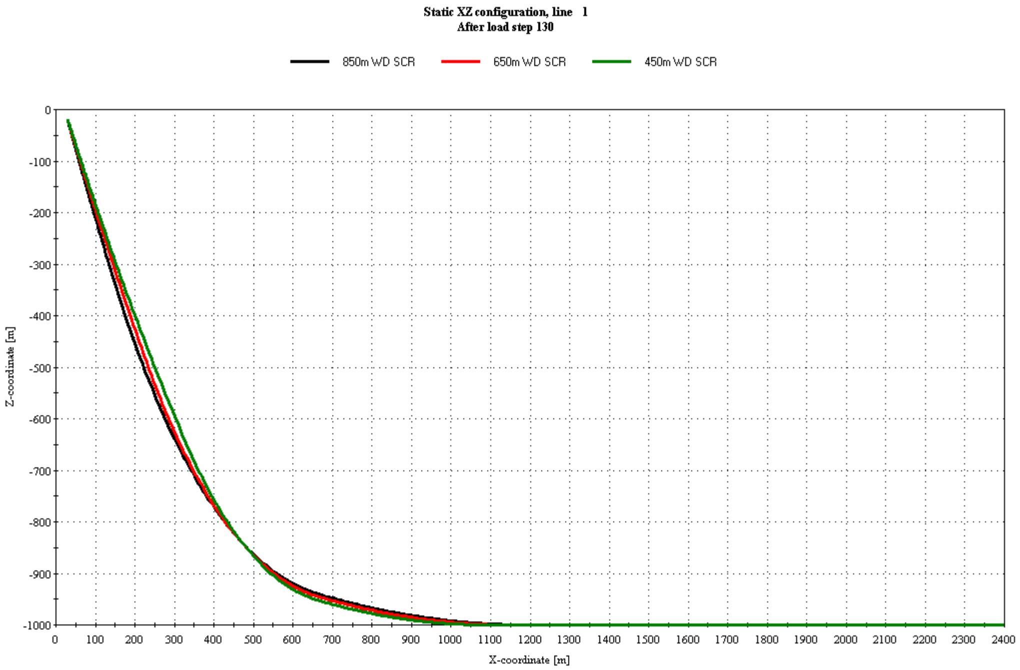


Figure 7-4 Riser Configurations – Base Case, Sensitivity 1 and Sensitivity 2

Analyzing the riser configurations from top-end of riser to the end of straight segment gives the idea that the heaviest riser configuration (figure 7.4 black curve) reduces the hang-off angle. It is important to establish sufficient hang-off angle to control the pipe curvature at sag-bend region and TDP. Further, the present of light segment after the heavy segment will lift the riser due to its low submerged weight and avoid a sudden drop of riser at TDP.

The 450m heavy segment length experiences a sudden riser drop to sea bottom due to insufficient riser weight at straight segment (green curve). Meanwhile, 850m heavy segment length has smooth sea bottom approach with very small angle formed by riser and sea bottom plane. Establishing smooth sea bottom approach is important for typical highly dynamic riser movement, in order to minimize excessive bending moment at TDP.

Table 7.9 presents the vertical and downward displacement at four riser locations for all sensitivity cases.

Table 7-9 Maximum Displacements (m) – Sensitivity in Heavy Segment Length

Location	Max Upward Displacement			Max Downward Displacement		
	Base Case	Sens. 1	Sens. 2	Base Case	Sens. 1	Sens. 2
End of heavy segment	8.00	8.00	8.35	-9.50	-9.50	-9.70
Z=-980m	4.15	4.50	4.78	-4.50	-4.00	-4.28
Z=-996m	3.70	3.75	3.58	-3.82	-3.50	-3.80
TDP	3.25	3.30	3.00	-1.50	-1.60	-1.75
Von Mises Stress @ TDP (MPa)	348	400	393	348	400	393

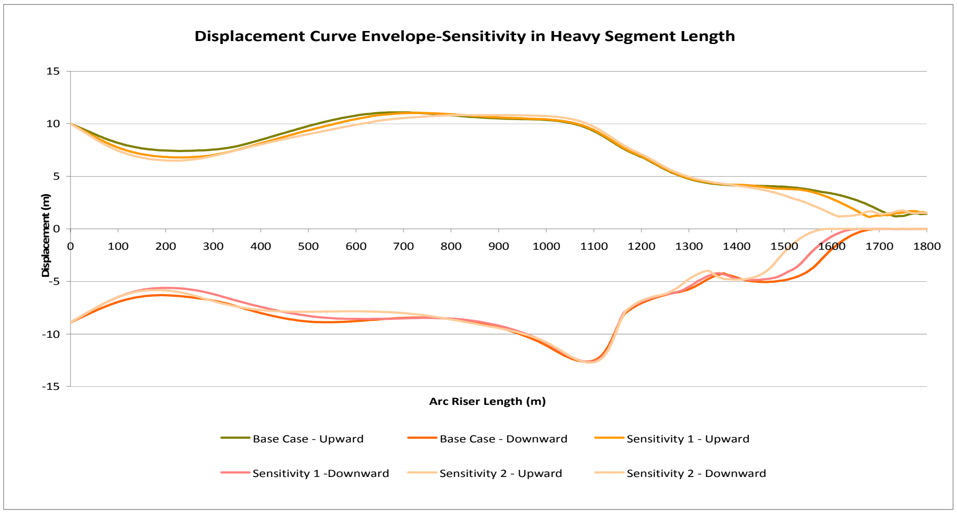


Figure 7-5 Displacement Envelope Curve – Sensitivity in Heavy Segment Length

Generally, the displacement curve for all cases are relatively uniform until riser length 1400m as shown in figure 7.5. This also confirms a slight difference of displacements in table 7.9. After riser length of 1400m, there is a significant difference between base case, sensitivity 1 and sensitivity 2. This represents on how the riser approaches the TDP with base case having the smoothest approach and smallest Von Mises Stress.

Table 7.10 presents the maximum upward and downward velocities for all cases.

Table 7-10 Maximum Velocities – Sensitivity in Heavy Segment Length

Location	Max Upward Vel (m/s)			Max Downward Vel (m/s)		
	Base Case	Sens. 1	Sens. 2	Base Case	Sens. 1	Sens. 2
End of heavy segment	2.90	2.85	3.00	-4.35	-4.28	-4.50
Z=-980m	1.68	1.72	1.88	-1.74	-1.73	-1.84
Z=-996m	1.55	1.58	1.59	-2.15	-2.34	-2.37
TDP	1.31	1.30	1.34	-2.28	-2.46	-2.46
Von Mises Stress @ TDP (MPa)	348	400	393	348	400	393

It is observed from table 7.10 that there is not much difference in velocities for all cases. However, since the base case Von Mises stress is already on the limit, any reduce in riser performance will result in exceeding allowable stress. It is experienced At TDP where increase in downward velocity for sensitivity 1 and sensitivity 2 results in excessive Von Mises stress.

Table 7.11 presents the maximum upward and downward accelerations for all cases.

Table 7-11 Maximum Accelerations – Sensitivity in Heavy Segment Length

Location	Max Upward Acc (m/s^2)			Max Downward Acc (m/s^2)		
	Base Case	Sens. 1	Sens. 2	Base Case	Sens. 1	Sens. 2
End of heavy segment	1.80	2.57	1.94	-2.35	-2.30	-2.19
Z=-980m	2.15	3.15	2.16	-1.05	-1.83	-2.00
Z=-996m	2.70	2.60	2.85	-2.25	-2.76	-2.63
TDP	4.40	4.83	4.55	-2.52	-2.70	-2.70
Von Mises Stress @ TDP (MPa)	348	400	393	348	400	393

The accelerations from different cases result in relatively uniform value. Table 7.12 presents the Von Mises stress for all cases at four different locations.

Table 7-12 Maximum von Mises Stress – Sensitivity in Heavy Segment Length

Location	Max Von Mises Stress (MPa)		
	Base Case	Sens. 1	Sens. 2
End of heavy segment	321	322	340
Z=-980m	128.7	133.5	133
Z=-996m	186	195	233.5
TDP	348	400	393

As it is already discussed in displacement, velocity and accelerations, Von Mises stresses show small difference between all cases. Therefore, it can be concluded form this sensitivity study on heavy segment length that the riser response is insensitive to heavy segment length. This leads to next sensitivity study by varying the heavy coating density hypothetically.

7.3.2 Sensitivity in Heavy Segment Coating Density

In this section, sensitivity on heavy segment coating density will be studied. Table 7.13 presents the case description along with maximum Von Mises stress. It is important to note that densities given in this table are proposed for study only. It is not necessarily available in industrial practice at this point of time.

Table 7-13 Optimisation Heavy Segment Coating Density

Description	Heavy Segment		Tension Force at top-end (kN)	Max Von Mises Stress (MPa)	Ratio
	Length (m)	Coating Density (kg/m^3)			
Case A	450	2800	4475	393	1.10
Case B	450	5600	6490	190	0.53
Case C	400	5600	5880	264.5	0.74
Case D	400	4500	5170	297	0.83
Case E	400	3500	4555	337	0.94

According to table 7.13, Von Mises stress in case B is significantly reduced to almost half of Von Mises in case A. In order to optimise the SCR design, case C, D and E were proposed. It is then concluded that case E with heavy segment length of 400m and density of 3500 kg/m^3 is the optimal configuration.

In order to study on the sensitivity of displacement, velocity and acceleration, case A, B and E were chosen.

Figure 7.6 presents the riser configurations for case A, B and E.

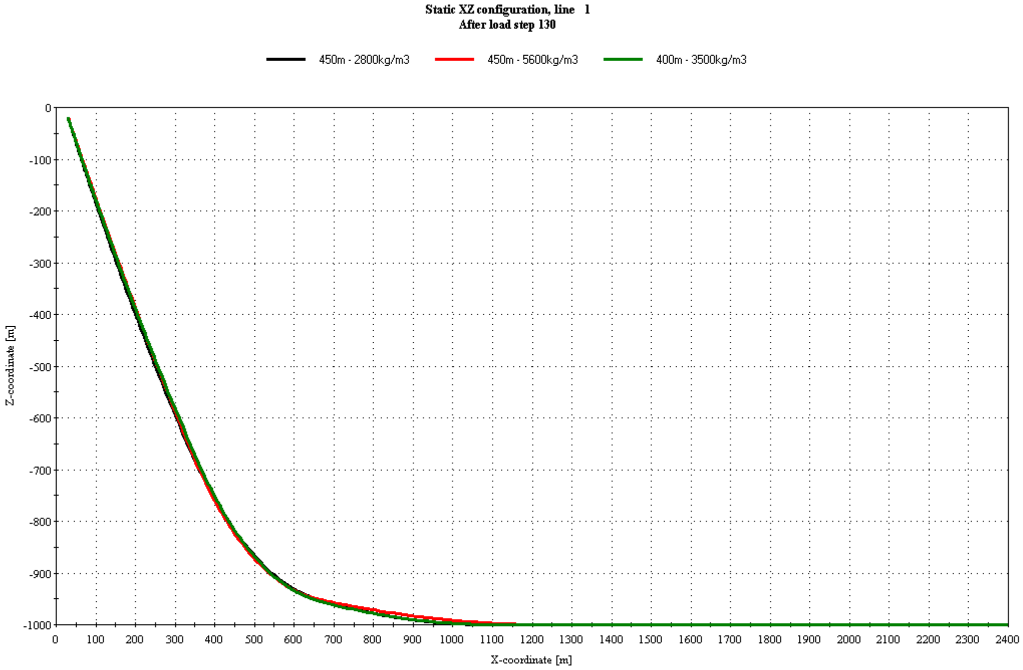


Figure 7-6 Riser Configurations – Case A, B and E

The only difference from these riser configurations is on how riser approaches the sea bottom. This is shown in figure 7.7 where the case B (450m-5600kg/m^3) has much smoother seabed approach compared to other cases. The smooth approach will result in relatively small bending moment compared to sudden approach.

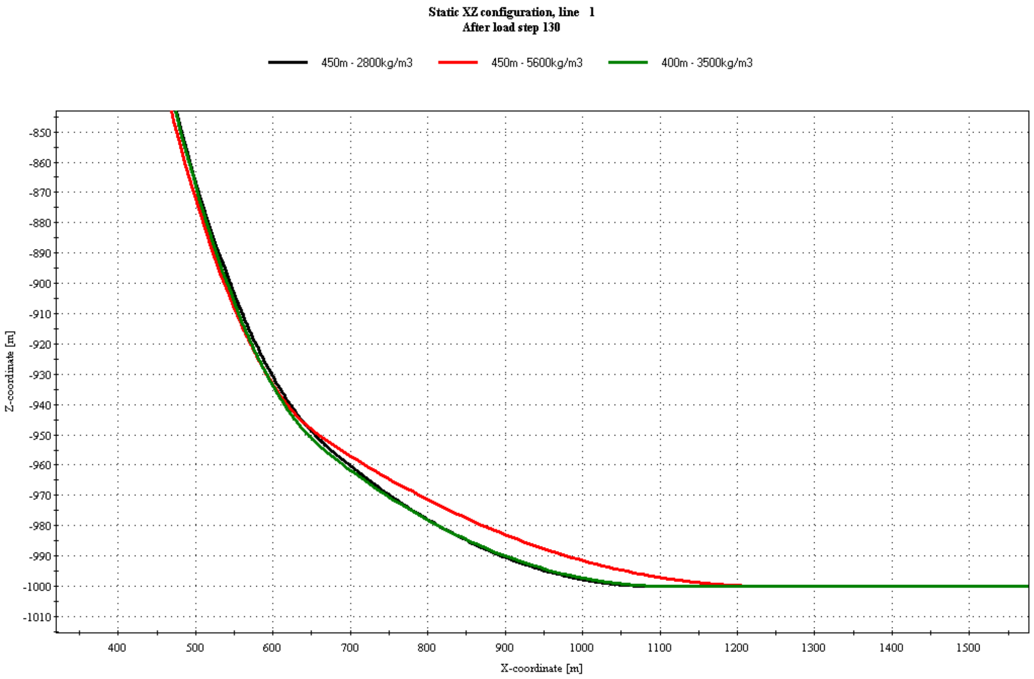


Figure 7-7 Riser Configurations Sea bottom Approach – Case A,B and E

Table 7.14 present the vertical upward and downward displacement along with Von Mises stress respectively.

Table 7-14 Maximum Displacements (m) – Sensitivity in Heavy Segment Density

Location	**Max Upward Displacement**			**Max Downward Displacement**		
	Case A	**Case B**	**Case E**	**Case A**	**Case B**	**Case E**
End of heavy segment	8.35	7.90	8.48	-9.70	-8.70	-9.20
Z=-980m	4.78	3.23	4.54	-4.28	-3.26	-4.00
Z=-996m	3.58	1.74	3.20	-3.80	-3.44	-3.65
TDP	3.00	1.54	2.80	-1.75	-2.65	-2.00
Von Mises Stress @ TDP (MPa)	393	156.5	344	393	156.5	344

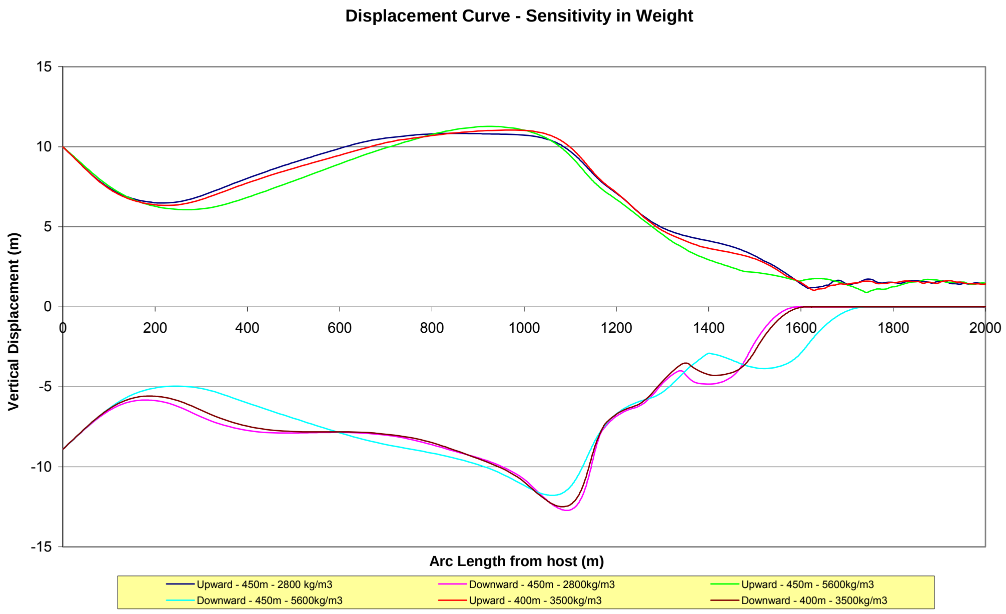


Figure 7-8 Displacement Envelope Curve – Sensitivity in Heavy Segment Weight

Case A and E have relatively similar pattern of displacement curve. Particularly for case B with very high weight along the heavy segment, the displacement at TDP is very small compared to case A and E. In addition, when the riser approaches sea bottom (1300-1600m), case B (green curve) has very gradual curve compared to case A (dark blue curve) and case E (red curve). This is mainly because of the ability of case B to have smooth approach to sea bottom as shown in figure 7.8.

Case E with 400m heavy segment length and 3500 kg/m^3 coating density, appears to be the "mid-solution" between case A and case B. The case E curve always appears in between curve from case A and B.

Table 7.15 presents the maximum upward and downward velocities for all cases.

Table 7-15 Maximum Velocities – Sensitivity in Heavy Segment Density

Location	Max Upward Velocity (m/s)			Max Downward Velocity (m/s)		
	Case A	Case B	Case E	Case A	Case B	Case E
End of heavy segment	3.00	2.70	2.95	-4.50	-3.70	-4.30
Z=-980m	1.88	1.47	1.80	-1.84	-1.26	-1.73
Z=-996m	1.59	1.20	1.64	-2.37	-1.6	-2.32
TDP	1.34	1.20	1.52	-2.46	-1.4	-2.27
Von Mises Stress @ TDP (MPa)	393	156.5	344	393	156.5	344

Case B appears to be the lowest velocity at every location. This means that the movement of riser is more stable than other cases. Significant difference occurs at TDP for downward velocity where the velocity is almost half than case A. This gives an indication that the low velocity gives stable SCR response and results in acceptable Von Mises stress.

Case E appears to be in between case A and B. This is similar pattern as discussion on displacements. Hence, it can be expected that in order to have acceptable Von Mises stress, the downward velocity shall be about 2.27 m/s.

Figure 7.9 shows the comparison velocity curves between all cases.

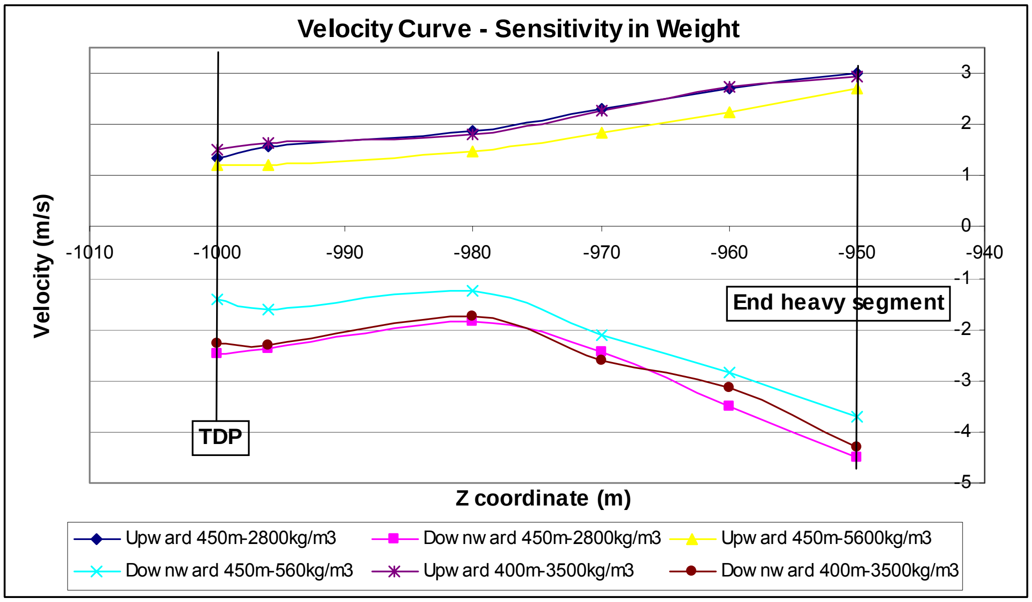


Figure 7-9 Velocity Envelope Curve – Sensitivity in Heavy Segment Weight

It is clearly seen from the figure that increases the density two times than before, results in significantly lower velocities (yellow curve). Significant difference is also observed at TDP (z=-1000m).

Downward velocities are more important for SCR design because it reflects the SCR behaviour in response to the present of sea bottom. Low downward velocity gives low movement of SCR which is desirable to reduce bending moment at TDP.

Table 7.16 presents maximum upward and downward accelerations for all cases.

Table 7-16 Maximum Accelerations – Sensitivity in Heavy Segment Density

Location	Max Upward Acc (m/s^2)			Max Downward Acc (m/s^2)		
	Case A	Case B	Case E	Case A	Case B	Case E
End of heavy segment	1.94	1.90	2.23	-2.19	-2.00	-1.97
Z=-980m	2.16	1.58	2.15	-2.00	-1.00	-1.41
Z=-996m	2.85	2.47	3.20	-2.63	-2.35	-2.50
TDP	4.55	2.41	4.10	-2.70	-2.58	-2.43
Von Mises Stress @ TDP (MPa)	393	156.5	344	393	156.5	344

As it is already discussed on displacement and velocity parameters, case B shows the lowest value i.e. the most controlled SCR behaviour. Case E appears to be most optimum solution compared to case A and case B.

Table 7.17 presents the Von Mises stress for all cases at four different riser locations.

Table 7-17 Maximum Von Mises stress – Sensitivity in Heavy Segment Density

Location	Maximum Von Mises Stress (MPa)		
	Case A	Case B	Case E
End of heavy segment	340	190	296
Z=-980m	133	120	131.6
Z=-996m	233.5	123.7	187.4
TDP	393	156.5	344

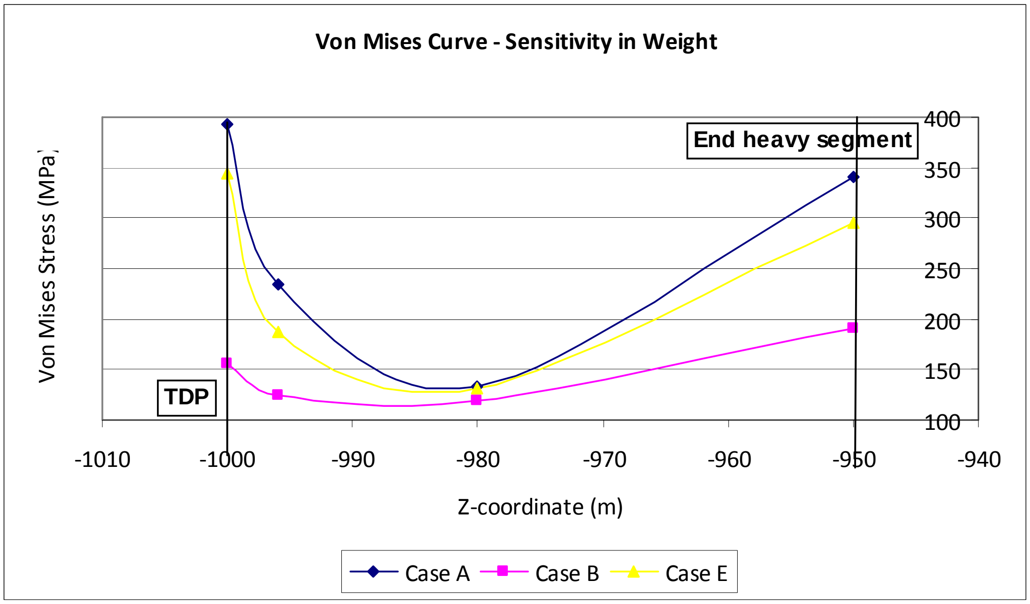


Figure 7.10 Von Mises Curve – Sensitivity in Weight

At all locations, case B gives the lowest Von Mises stress and follows with case E and case A (pink curve). This confirms that the displacement, velocity and acceleration have strong relation to Von Mises stress. High displacement, velocity and acceleration result in high Von Mises stress and vice versa. Maximum Von Mises of 393 MPa from case A is above the allowable stress of 358.4MPa for storm condition. Case B and case E have maximum Von Mises stress within allowable stress for storm condition. The maximum Von Mises stress for case B is “too good” and optimisation is required for more economical SCR design. Hence, case E is proposed and has proved to be an optimal configuration.

However, case E comprises heavy segment length of 400m and coating density of 3500 kg/m^3. This coating density is not available in industrial practice. Therefore, further optimisation is required in order to come up with a reasonable riser configuration.

7.4 Optimisation Study

The study from section 7.3 concludes that SCR response is more sensitive to increment in heavy segment weight rather than increment in heavy segment length. It is observed from 50% reduction in Von Mises stress when the heavy segment weight is increased twice. Meanwhile, it is only 15% reduction in Von Mises stress when the heavy segment length is increased twice. Therefore, it can be concluded that concentrated heavy weight for relatively short distance is more efficient for SCR response rather than having long medium weight.

In chapter 6, there are two different approaches to weight distributed SCR. The first approach is distributing weight achieved by varying coating density. This represents the concept of spreading medium weight due to limitation in maximum coating density. The second approach is providing a number of clump weights. This represents the concept of having concentrated heavy weight.

Both concepts have some limitations. The limitations for weight distributed SCR by coating are:

- There is limitation on providing length of heavy segment coating. The limitation comes from near load case where it has the closest distance between host platform and TDP. The heavy segment is not allowed to exceed TDP, because it will amplify the Von Mises stress at TDP significantly.
- Heavy segment at TDA reduces the fatigue performance. It is important to have as light weight as possible at touch down region.
- Limitation on available heavy coating density. The use of 2800 kg/m^3 coating density is considered too high for normal practice.

The limitations for weight distributed clump weights are:

- Limitation on weight of the clump. On the other hand, it requires heavy weight clump to reduce numbers of clump weight required. 4 ton/m was used on study in chapter 6, which is considered too heavy to be manipulated on deck with existing equipment during riser installation.
- Limitation on numbers of clump weight. Too many clump weights will complicate the installation procedure and vulnerable for fatigue performance due to additional drag imposed from the clump weights.

Consequently, optimisation study will be provided in this section by combining the concept of varying riser coating density along the riser length and providing a number of clump weights over the heavy segment.

Table 7.18 presents the proposed riser configuration to start the study.

Table 7-18 SCR Configuration A – Combination Study (Mean Load Case)

Combination	**Heavy Coating**		**Clump Weight**			**Von Mises Stress (MPa)**	**Ratio**
	Length (m)	**Density (kg/m^3)**	**Weight (Ton/m)**	**Length (m)**	**No**		
Combination-A	420	2200	4	300	25	345	0.96

Maximum coating density of 2200 kg/m^3 has been achieved from this combination and it is considered to be available in industrial practice. The numbers of clump weights have significantly been reduced to 25 from 31. The combination of variation in coating density and a number of clump weights gives a promising solution.

However, 4 ton/m of each clump weight is too heavy. Further optimisation is provided in table 7.19.

Table 7-19 SCR Configuration B – Combination Study

Load Case	Heavy Coating		Clump weight-Heavy			Clump Weight-Light			VM Stress (MPa)	Ratio
	Length (m)	Density (kg/m^3)	Weight (Ton/m)	Length (m)	No	Weight (Ton/m)	Length (m)	No		
Extreme Storm Condition										
Mean	420	2200	3	204	17	2	36	3	357.8	0.99
Near	420	2200	3	204	17	2	36	3	343.7	0.96
Far	420	2200	3	204	17	2	36	3	344.8	0.96
Survival Condition										
Near	420	2200	3	204	17	2	36	3	334	0.80
Far	420	2200	3	204	17	2	36	3	371	0.83

The concept of providing heavy clump weight and light clump weight apparently improves the SCR response. From table 7.18, the Von Mises stress is just below the limit and any reduction in clump weight will increase the Von Mises stress. Therefore, the combination of heavy and light clump weight was proposed in order to provide smoother transition from heavy segment over straight part to light segment over TDA. The results from table 7.19 show that the maximum clump weight has been reduced from 4 ton/m to 3 ton/m and total number of clump weights have been reduced significantly to 20 from 25. Near load case and far load case for both storm and survival condition have also been checked and considered to be within allowable stress.

Therefore, this configuration is the most optimum solution for SCR design in deepwater field and harsh environmental conditions.

7.5 Comparison Study

Up to now, there are four different riser configurations that have satisfied strength design criteria. They are weight distributed coating SCR, weight distributed clump weights SCR, combination of distributed coating and clump weights SCR and combination of distributed coating and heavy-light clump weight SCR. Table 7.20 presents the riser configuration for all cases.

Table 7-20 SCR Configurations – Comparison Study

Load Case	Heavy Coating		Clump weight-Heavy			Clump Weight-Light		
	Length (m)	Density (kg/m^3)	Weight (Ton/m)	Length (m)	No	Weight (Ton/m)	Length (m)	No
A	850	2800	-	-	-	-	-	-
B	400	3500	-	-	-	-	-	-
C	420	2200	4	300	25	-	-	-
D	420	2200	3	204	17	2	36	3

The purpose of this comparison is to verify the values of acceptable velocity at end of heavy segment and TDP.

Table 7.21 presents the maximum downward velocities along with associated Von Mises stress at end of heavy segment and TDP.

Table 7-21 Downward Velocities and Von Mises Stress – Comparison Study

Location	Maximum Downward Velocity (m/s)				Von Mises Stress (MPa)			
	Case A	Case B	Case C	Case D	Case A	Case B	Case C	Case D
End of heavy segment	-4.35	-4.30	-4.42	-4.44	313	296	318	283
TDP	-2.28	-2.27	-2.18	-2.60	350	344	293	346

It can be analyzed that the velocities are about in the same range between all the cases. The velocity has also strong relation to Von Mises Stress. High velocity results in high Von Mises stress and vice versa. Although all these cases were configured from different approaches, the velocities fall on the same range. For acceptable SCR design in deepwater field and harsh environmental conditions, the downward velocity shall fall in the range of 4.3 – 4.5 m/s at the end of heavy segment and in the range of 2.1 – 2.6 m/s at TDP.

7.6 Discussion and Conclusion

Some discussions and conclusions can be derived from study on this chapter:

- There is a significant difference on displacement, velocity and acceleration from study on comparison between conventional SCR and weight distributed SCR. This indicates the strong relation between these parameters and riser response. The ability to reduce displacement, velocity and acceleration from weight distributed SCR results in acceptable strength design for both storm and survival conditions.
- There is a small difference (less than 15%) on displacement, velocity and acceleration from study on sensitivity in heavy segment length. Hence, riser response is insensitive to heavy segment length.
- There is a significant difference (about 50%) on displacement, velocity and acceleration from study on sensitivity in heavy segment weight. Hence, increase in heavy segment weight improves the SCR response significantly.
- It can be concluded that sensitivity in heavy segment weight is more significant to riser response compared to sensitivity in heavy segment length. In other words, having highly concentrated heavy weight on heavy segment results in better riser performance rather than having long medium weight.
- The study on combination concept between variation in riser coating and provide a number of clump weights results in a promising solution where the maximum coating density can be reduced to 2200 kg/m^3 and numbers of clump weight are reduced to 20.
- The study on comparison between all the working riser configurations shows that the velocity values fall approximately on the same range. At the end of heavy segment, the downward velocities fall on range 4.3 – 4.5 m/s and in the range of 2.1 – 2.6 at TDP. Therefore, it is suggested to design SCR for typical 1000m water depth and offshore Norway environment with velocity around these values.

CHAPTER 8 FATIGUE ANALYSIS OF DEEPWATER WEIGHT DISTRIBUTED SCR

8.1 Introduction

Steel catenary riser in deepwater and harsh environments is continuously subject to oscillatory environmental loads. Ocean waves impose the riser coupled with complex movements of the vessel which itself comprise high frequency response to the waves and low frequency (slow drift) excursion. Therefore, the sources of fatigue damage on the riser are mainly due to:

- First order vessel motion
- Slow-drift
- Vortex-induced vibrations (VIV) due to current along the water column
- Vortex-induced hull motions due to loop current
- Installation

The source of failure in fatigue is metal weld at the joint of riser due to oscillatory stresses. The critical fatigue regions are the welded joints near the touch down point. It is because fatigue damage at this location is a direct effect of the soil-riser interaction. The SCR dynamically and repeatedly impacts upon the soil in the TDA, being lifted up from soil and brought back down again.

In this chapter, fatigue due to wave is discussed. VIV fatigue is not addressed in this study due to limitation of time. In addition, the study is focused on analyzing the mechanism of weight distributed SCR as a solution to conventional SCR for deepwater and harsh environments. However, in section 8.6, VIV issue will be discussed theoretically in order to describe the significance of VIV for SCR design.

Fatigue analysis is checked for weight distributed SCR in order to ensure that the solution could satisfy all SCR design criteria.

8.2 Fatigue Design Conditions

8.2.1 Riser Structural Modelling

There are three different riser configurations that are checked for fatigue analysis. Basic riser properties are given below:

Inner diameter : 10 inch
Wall Thickness : 19mm - 25.4mm
Top Angle : 15 degree
Riser length : 2900m
Carbon Steel Density : 7850 kg/m^3
Steel Material Grade : X65
Yield Stress : 448 MPa
Steel Young's Modulus : 207000 MPa
Riser coating wall thickness : 100mm
Riser coating density : Varies

First configuration is from weight distributed SCR coating. Configuration G from chapter 6 section 6.2.4 is the final configuration that has satisfied strength design criteria. Further, fatigue check is performed for this configuration. Table 8.1 presents the riser configuration G.

Table 8-1 SCR Segment Configuration (Distributed Coating SCR)

Riser Segments	Segment Length (m)	Wall thickness (mm)	Density Coating (kg/m^3)
Upper	285	25.4	800
Straight	750	25.4	2800
Sag-bend	100	25.4	2800
TDZ-top	25	25.4	1500
TDZ-low	1165	19	670
Bottom	575	22	800

Second configuration is taken from weight distributed SCR with clump weights. Configuration F was derived in chapter 6 section 6.3.4 and was the optimum configuration to satisfy strength design criteria. Table 8.2 presents the detail of configuration F.

Table 8-2 SCR Segment Configuration (Distributed Clump Weight SCR)

Riser Segments	Segment Length (m)	Wall thickness (mm)	Density Coating (kg/m^3)
Upper	732	25.4	1000
Straight-Heavy Clump Weight	348	25.4	1000
Sag bend-Light Clump Weight	24	25.4	1000
TDZ-top	129	25.4	800
TDZ-low	1172	19	600
Bottom	495	22	800

Last configuration that is checked for fatigue analysis is taken from optimisation study in chapter 7 section 7.4. The combination of variation in coating density and applying a numbers of clump weights is the basic for this configuration. Table 8.3 presents the detail of configuration B.

Table 8-3 SCR Segment Configuration (Distributed Weight SCR - Combination)

Riser Segments	Segment Length (m)		Wall thickness (mm)	Density Coating (kg/m^3)
	Coating	Clump Weight		
Upper	880	-	25.4	2200
Straight/Heavy Clump Weight	-	204	25.4	2200
Sag bend/Light Clump Weight	-	36	25.4	2200
TDZ-top	50	-	22	800
TDZ-low	680	-	19	600
Bottom	1050	-	22	800

8.2.2 Time Domain Simulation Parameters

Table 8.4 contains parameters used to perform time-domain simulations.

Table 8-4 Time Domain Simulation Parameters

Parameter	Value
Simulation time	45min*
Time Step	0.33s
Parameter gamma of the Newmark operators	0.5
Global damping	1.27%

*) Three independent simulations of 45 min each at one sea state and fatigue life were simulated and the variation result is less than 1% between the simulations.

8.2.3 Hydrodynamic Coefficients

Similar hydrodynamic coefficients used for strength analysis are applied for fatigue analysis. Cd of 0.9 and Cm of 2.0 are considered.

8.2.4 Fatigue Environmental Conditions

There are 18 sea-states blocks that were taken from scatter diagram. This high numbers of blocks will result in fine description of the wave environmental. Table 8.5 provides fatigue damage probability per sea-state for 8 wave directions.

Table 8-5 Fatigue Sea-state Probability

Seastate No	Hs [m]	Tp [s]	Fatigue seastate probability							
			0°	45°	90°	135°	180°	225°	270°	315°
1	1	7	16.01%	20.53%	16.54%	12.75%	9.46%	7.72%	6.96%	8.53%
2	1	10	9.19%	15.07%	11.07%	9.71%	9.59%	7.73%	8.19%	7.91%
3	1	16.5	1.22%	1.54%	1.03%	0.42%	0.34%	0.45%	0.62%	0.80%
4	2.5	7	15.23%	10.69%	20.06%	17.50%	10.26%	11.31%	14.46%	18.16%
5	2.5	10.5	23.03%	33.86%	28.45%	25.51%	25.93%	25.44%	26.20%	19.70%
6	2.5	17	3.69%	3.00%	2.37%	1.66%	1.97%	2.67%	3.54%	3.45%
7	3.5	7	2.61%	0.68%	1.13%	1.29%	1.12%	2.17%	3.24%	4.58%
8	3.5	11	11.68%	9.13%	10.79%	13.62%	15.88%	14.32%	11.49%	11.14%
9	3.5	17	1.27%	1.40%	0.77%	1.06%	2.25%	3.14%	3.78%	2.25%
10	4.5	9.5	7.49%	1.92%	4.28%	6.18%	7.75%	8.64%	8.57%	9.94%
11	4.5	14.5	0.81%	1.17%	1.40%	2.43%	4.47%	4.06%	3.30%	1.29%
12	5.5	10.5	3.27%	0.43%	0.99%	2.27%	3.24%	4.15%	3.82%	6.01%
13	5.5	15.5	0.58%	0.41%	0.56%	2.21%	2.53%	2.98%	1.85%	0.74%
14	6.5	12.5	2.10%	0.15%	0.39%	1.81%	3.15%	2.95%	2.47%	3.39%
15	7.5	12.5	1.08%	0.02%	0.13%	0.95%	1.25%	1.48%	1.00%	1.11%
16	8.5	13.5	0.59%	0.01%	0.03%	0.52%	0.64%	0.62%	0.44%	0.77%
17	10	15	0.09%	0.00%	0.00%	0.08%	0.13%	0.12%	0.07%	0.17%
18	12	15.5	0.06%	0.00%	0.00%	0.02%	0.03%	0.05%	0.01%	0.05%

This table shows that the main contribution to the total fatigue damage in most cases comes from low- to moderate sea-states with high probability of occurrence rather than a few extreme sea-states. This also means that the degree of non-linearity involved is generally smaller in compared to extreme response analysis.

Table 8.6 provides fatigue probability for each direction.

Table 8-6 Fatigue Probability per direction

Wave direction	Fatigue probability per direction
0	8.50%
45	4.90%
90	8.40%
135	16.00%
180	11.10%
225	13.80%
270	15.70%
315	21.60%

The highest probability is given by wave direction from 315 degree. The wave direction from 315 degree which comes from the other side of riser will cause the riser slack and result in excessive stress cycle due to high bending moment at TDP. Therefore, the initial design of fatigue analysis shall satisfy the damage from low-to moderate sea-states from 315 wave direction.

8.2.5 Design Fatigue Factor (DFF)

A DFF of 10 is used in this analysis by considering riser is a high safety class i.e. the structural failure would cause catastrophic accident. In addition deepwater SCR is considered to be difficult to perform inspection and repair in this area.

8.2.6 Selection of S-N Curve

The basic fatigue capacity is given in terms of S-N curves expressing the number of stress cycles to failure, N, for a given constant stress range, Δσ:

$$N = \bar{a}\Delta\sigma^{-m}$$

Or can also be written:

$$\log N = log\bar{a} - m\ log\Delta\sigma$$

Where a and m are empirically derived and are properties of the material.

To some extent, the fatigue strength of welded joints is dependent on material thickness. The thickness effect is accounted for by a modification on stress such that the design S-N curve for thickness larger than the reference thickness reads:

$$\log N = log\bar{a} - m\log\left(\Delta\sigma\left(\frac{t}{t_{ref}}\right)^{k}\right)$$

Where

t_{ref} = reference thickness equal 25mm for welded connection other than tubular joints. For tubular joints the reference thickness is 32mm. For bolts t_{ref} =25mm

t = thickness through which a crack will most likely grow. $t=t_{ref}$ is used for thickness less than t_{ref}.

k = thickness exponent on fatigue strength
= 0.10 for tubular butt welds made from one side
= 0.25 for threaded bolts subjected to stress variation in the axial direction

The selection of S-N curve depends on [DnV, 2008]:

- The geometrical arrangement of the detail
- The directional of the fluctuation stress relative to the detail
- The method of fabrication and inspection of the detail.

It has been the practice to use seawater S-N curve with cathodic protection for riser joints. Reference is made to DnV RP C203 Table 2-2. Figure 8.1 shows different S-N curves in seawater with cathodic protection. It can be analyzed that the top curve has the highest fatigue strength and vice versa. Therefore, it is important to choose the S-N curve that represents the real situation.

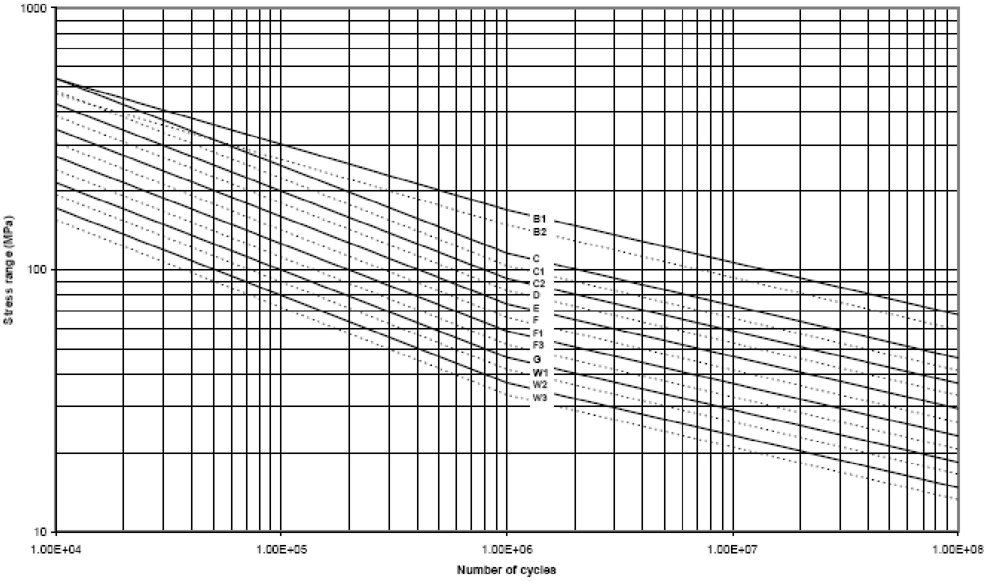


Figure 8-1 S-N Curves in Seawater with Cathodic Protection [DnV, 2008]

In this present study, it is decided to use C-curve. Even though C-curve is considered as high specification, today’s fabrication and inspection technique are able to meet this requirement. In addition, since deepwater SCR is fatigue sensitive, it is important to establish design that is not too conservative.

A lower S-N curve could be applied if the fatigue analysis gives reasonably high fatigue life.

8.2.7 Determination of Stress Concentration Factors (SCFs)

Over the cross section of the pipe, stress is concentrated at some points due to a local increase in the intensity of a stress field. This could be caused by cracks, changes in the cross-sectional area of the object. In SCR weight distributed concept where different wall thicknesses are used, SCF shall be considered. High local stresses can cause the pipe to fail more quickly.

Theoretically, a stress concentration factor may be defined as the ratio of hot spot stress range over nominal range.

In this present study, a SCF of 1.05 is considered. This number is relatively low value for SCF. Therefore it is important to establish fabrication technique such that it could eliminate any major stress concentration over pipe cross section. A higher SCF can be applied if the fatigue life shows acceptable result.

8.3 Assumptions

The following assumptions are used for fatigue analysis:

1. The SCR material is assumed to obey the S-N relationship
2. The Palmgren-Miner linear damage accumulation hypothesis (Miner's Rule) is assumed to apply. When the long-term stress range distributed is expressed by a stress histogram, consisting of a convenient number of constant stress range blocks $\Delta\sigma_i$ each with a number of stress repetitions n_i the fatigue criterion reads:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{1}{\bar{a}} \sum_{i=1}^{k} n_i . (\Delta\sigma_i)^m \leq \eta$$

   Where
   D = accumulated fatigue damage
   $\bar{a}$ = intercept of the design S-N curve with the log N axis
   m = negative inverse slope of the S-N curve
   k = number of stress blocks
   n_i = number of stress cycles in stress block i
   N_i = number of cycles to failure at constant stress range $\Delta\sigma_i$
   η = usage factor
   = 1/ DFF

3. The scatter diagram is assumed to cover the range of possible conditions at the site and to be sufficiently finely defined that a finer discrimination between distinct sestates would not materially alter the predicted fatigue life.

8.4 Fatigue Analysis Procedure

Wave-induced fatigue is contributed from wave frequency (WF) and low frequency (LF) stress cycle. The direct wave loading on the riser and WF floater motions contribute to WF fatigue damage. LF floater motions govern LF fatigue damage. According to DnV, 2001, the step-by-step procedure for calculating WF and LF fatigue damage is described below:

- Divide the wave scatter diagram into a number of representative blocks.
- Perform nonlinear time domain analysis for one representative sea state for each of these blocks. This representative sea state has the highest occurrence within that block.
- Estimate the fatigue damage within each simulation using rain-flow counting procedure and weight that with the probability of each block.
- Sum-up the fatigue damage over all the blocks and obtain the fatigue damage for that direction
- Perform the same procedure for all 8 directions and sum-up the total fatigue damage by applying directional probabilities.
- The predicted fatigue life is the reciprocal of this cumulative damage rate.

8.5 Fatigue Analysis Results

In this section, there are three fatigue results:

- Fatigue analysis for SCR weight distributed by varying coating's density.
- Fatigue analysis for SCR weight distributed by applying a numbers of clump weights.
- Fatigue analysis for SCR weight distributed by combining a variation in coating density and a number of clump weights.

All these solutions have proved a promising solution for strength design check according to study in chapter 6 and 7.

8.5.1 Fatigue Life at Hang-off Location

Table 8.7 presents the minimum fatigue life for all cases. S-N C-curve with SCF 1.05 was applied in fatigue analysis.

Table 8-7 Minimum Fatigue Life at Hang-off Location

Location	**Minimum Fatigue Life (Years)**		
	Coating	**Clump weight**	**Combination**
Hang-off	288	140	200

Figure 8.2, 8.3 and 8.4 show the fatigue life at hang-off region for weight distributed SCR with external coating density, weight distributed SCR with clump weights and weight distributed SCR with combination of both respectively.

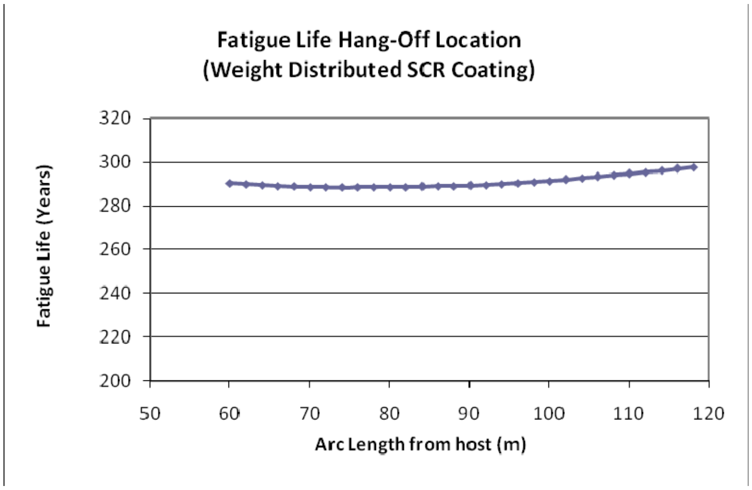


Figure 8-2 Fatigue Life Distributed SCR Coating at Hang-off Location

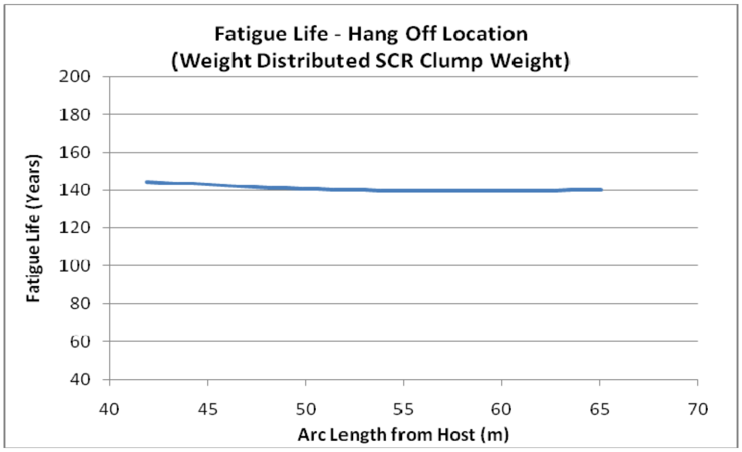


Figure 8-3 Fatigue Life Distributed SCR Clump Weight at Hang-off Location

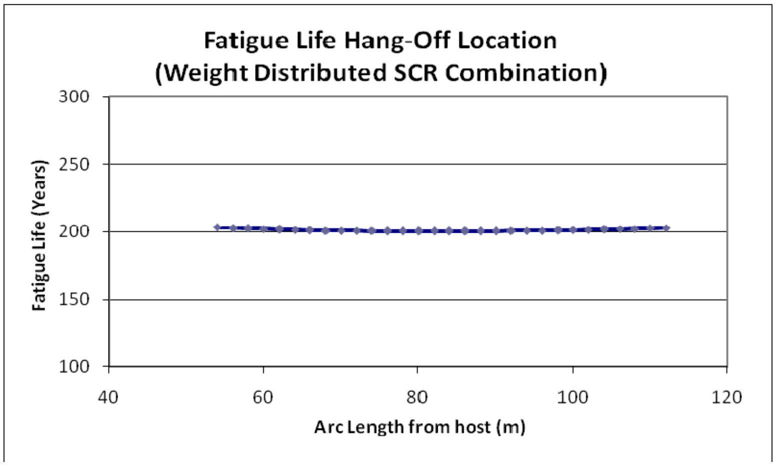


Figure 8-4 Fatigue Life Distributed SCR Combination at Hang-off Location

Minimum fatigue life from weight distributed SCR coating is 288 years which is acceptable (above 200 years). However, fatigue life derived from weight distributed clump weight is beyond the limit with only 140 years and fatigue life from weight distributed combination is just at the limit with 200 years.

The low fatigue life at hang-off location for weight distributed SCR with clump weight is suspected due to highly platform motions and high tension force. In order to increase fatigue performance, reducing SCR weight may be necessary. This can be achieved by combining the concept of clump weights and external coating density, and the result shows increment in fatigue life to 200 years and hence acceptable.

8.5.2 Fatigue Life at Touch-Down Region

Fatigue analysis results at touch-down region are provided in table 8.8.

Table 8-8 Minimum Fatigue Life at TDA

Location	Minimum Fatigue Life (Years)		
	Coating	Clump weight	Combination
TDA	385	350	385

In addition, figure 8.5, 8.6, and 8.7 are provided to understand the fatigue life curve at TDA.

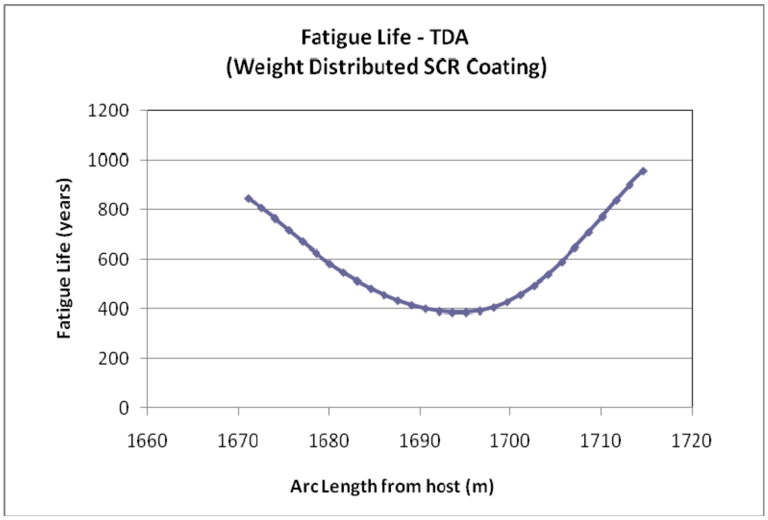


Figure 8-5 Fatigue Life Distributed SCR Coating at TDA

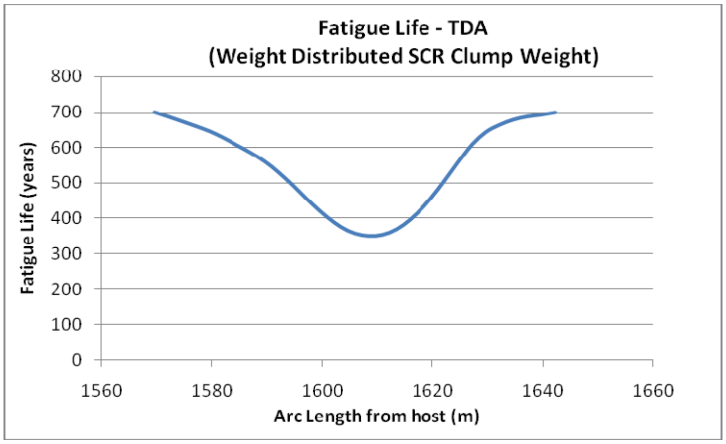


Figure 8-6 Fatigue Life Distributed SCR Clump Weight at TDA

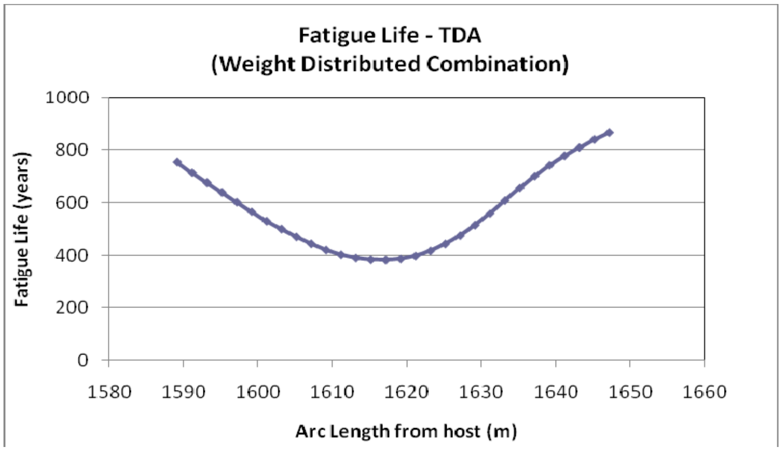


Figure 8-7 Fatigue Life Distributed SCR Combination at TDA

All riser configurations have shown acceptable fatigue limit. Small difference is observed between all the riser configurations with highest minimum fatigue life of 385 years and lowest minimum fatigue life of 350 years. The concept of applying heavy weight at straight part of riser and light weight at TDA leads to small displacement at this region. Hence, lower S-N curve and higher SCF value can be applied to reduce the development cost.

In addition, it can also be observed that the minimum fatigue life appears to be concentrated over a small length of SCR. It is noted that only about 30m at TDA has fatigue life below 500 years for all riser configurations. It is a good indication if any fatigue improvement is required. For instance, particular weld quality improvement is applied over span 30m in order to increase fatigue performance.

8.6 VIV Fatigue

Riser vortex induced vibration (VIV) has been a primary design challenge for deepwater applications. Vortex-induced vibration occurs anytime when a sufficiently bluff body is exposed to a fluid flow that produces vortex shedding at, or near, a structural natural frequency of the body. There are two modes of VIV according to flow direction: in-line and cross flow (Figure 8.8).

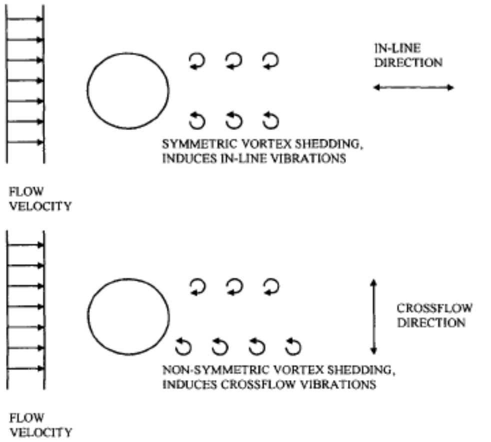


Figure 8-8 Typical Flow behind the Cylinder

There are two different VIV aspects, current induced VIV and vessel heave induced VIV, and the first of these is usually of major concern. High levels of VIV fatigue damage can be accumulated in relatively short periods of time in the severe currents encountered in most of the deep water development areas worldwide.

Although VIV does not contribute significantly to extreme stresses as it occurs in the plane perpendicular to the current stream plane where peak bending stress occur, it can cause high fatigue damage due to its high vibration frequency. The study from STRIDE project [Stride, Sept 1997] shows that damage response from VIV for simple catenary can be high with failure predicted in months rather than years.

For typical riser in deepwater field and harsh environments, riser becomes more critical to VIV for reasons provided below [Bai, 2005]:

1. Strong currents are typically observed in deepwater.

2. The increased length of the riser lowers its natural frequency thereby lowering the magnitude of current required to excite VIV
3. Since deepwater riser is connected to floating platform, there are no structures adjacent to which riser could be clamped.

In addition, deepwater currents usually change in magnitude (and direction) with depth. As a result, it is possible that multiple modes of the riser can be excited into VIV. This makes deepwater riser VIV prediction much more complex than that for short riser spans typical of fixed platforms in shallow water.

8.6.1 SCR VIV Fatigue Analysis Procedure

In order to predict fatigue life of deepwater steel catenary riser experiencing VIV, it is important to estimate response amplitude and frequencies accurately. There are several basic parameters that have to be considered to predict accurate amplitude and frequencies:

- The current profile in terms of magnitude and shape variation with depth.
- The frequency and magnitude of the lift force imparted to the riser by the vortex shedding.
- The excitation and correlation lengths of the lift forces and vortex shedding.
- The hydrodynamic damping.
- The riser structural properties: damping, mass, tension, bending stiffness, and cross sectional geometry.

Cross flow response is more significant than in-line response [Bai, 2005]. In addition, cross flow vibrations of a riser in severe currents can diminish the riser fatigue life, dictate the riser arrangement, fabrication details, vessel layout, installation method, and thus have significant cost impacts at all stages of the field development [Dale, N and Bridge, C, 2007].

General methods of predicting long term VIV fatigue damage are described below:

- Analysis must be conducted with a number of current profiles of varying severity, typically based on exceedence level.
- The fatigue damage obtained assuming continuous application of each profile is then factored according to the assumed duration of the profile
- The total long term damage is given by the sum of the factored damage from each profile. As the more severe current profiles generally produce greater rates of fatigue damage, a more refined selection of profiles is required amongst the low exceedence levels.

Analysis of vortex induced vibrations in riser systems is widely carried out using the program SHEAR7, developed at MIT under a joint industry research study. The program enables prediction of riser VIV response under uniform and sheared current flows. In addition, the program called VIVANA which was developed by Marintek Norway can also be used to predict fatigue life due to VIV.

8.6.2 VIV Suppression Devices

As it is understood from the discussion in previous section, in most deepwater development areas, SCR may fail to meet fatigue design criteria due to VIV. One solution is to change to riser system e.g. changing the mass, increasing the tension or even changing the riser configuration. However, this solution gives a major change in riser system concept. More acceptable solution is to provide VIV suppression devices to reduce the vibration.

A numbers of VIV suppression devices have been extensively used in industrial practice. Strakes, fairings or a combination of both are normally applied to steel riser.

(a) Stakes (b) Fairings

Figure 8-9 VIV Suppression Devices

Helical strake is the most common strakes used as VIV suppression devices. The strakes are screw-like protrusions that are wrapped around the cylinders to suppress flow vortices by shortening their correlation lengths. The efficiency of the helical strakes is dependent on the height of the protrusion and the pitch of the helical, i.e. the length of a full wrap around the cylinder. However, strakes have disadvantage of increasing riser drag. This may lead to higher extreme storm stresses. They will also increase the fabrication and installation cost. Description of stakes is shown in figure 8.9a.

On the other hand, fairings can reduce Vibration without incurring an increased drag loading. However, the difficulty of handling which results in costly development cost remains the same for fairings. Description of fairings is shown in figure 8.9b.

Therefore, accurate VIV prediction is highly important in order to have high level of confidence result. The prediction from software program may be overly conservative due to some uncertainties in describing VIV. Therefore, model testing of VIV may be necessary to have more economical SCR design.

Detail VIV analysis is not performed in this present study due to limitation of scope of study. For further work, the study on VIV fatigue with different riser configurations may be useful in order to have complete deepwater SCR design.

8.7 Discussion and Conclusion

Some discussions and conclusions can be derived from the study in this chapter:

- Fatigue life at hang-off location shows lower value than fatigue life at TDA. It might be influenced by excessive host platform movement. Semi-submersible allows significant movement in all degrees of freedom. At TDA, the high movement of SCR from host platform has been taken care by heavy segment along the straight segment of SCR. This leads to acceptable movement of SCR at touch down region. Hence, it can be concluded that the concept of weight distributed SCR results in acceptable fatigue performance around TDA and SCR tension force at top-end shall be limited such that it is still above acceptable fatigue limit.

- Critical fatigue life at TDA is within short span. It is a good indication if any fatigue improvement is required. On the other hand, at hang off location, the fatigue life is rather constant along the wave affected region.
- Fatigue life at hang-off location has strong relation with top tension force. Results from three different SCR configurations (weight distributed coating, clump weights and combination) show that higher tension force at top-end gives lower fatigue life. This requirement is opposite with strength design where heavy segment is required to reduce excessive stress around TDA. Therefore, it is important to establish optimum solution that works for both strength and fatigue design.

CHAPTER 9 DEEPWATER SCR INSTALLATION SCHEME

9.1 Introduction

One of the major issues in designing steel catenary riser is total development cost. Operators are facing the challenge to reduce development cost, especially for deepwater riser installation. High specification vessels with high day rates and mobilization costs are required to install deepwater riser systems. Therefore, it is important to choose installation method to keep the development in acceptable margin.

Steel catenary riser may be installed as an extension of the seabed pipeline. However, unlike the pipeline, the riser is highly dynamic and consequently requires a higher level of fabrication quality, installation accuracy and component design than the pipeline section. Furthermore, installation of SCR in harsh environments has very small weather window which results in non-flexible installation schedules. One way to deal with this situation is by pre-installing the riser in summer months. As the host platform is in-place, the riser is pulled in separately using the platform winch. This concept leads to two main parts of SCR installation execution:

- Laying pipe on the seafloor
- Pull-in

It is also possible to have direct connection from lay vessel to host platform for the case that host platform is already in-place. The procedure may be different. In this present study, it is assumed that the host platform will come after the riser installation. Therefore, pre-installed riser on sea-floor and further hook up to host platform is chosen.

9.2 Pipe Laying

There are many ways in laying the pipe on the seafloor. Many pipes are constructed by the lay barge method. Many small and intermediate diameter lines are constructed by the reel ship method. Another method of pipe construction is tow-in.

The lay barge method is normally applied for intermediate to large diameter lines. The pipe laying can be performed by 2 methods: S-lay and J-lay.

9.2.1 S-Lay Pipe Installation

Pipe leaves the stern end of the barge almost horizontally, then goes over stinger in an overbend (convex upward) until it leaves the stinger at the lift-off point. It then bends the other way in a suspended span forming a sag-bend (convex downward). The weight of the pipe in the sag-bend is supported by the applied tension. The schematic figure of S-lay is presented in figure 9.1 below.

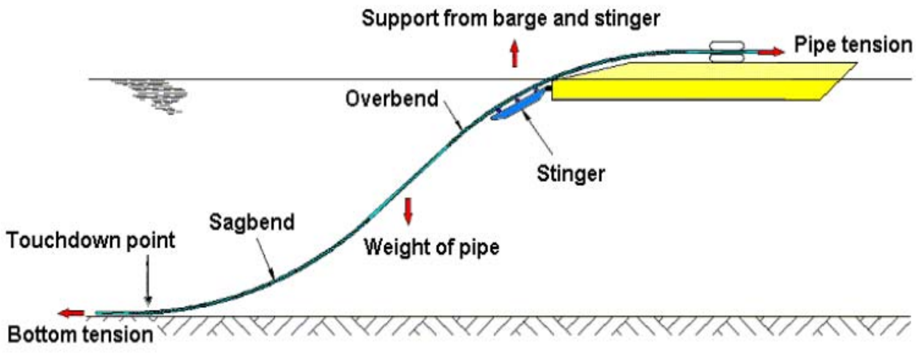


Figure 9-1 S-Lay Pipe Laying Schematic

S-lay pipe lay is considered to be the most common use world-wide. It is suitable for shallow water and to some extent deep water field. It is also fast and efficient way of welding pipe offshore. However, this method has some constraints especially in deep water installation. In deepwater, the tension has to be high, and the stinger has to be long. A very long stinger is undesirable because it is excessively vulnerable to wave and current forces. High tension is undesirable because of the risk of tensioner damage to the pipe coating and because the tension has to be balanced by the barge's mooring or dynamic positioning system.

9.2.2 J-lay Pipe Installation

J-lay installation overcomes some of obstacles of S-lay installation. J-lay pipe installation puts less stress on the pipeline by inserting the pipeline in an almost vertical position (75 deg to the horizontal). This results in no overbend and the entire suspended span has the form of an extended letter J (Figure 9.2). Therefore, J-lay can work in deep water depths.

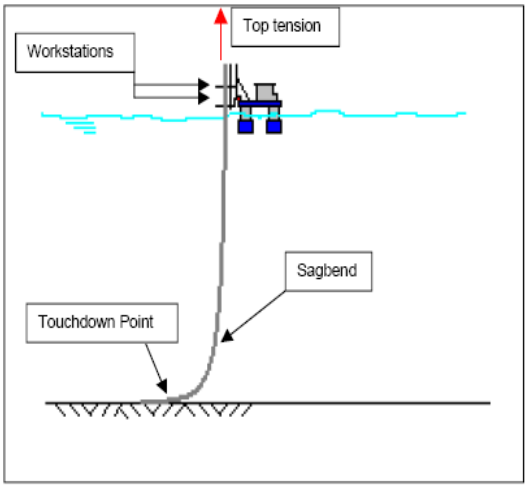


Figure 9-2 J-lay Pipe Laying Schematic

9.2.3 Reel Lay Pipe Installation

The reel ship method can perform S-lay and J-lay method depending upon reel barges. Horizontal reel barges perform S-lay installation; while vertical reel barges can perform both S-lay and J-lay pipeline installation. The pipe fabrication is done onshore, hence reducing installation costs. Reeled pipe is lifted from the dock to the vessel, and the pipe is simply rolled out as installation is performed. Figure 9.3 shows the Seven Oceans vessel from subsea7 that uses reel method for laying the pipes.

Figure 9-3 Reel Ship "Seven Oceans"

9.2.4 Tow-Out Installation

Last pipe laying method is tow-out installation. The pipe is suspended in the water via buoyancy modules, and one or two tug boats tow the pipe into place. Once on location, the buoyancy modules are removed or flooded with water, and the pipe floats to the seafloor. There are four main forms of tow-in pipe installation according to the location of pipe on the seawater. **Surface tow** involves towing of pipe on top of the water. Using less buoyancy modules than the surface tow the **mid-depth tow** uses the forward speed of the tug boat to keep the pipeline at a submerged level. **Off-bottom tow** uses buoyancy modules and chains for added weight, working against each other to keep the pipe just above the sea bed. The **bottom tow** drags the pipe along the sea bed, using no buoyancy modules [Hellestø, et al, 2007].

9.3 Selection of Pipe Lay Installation Method

A selection of pipe installation is important in order to optimize development cost. Discussion on advantages and disadvantages of S-lay, J-lay and reel lay is presented as follows:

S-Lay:

- Most common use world-wide
- Fast and efficient way of welding pipe offshore i.e. in high pipe laying rate
- Several lay vessels and barges available on the market
- Encounter difficulties in very deep water

J-Lay:

- Feasible for laying pipelines in very deep water (>1000m)
- Field proven for simple steel catenaries
- Required lower tension compared to S-Lay method
- Result in low bottom tensions, i.e. reducing seabed span

- Pipe progress depends entirely at one spot (welding, testing and coating)
- Slower pipe laying rate than S-lay method

Reeling

- A number of reel-ship are available in the market
- Pipe is welded onshore, reducing critical path offshore
- Efficient for short pipelines close to onshore spoolbase
- Fast laying operation
- Limited to 16" pipe diameter
- Length limited by maximum reel size
- Long pipelines or remote locations result in long transit time and need for return trips

Tow-Out

- Elimination of high specification vessels
- Fast offshore operations
- Improved control over fabrication quality
- Less static stress during installation
- Additional fatigue damage consideration during tow
- Requires suitable location for launch
- Additional cost of ballasting

By considering all the advantages and disadvantages above pipe lay method, it is decided to use reel lay method to install SCR in this study, because:

- Small diameter used (10" ID)
- Relatively short total pipe length (2900m)
- Thick wall thickness has already been considered for collapse resistance in deepwater field.
- High quality welding is required due to fatigue sensitive during SCR operation.
- Riser installation in Offshore Norway is not considered as remote locations.

9.4 Reeled Pipe Installation Procedures

The reeled pipe laying comprises a number of sequences. It is started from pipe fabrication onshore until offshore installation as discussed below.

9.4.1 Onshore Fabrication

Pipes for SCR are assembled at an onshore spool-base facility. All welding and testing are completed in the controlled environment of an onshore spool-base, and hence ensure the pipe quality.

Figure 9-4 Pipes Onshore Fabrication – Vigra Spoolbase

9.4.2 Spooling and Reeling

After the pipes are fabricated onshore, the pipe is wound onto a large diameter drum of a reel vessel.

Figure 9-5 Pipe Spooling onto Pipelay Vessel - Scandi Navica Subsea 7 Vessel

As shown in figure 9.6, pipe is reeled on the big drum diameter. The back-tension is initially applied on the pipe in order to have desirable pipe curvature on the drum (Figure 9.7). The applied back tension is indicated in point 1 figure 9.6. Figure 9.8 shows the pipe curvature if back tension is not sufficiently applied. After the pipe is reeled onto the drum, the vessel travels to the site of the riser.

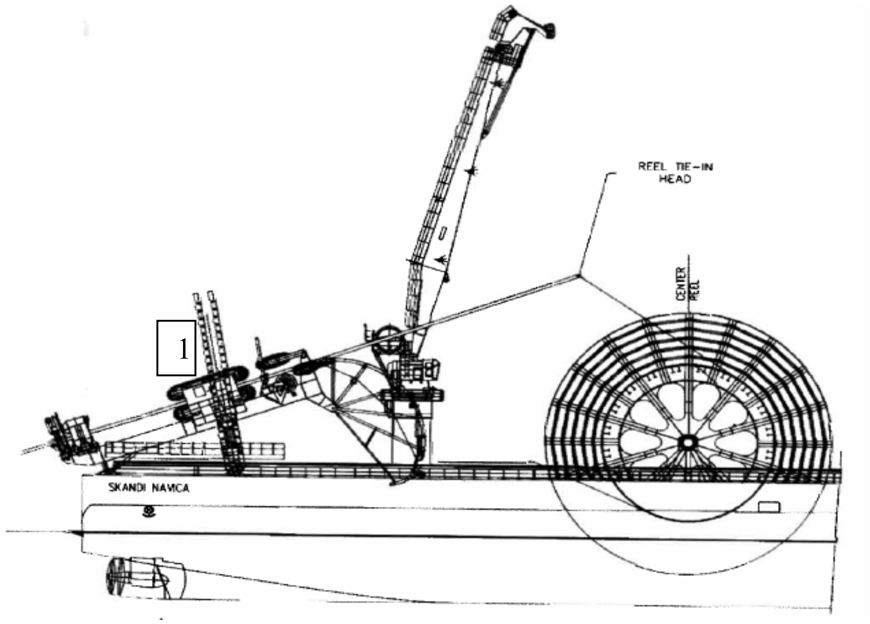


Figure 9-6 Pipe Reeling Process -Scandi Navica Subsea 7 Vessel

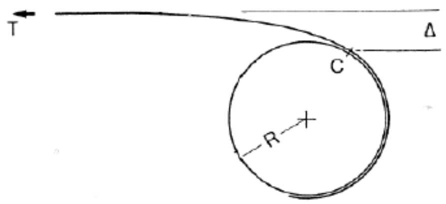


Figure 9-7 Desirable Pipe Curvature on reel drum

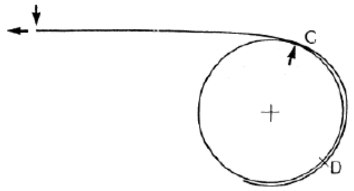


Figure 9-8 Undesirable Pipe Curvature on Reel Drum

9.4.3 Offshore Installation: Unreeling & Straightening

Once the vessel is at the site, unreeling process is performed. During unreeling of the pipe, it follows the following sequences (Figure 9.9):

1. Reeling onto reel
2. Unreeling with the pipe having a curvature with some radius between the reel and aligner.
3. Bending over the aligner
4. Straightening

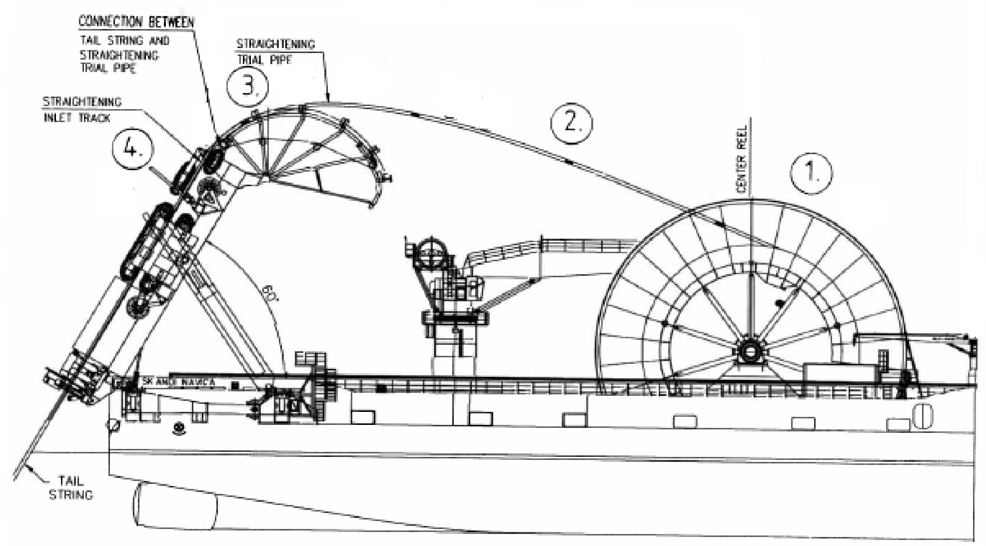


Figure 9-9 Unreeling and Straightening Process - Scandi Navica Subsea 7 Vessel

Typical stress-strain relationship for a pipe undergoes reeling-unreeling-straightening process is provided in figure 9.10 below.

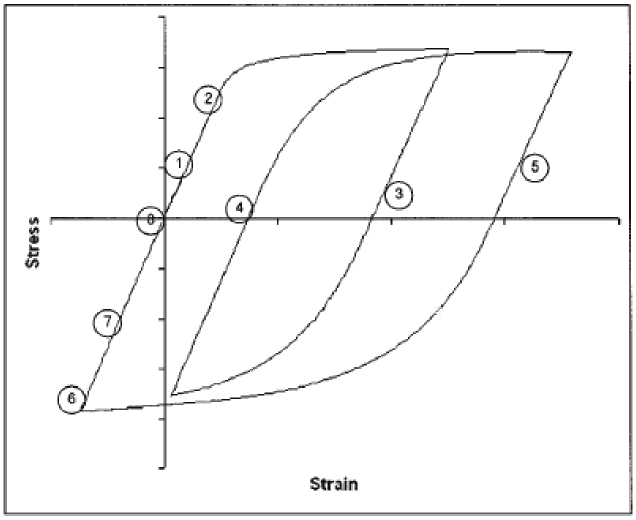


Figure 9-10 Typical stress-Strain Relationship for a Pipe undergoes Reeling-Unreeling-Straightening

Explanation on the numbering in the figure:

1. Tensioned before reeling
2. Bending to get onto the reel
3. Release of bending when unreeling, straightening between reel and aligner
4. bending when entering into the aligner
5. release of bending when going out the aligner
6. Bending when going into the straightener
7. release of bending when going out the straightener
8. release of tension

9.4.4 Offshore Installation:Laying on the seabed

The last step on riser lay on sea-floor is deployment of pipe from vessel to seafloor. The pipe is laid in a J-lay configuration using a variably ramp. As the pipe enters the water at a steep angle, the sag-bend is controlled by lay tension imparted by the reel. ROV is used to provide a visual reference, especially at touch down point of the pipe.

It is also important to design that there will be no compression in sag-bend. There is a possibility of pipe experiences compression due to excessive vertical dynamic effects on the pipe (heave velocity at the vessel).

9.5 SCR Pull-in and Hang-off Procedures

A support vessel is required to retrieve the SCR from the seabed and transfer the handover to the host platform. Although this method is technically feasible, it requires a complex offshore operation in which the riser is retrieved from the seabed by a support vessel and handed to the host platform prior to the connection of the platform anchor system.

An installation sequence that was adopted from STRIDE project study is presented below for description purpose:

1. The riser is laid past the theoretical FPS location and after installation of the Flex-joint abandoned on the seabed.
2. When the FPS arrives in the field and prior to the hook-up of the anchor system, an MSV (Multipurpose Support Vessel) can retrieve the SCR from the seabed using a single point lift technique with a swivel joint on the recovery head.
3. Prior to anchor leg hook-up, the MSV can then manoeuvre to a position with its stern facing the FPS unit and with the assistance of the FPS unit crane or project supplied winch, lay the SCR into the hangoff receptacle.
4. The final mean hang off angle can then be verified using an inclinometer.

In this procedure, it is important to note that the entire length of SCR must be designed to withstand the installation water depth hydrostatic pressure. For the case that SCR has VIV suppression strakes, there is potential damage to strakes when the riser is laid on the seabed.

9.6 Reel Lay Vessel – Installation Equipment

Typical reel-lay operations are supported by four main items of equipment as detailed below:

1. Stern Ramp
2. Tensioner
3. Straightener / Aligner
4. Reel

9.6.1 Stern Ramp

The stern ramp assembly carries all the pipe laying and straightening equipment. The angle of the ramp can be adjusted to provide departure angles for laying. During reeling operations, ramp angle is adjusted to be about 15-18 degree depending on riser diameter. During pipe lay, a departure angle of about 70 degree can be achieved by adjusting the height of the stern roller box.

9.6.2 Tensioner

The pipe tensioner is normally located on the stern ramp forward of the welding station. Its function is to assist the reel in maintaining constant tension on the pipe, to prevent spontaneous unwind, to assist feeding pipe to and from the reel, and to maintain the pipe in position during tie-in [STRIDE, 1997].

9.6.3 Starightener/Aligner

The pipe straigtener is positioned on the stern ramp forward of the tensioner. The essential parts are the pipe aligner; and a lower and upper track type roller, longitudinal offset. All three parts can be adjusted to compute settings, to induce a reverse curvature and thereby effect straightening of pipe after reeling.

The pipe aligner comprises a series of rollers mounted in a radius arm and is located at the top of the stern ramp. It aligns and supports the pipe going onto or off the reel [STRIDE, 1997]

9.6.4 Reel

The reel is located forward of the ramp and midship on the vessel. The function of the reel is to store the pipe to be laid, hold constant tension on the pipeline, and reel pipe on or off the vessel.

9.7 Design Considerations

There are some design parameters that are important during riser installation design.

9.7.1 Tensioner Capacity

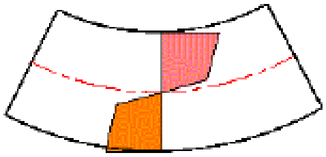
Tensioning system during pipe lay onto seafloor is important. The interaction between applied tension and the submerged weight of the pipe control the shape of the pipe in the sagbend. If applied tension is not sufficient, excessive curvature might be experienced and the pipe may buckle. Therefore, it is important to have sufficient tensioner capacity on the lay vessel.

9.7.2 Bending Strain

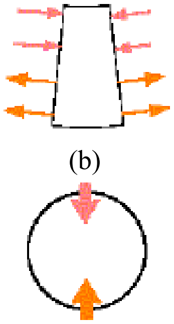
The bending strain of the pipe is mainly influenced by pipe's wall thickness. Too thin a wall thickness will result in the pipe buckling when subject to plastic bending. However, for deepwater riser, the requirement of wall thickness to satisfy hydrostatic collapse is considered to be sufficient to prevent pipe buckle during installation.

9.7.3 Ovalisation

Ovalisation is deviation of the perimeter from a circle. This has the form of an elliptic cross section. During unreeling process, plastic pipe bending induces ovality. Figure 9.11 shows the mechanism of ovalisation during bending of the pipe.



(a)

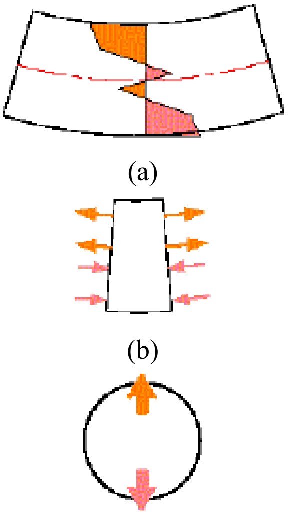

(b)

(c)

Figure 9-11 Pipe Ovalisation due to Bending

The longitudinal stress is experienced by the pipe due to applied bending. Figure 9.11a shows the distribution stress over the pipe. Pipe is bent beyond yield. Force on a short component is shown in figure 9.11b. Since the ends of element not in line, net effect of the forces tends to induce ovality as shown in figure 9.11c.

Straightening processes recover some of the ovality induced by the initial bending. The recovery mechanism is shown in figure 9.12. Pipe is bent plastically to positive curvature results in tension force on the upper region of the pipe and compression force on the lower region of the pipe as shown in figure 9.12a and 9.12b. Flex pipe back towards circular form (figure 9.12c).


(a)

(b)

(c)

Figure 9-12 Ovalisation Recover from Straightening Processes

According to DnV OS F101, recommended ovalisation should not exceed 3% unless additional design considerations are considered.

9.7.4 Collapse Resistance

Steel catenary risers in deepwater is often limited by the collapse resistance of the riser as they may be installed empty to keep the riser weight within the pipe lay vessel's tensioning capacity. In order to resist overpressure, thick wall thickness may be required.

9.7.5 Design Limiting Sea-states

Considering all environmental loads and vessel motions to determine allowable lay sea-states with the limits being set based on pipe strains. Dynamic analyses shall be performed for different sea-states with the sea-states being defined by a JONSWAP spectrum.

The limiting sea-state can be defined by limiting significant wave height (Hs) for each operation step (In air, splash zone, submerged, sag-bend).

9.7.6 Limiting Vessel Motions

In order to secure the pipe during laying on the seabed, vessel motions (roll and pitch motions) shall be limited and adhered to for each operation step. The vessel shall also be oriented such that it reduces to effect of environmental load.

9.7.7 Fatigue Life

It is important to synchronize the stress concentration factor (SCF) and S-N curve used for fatigue design and with what maximum can be achieved in a reeled pipe. There might be a possibility that high quality of S-N curve and low value of SCF could not be used due to reeling process that pipe is experienced. Furthermore, it is important to reduce the possibility of accumulated plastic strains imposed during reeling, unreeling and straightening during the reel-lay process would not affect the pipe fatigue life. In order to avoid this possibility, each of the full scale weld fatigue test pipe samples is pre-strained in a rig to simulate the reeling and unreeling process.

9.7.8 Lay Vessel Operation

It is important to notice that for typical SCR which operates in harsh environments, there are small weather windows for installation. Hence, riser installation can not be conducted all year round. Instead, risers are often pre-installed in summer months and later recovered as the host platform is in-place.

In addition, with respect to fatigue during pipe installation, allowable standby durations shall be designed to avoid fatigue limit during installation e.g. maximum fatigue damage 0.01.

9.7.9 Clearances

During pipe lay, clearance between riser and moon-pool edges shall be monitored. As the pipe approaches seabed, clearance between sag-bend and seabed is also important. Sag-bend section shall not touch the seabed in order to avoid any compression on the pipe.

9.8 Conclusion

There are a number of installation methods available in the market. However, Deepwater SCR installation limits the method to J-lay, reel-lay or tow out. In addition, installation in harsh environmental conditions requires high rate of pipe lay. Therefore, J-lay method is rather difficult due to slow production rate.

In this present study, 10” inner diameter with thick wall thickness has been considered. It is therefore preferable to use reel-lay method for laying the pipe. A number of design considerations shall be taken care such as tensioner capacity, maximum bending strain, ovalisation, collapse resistance, etc.

CHAPTER 10 CONCLUSION AND RECOMMENDATION

10.1 Conclusion

Steel Catenary Riser posed several significant technical challenges for application in deepwater and harsh environments. Large vessel motions and significant riser dynamic behaviour are some challenges that SCR design has to address. In addition, solution to SCR concept for deepwater and harsh environments is still limited to date. On the other hand, future exploration of oil and gas is predicted to go into deeper water and harsher environments, as explorations in shallower water and milder environments have been extensively explored. Therefore, it is important to establish suitable deepwater SCR design.

Conventional SCR with uniform external coating found difficulty in meeting the strength design requirement. High displacement, velocity and acceleration were observed at touch down region. This reflects the situation of high movement of soil-riser interactions. An excessive bending moment at TDP was observed as a result of inability to distribute the bending moment peak before TDP.

This leads to the requirement to establish “near-bottom support”, in addition to “bottom support” at TDP. This is the same concept as lazy wave riser configuration. Instead of providing positive buoyancy at lower part of riser to form a wavy shape, negative buoyancy is applied by increasing the weight at the region before sag-bend. This concept is then called weight distributed SCR.

The concept of weight distributed SCR shows a promising solution to conventional SCR by establishing additional near-bottom support. Providing heavy segment before sag-bend and light segment at touch down region improve the SCR response significantly.

There is a conflicting requirement in satisfying both strength and fatigue design criteria. In strength design, providing sufficient heavy segment is important to reduce SCR’s movement at TDP. However, fatigue analysis requires as light weight as possible at top-end tension and TDA. This leads to concept of providing intermediate coating density in weight distributed SCR by coating and light clump weight in weight distributed SCR by clump weight, in order to provide smooth transition from heavy segment to light segment. This concept could reduce total length of heavy segment and numbers of clump weights significantly. Therefore, optimum configuration can be obtained.

The comparison study between conventional SCR and weight distributed SCR shows that displacement, velocity and acceleration of riser has strong relation to Von Mises stress. Weight distributed SCR concept can reduce these parameters almost half than conventional SCR i.e. more stable riser behaviour. In addition, there is significant different in riser configurations. In conventional SCR, there is a sudden drop of pipe as it touches sea bottom. Meanwhile in weight distributed SCR, there is a smooth approach of pipe to sea bottom. This is mainly because of the application of light segment at touch down region for weight distributed SCR. Therefore, it is suggested to establish smooth approach to sea bottom in order to avoid excessive bending moment at TDP.

Detail sensitivity studies on varying total length of heavy segment and varying heavy segment weight in weight distributed SCR have been performed. The results show that SCR response is insensitive to length of heavy segment; meanwhile there is significant response to SCR due to variation in heavy segment weight. In other words, providing concentrated heavy segment is more significant than providing spread medium segment before sag-bend region.

The study on weight distributed SCR by varying density coating along the riser has limitation in maximum density coating to be used. The 2800 kg/m^3 coating density was considered to be difficult to be applied in industrial practice. The study on weight distributed SCR by applying a numbers of clump weights has also limitation in clump weight. 4 ton/m clump weight is considered to be too heavy during installation.

This leads to optimisation study of SCR configuration. Combination of varying external coating density and applying a numbers of clump weights gives an innovative solution. Maximum heavy coating density can be limited to 2200 kg/m^3 which considered available in industrial practice and maximum clump weight is limited to 3 ton/m with the total numbers of clump weight of 20.

The comparison study between weight distributed SCR coating, weight distributed SCR clump weight and weight distributed combination show that the velocities at TDP fall in about the same region (2.1 m/s – 2.6 m/s).

Weight distributed SCR concept with light weight at TDA gives good fatigue performance with 350 years as minimum of fatigue life. Providing a number of clump weights on SCR results in relatively high tension force at the hang-off location. This leads to low fatigue performance at this region with fatigue life of only 140 years. A combination of variation in coating's density and a number of clump weights improves the fatigue life at hang-off location to 200 years and fatigue life at TDA remains high with 385 years.

A numbers of installation methods are available. Reel lay method is chosen for installing SCR in this study due to small diameter pipe (10 inch), short total pipe length (2900m), thick wall thickness and requirement of high quality welding to meet fatigue requirement. A number of design considerations such as tensioner capacity, bending strain, ovalisation, collapse resistance during pipe lay, limiting seastates, limiting vessel motions, clearances and fatigue life are important.

In summary, the concept of distributing weight along the riser improves the SCR response for both strength and fatigue design. An optimisation riser configuration by combining a concept of variation of coating density and applying a number of clump weights results in more applicable concept than any other riser configurations.

10.2 Recommendation

For global response:

- In this present study, the attainment of platform motions applied to the top of riser consists in the use of de-coupled methodologies. This methodologies consider the static environmental loads over the platform (current and wind) through a static offset and dynamic environmental loads are incorporated through vessel's RAO (Response Amplitude Operators). As the explorations of oil and gas shifts to deeper water, more accurate methodologies is required in order to optimise the SCR design. New method of so-called coupled analysis considers the interaction between the hydrodynamic behaviour of the hull and the structural behaviour of mooring lines and risers submitted to environmental loads. The coupled analysis is considered to be a more accurate analysis and less conservative method. Hence, coupled analysis methodology is recommended for further work of SCR in deepwater and harsh environments. Combined software between RIFLEX and SESAM's DeepC package can be used to perform coupled analysis of mooring and riser systems connected to floating production units in deep water.

- A number of different riser sizes may be useful to be studied in order to understand the riser's behaviour with respect to different sizes. Clearance between risers becomes an issue because different riser sizes have different riser behaviours. Static vessel offset to transverse direction shall be applied.

For fatigue Analysis:

- Vortex induced Vibration fatigue analysis shall be analyzed because this issue becomes critical as the development goes into deeper water with high current.
- Fatigue during SCR's installation is recommended to be analyzed, particularly for reel-lay method where the pipe is forced to go into plastic deformation during reeling-unreeling process.

For installation Analysis:

- Detail analysis of SCR installation is recommended. Some critical phases during reeling-unreeling process as well as during pipe lay to sea floor may change riser properties. Wall thickness is one of important parameters for typical deepwater installation.

REFERENCES

Alderton, N and Thethi, R (May 1998): Choosing the Most Appropriate Rigid Catenary Riser Design for Various Deepwater and Harsh Environments. Advances in Riser Systems & Subsea Technologies for Deepwater. Aberdeen, UK.

API Recommended Practise 2RD First Edition (1998): Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs), American Petroleum Institute, June, USA.

Bai, Yong and Bai, Qiang (2005): Subsea Pipelines and Risers. pp. 401-453.

Baltrop N.D.P (1998): Floating Structures: A Guide for Design and Analysis Vol.1 and 2, the Centre of Marine and Petroleum Technology.

Burgess, M and Lim, F: Installation of Deepwater Risers, 2H Offshore, UK

Clausen, T and D'Souza, R (May 2001): Dynamic Risers Key Component for Deepwater Drilling, Floating Production. Offshore Magazine May 2001.

Dale, N and Bridge, C (July 2007): Measured VIV Response of a Deepwater SCR. Proceeding of the 17th International Offshore and Polar Engineering Conference, 1-6 July 2007. Lisbon, Portugal.

DNV-RP-C203 (April 2008): Fatigue Design of Offshore Steel Structures, Det Norske Veritas, Norway

DNV-OS-F201 (2001): Dynamic Risers, Det Norske Veritas, Norway

Flylling, I.J, Larsen C.M, Sodahl N., Ormsberg H, Engseth A, Passano E., Hoelthe K. (2005), Riflex-User Manual, Sintef, Structural Engineering, Trondheim, Norway

Flylling, I.J, Larsen C.M, Sodahl N., Ormsberg H, Engseth A, Passano E., Hoelthe K. (2005), Riflex-Theory Manual, Sintef, Structural Engineering, Trondheim, Norway

Foyt, E., Griffin, Cary., Campbell, Mike., (2007): Weight Optimized SCR – Enabling Technology for Turret Moored FPSO Developments. Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering, 10-15 June 2007. San Diego, California, USA.

Hellestø, A.F, Karunakaran, D, Grytten, T, Gudmestad, O.T (2007): Combined Tow Method for Deepwater Pipeline and Riser Installation. Proceeding Offshore Technology Conference 2007, 30 April – 3 May 2007. Houston, Texas USA.

Howells, Hugh and Hatton, Stephen A. (1997):Challenges for Ultra-deep Water Riser Systems. Floating Production Systems IIP April 1997, London.

Howells, Hugh and Hatton, Stephen A. (1996): Catenary and Hybrid Risers for Deepwater Locations Worldwide. Advances in Riser Technologies Conference June 1996, Aberdeen.

Karunakaran, D, Subsea 7, & T.S. Meiling, S. Kristoffersen, & K.M. Lund, Statoil. (2005): Weight Optimized SCRs for Deepwater Harsh Environments. Proceedings Offshore Technology Conference, 2-5 May. Houston, Texas, USA.

Moros, T.A. and Fairhurst, P. (April 1999). “Production riser design: integrated approach to flow, mechanical issues”. Offshore Magazine April 1999, pp. 82-89.

Rodrigues, M.V, Hansen, V.L, Bahiense, R.A, and Raposo, C.V (2008): Steel Catenary Riser Design Based on Prescribed Motions from Coupled Analysis Methodology. Proceedings Offshore Technology Conference, 5-8 May. Houston, Texas, USA.

STRIDE (September 1997): Stride – Steel Risers for Deepwater Environments – Simple Catenary Riser VIV Analysis. 2H Offshore Engineering Ltd. 1094-RPT-0009

STRIDE (December 1997): Stride – Steel Risers for Deepwater Environments – Installation Study Scope of Work. 2H Offshore Engineering Ltd. 1094-SOW-0001

APPENDIX A RIFLEX SYSTEM ANALYSIS PROGRAM

RIFLEX is a tailor-made and advanced tool for static and dynamic analysis of slender marine structures. It represents state-of-the-art technology for riser analysis suitable for flexible, metallic or steel catenary riser applications. In addition, RIFLEX is an efficient program system for hydrodynamic and structural analysis of slender marine structures.

There are some advantages by using RIFLEX program to analyze slender structure:

- Extremely efficient and robust non-linear time domain formulation applicable for irregular wave analysis
- High flexibility in modeling, enabling analysis for a wide range of structures

A numbers of simple or complex marine systems can be analyzed by this program such as flexible risers, top tensioned risers, metallic catenary risers, mooring lines, TLP tendons, loading hoses, umbilicals, towing lines, pipe laying, seismic cables, and fish farming systems.

RIFLEX can perform various analyses of riser system:

- Static Analysis
- Static Parameter Variation Analysis
- Dynamic Time Domain Analysis including eigenvalue analysis
- Frequency Domain Analysis

Basic results are:

- Nodal point coordinates
- Curvature at nodal points
- Axial force
- Bending moment
- Shear force
- Torsion

A.1 Structures of RIFLEX Computer Program

According to RIFLEX-User manual [Flylling, I.J, et al, 2005], the program consists of different modules for performing different tasks:

1. INPMOD, Input Module

   This module reads the input data required for describing the riser system. After running INPMOD, several analyses will be performed by other modules without changing the INPMOD file.

2. STAMOD, Static Module

   This module establishes the static equilibrium configuration of the riser system which will form the basis for subsequent dynamic and Eigen value analysis.

3. DYNMOD, Dynamic Module

In dynmod module, time domain dynamic analysis is conducted based on static equilibrium established by STAMOD. It is possible to re run dynamic analyses without re run INPMOD and STAMOD module.

4. FREMOD, Frequency Module

   The FREMOD module is designed as a modular program which carries out frequency domain analyses with stochastic linearization of the quadratic Morison drag term.

5. OUTMOD, Output Module

   This module performs post processing of results carried out by STAMOD and DYNMOD. This also provides files for viewing the results in the graphical interface.

6. PLOTMOD, Plot Module

   This is a graphical interface developed for viewing the results from static and dynamic analysis. This module can read only the files which are generate by the OUTMOD.

The structure of the computer program is shown in the following figure A.1

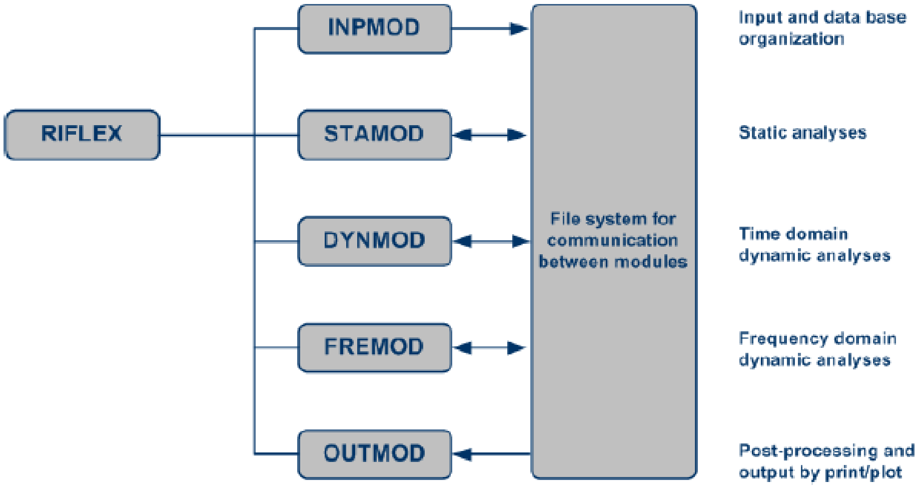


Figure A.1 Structure of Program System [RIFLEX User Manual, 2005]

A.2 Riser Modelling (INPMOD)

This section provides the description and principle for system modeling in RIFLEX. The riser can be defined as a general system called arbitrary riser (AR) system. In this system, the user has to specify the riser structural properties including all the boundary conditions. However, several alternatives are also available for simplified input of commonly used configurations with well defined standard properties. The different standard systems are categorized as follows:

1. Single Risers
   a) “SA”- Seafloor to Surface Vessel, One-Point Seafloor Contact

The riser is suspended between two defined points. The lower is fixed while upper end is connected to the support vessel. The system is used to model steep wave, steep S and jumper flexible riser configurations.
Figure A.2 presents some examples of configuration covered by “SA”

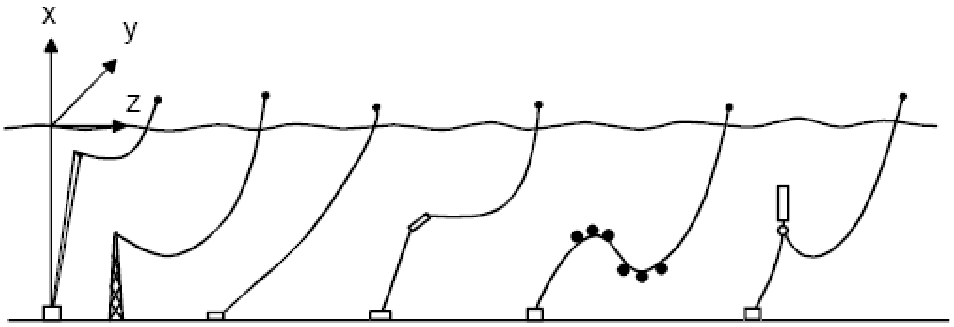


Figure A.2 Examples Configuration of SA system [RIFLEX User Manual, 2005]

b) “SB”- Seafloor to Surface Vessel, Seafloor Tangent

This system has additional features from previous system:

- Seafloor tangent boundary condition
- Buoyancy guide at one point

Seafloor contact is modeled by bilinear stiffness. This stiffness is dicretized and implemented as springs at the nodal points that may touch seafloor. This system models simple catenary, lazy wave and lazy S configurations. Figure A.3 presents some examples of configuration covered by “SB”

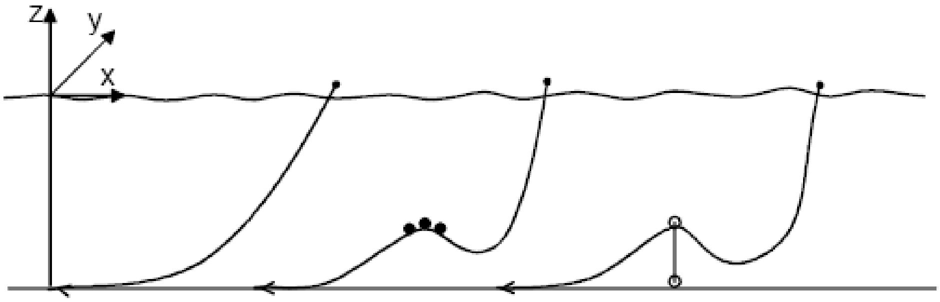


Figure A.3 Examples Configuration of SB system [RIFLEX User Manual, 2005]

c) “SC” - Free Lower End, Suspended from Surface Vessel

This group is characterized by a free lower end, all degrees of freedom being specified at the upper end. This configuration represents typical installation phases. Figure A.4 presents some examples of configuration covered by “SC”.

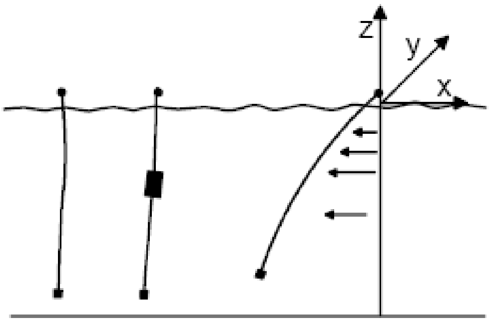


Figure A.4 Examples Configuration of SC system [RIFLEX User Manual, 2005]

d) "SD" – Free Upper End

Single line system is connected to seafloor at lower end and with free upper end. There are some examples of this system such as buoyed riser, loading system, etc. Figure A.5 presents some examples of configuration covered by "SD".

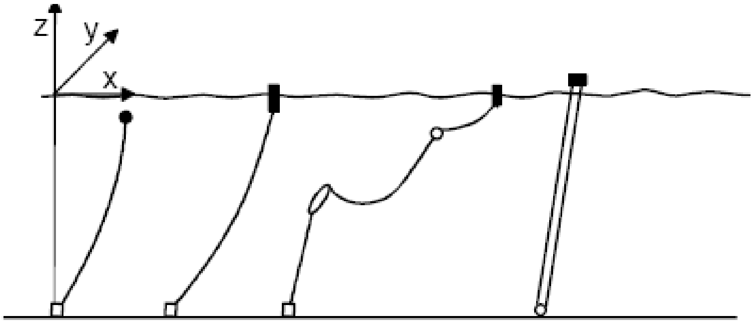


Figure A.5 Examples Configuration of SD system [RIFLEX User Manual, 2005]

2. Connected risers

   a. Parallel Risers with Cross Connections - CA

   This system category includes parallel risers connected by common buoyancy elements or kept apart with rigid spacers. The individual risers can either be of type SA or SB. Figure A.6 shows how parallel risers are configured.

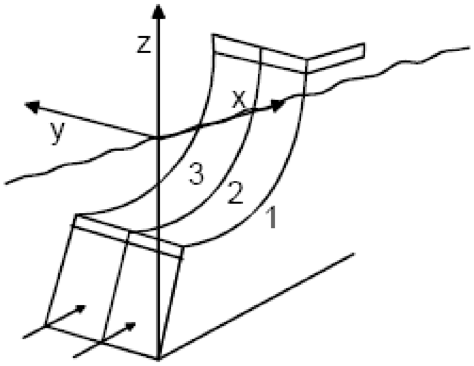


Figure A.6 Parallel Connected Risers [RIFLEX User Manual, 2005]

b. Branched Riser System – CB

This system is a composite system with one section of rigid or articulated column together with a set of single lines branching out from the top of the column. Figure A.7 shows how branched risers are configured.

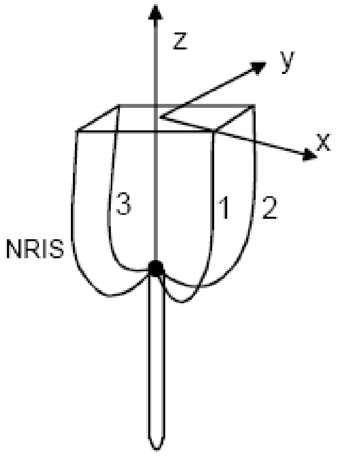


Figure A.7 Branched Riser System [RIFLEX User Manual, 2005]

In this present study, arbitrary system is chosen to give flexibility in modeling the steel catenary riser.

A.2.1 Line and Segment Description

A line is basically a linear structural element between two supernodes with specified boundary conditions. Each line is composed of different segments with homogeneous cross-section properties. These segments are to be used for finite element discretization for each element. It is also possible for internal fluid flow component in the line. The line specification can be shown in figure A.8.

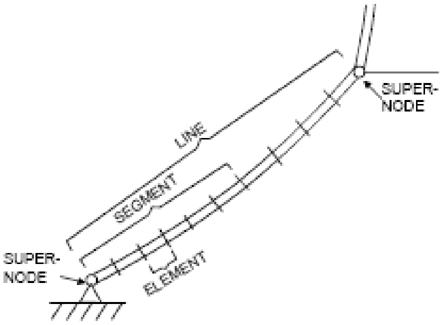


Figure A.8 Line Specification [RIFLEX User Manual, 2005]

Simple steel catenary riser basically comprises of one single line with two supernodes. It is important to define sufficient length of segment for dynamic analysis in order to avoid any instability in analysis process.

A.2.2 Component Description

A component with elementary description of the mechanical properties is identified by a numerical identifier called component type number. Those components available in RIFLEX are:

1. Cross sectional component: mechanical properties of the component (Axial, bending and torsional stiffness).

   For simple catenary riser without any devices attachment, component is simply described as pipe cross section (CRS0). For weight distributed SCR with a number of clump weights, a special component is defined. Clump weight is defined as external wrapping (EXT1).

2. Nodal component: used to model the submerged buoys, clump weight, etc.
3. Special component: used for modeling elastic contact forces between lines and for modeling of tensioner mechanism.

Neither nodal component nor special component is required for modeling steel catenary riser in this study.

A.2.3 Seafloor Contact Modeling

As riser is partly resting on the bottom, seafloor contact is important to be modeled in order to establish proper riser-soil interaction. Horizontal contact with the seafloor is modelled independently in the axial and lateral directions. Contact is initially modelled with linear springs. Sliding will occur when an axial or lateral spring force reaches the friction force value. Springs will be reinstated if the line starts sliding in the opposite direction, or if the friction force increases and is greater than the spring force. The seafloor friction forces are calculated as friction parameter multiplied by vertical forces, and applied against the axial and lateral displacement. The seafloor spring stiffness and seafloor friction constants are given by the user.

A.2.4 Load Modeling

Waves can be defined either as regular or irregular waves. Several model spectra to describe irregular wave are build-in in the program such as Pierson-Moskowitz, Jonswap, etc. Wave spectral parameters are specified by significant wave height and period. The current speed and direction is assumed to be constant with time and can be arbitrarily defined by specifying the velocity and direction at any given water depth.

Hydrodynamic loading is modeled by means of drag and inertia force coefficient in longitudinal and transverse directions. Both quadratic and linear drag terms can be included. Force motions at vessel attachment points are modeled either by specifying vessel motion transfer function or by specifying motion amplitudes and phase angles directly. In this present study, the former method is applied from RAO semis vessel as an application of de-coupled analysis.

A.3 Static Analysis (STAMOD)

In this analysis, the riser static equilibrium is established by incorporating volume forces (weight and buoyancy), prescribed displacements, specified forces (e.g. applied top tension), and displacement dependent forces (current loading).

There are three different methods to achieve riser static equilibrium; catenary method, finite element method, or combination of catenary and finite element method

(CATFEM). In this present study, finite element method is applied. The outputs of STAMOD are:
- Static XZ, YZ and XY configuration
- Static Forces
- Static Bending moment
- Static curvature

The outputs from STAMOD give initial impression of riser system analysis and will be used as input for dynamic analysis.

A.4 Dynamic Analysis (DYNMOD)

The purpose of these analyses is to study the influence of support vessel motions as well as of direct wave induced loads on the system.

The following types of dynamic analyses are included:

1. Eigenvalue analysis.
2. Harmonic (periodic) excitation.
    - Forced displacements (harmonic) at one or more specified nodes
    - Regular waves
3. Irregular excitation.
    - Stochastic, stationary excitation due to support vessel motions and irregular waves
    - Transient excitation. Special options available to simulate release or rupture, slug flow, time dependent current and external force variations

In this present study, time domain analysis with 3 hour duration is performed to develop the SCR response due to dynamic loading from irregular waves and currents and host platform motions. The outputs from DYNMOD are:
- Displacement envelope curves
- Force envelope curves
- Moment envelope curves
- Curvature envelope curves

A.5 Frequency Domain Analysis (FREMOD)

This module performs the dynamic analysis in frequency domain. The frequency domain analysis is based on the linearized dynamic equilibrium equation at static equilibrium position by application of stochastic linearization of the hydrodynamic loading.

In this present analysis, frequency domain analysis is not performed because the strength and fatigue analyses are done by applying time domain analysis.

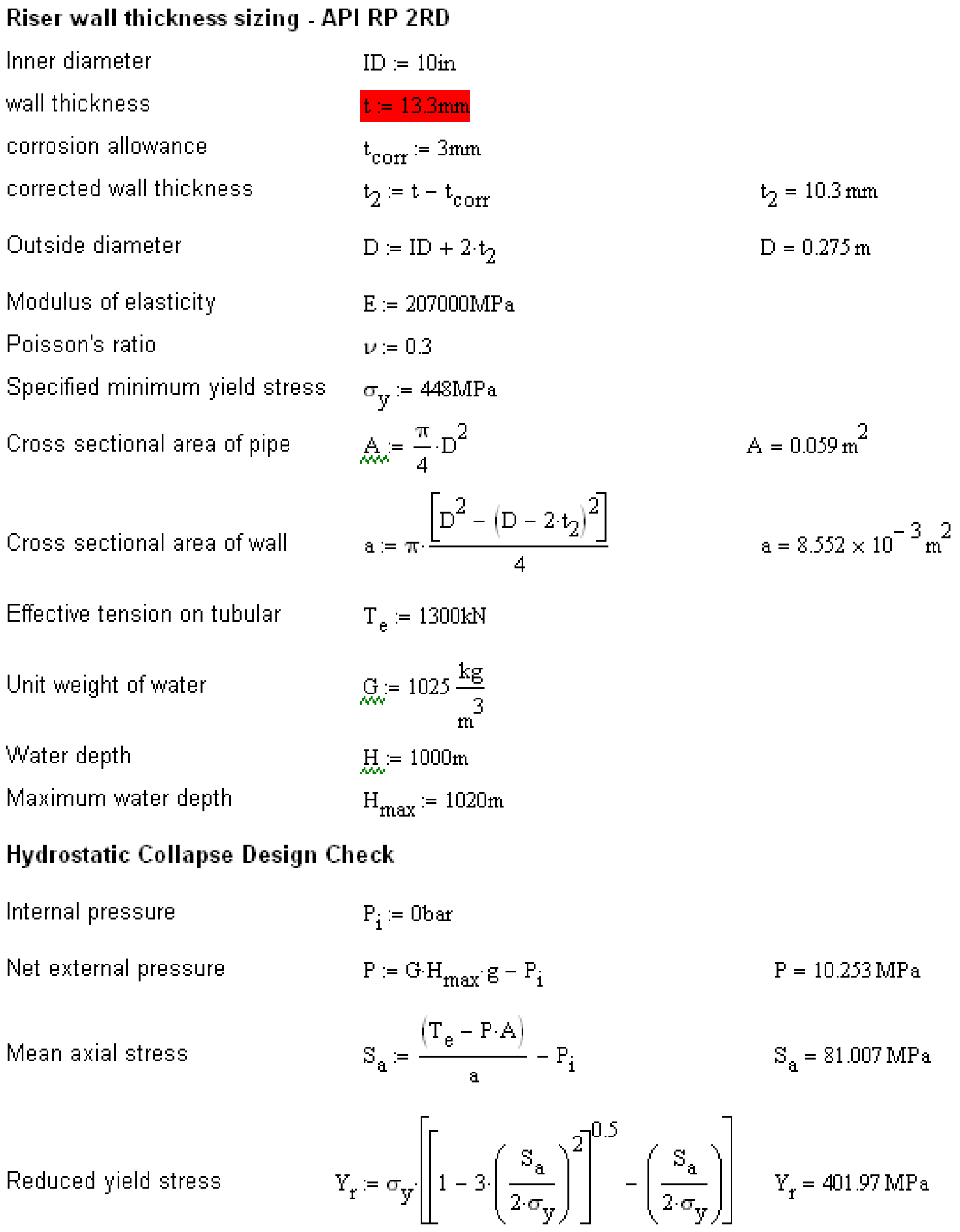
A.6 Output Analysis (OUTMOD)

The post-processing module OUTMOD has two main purposes:
- Generate result printout from the INPMOD, STAMOD and DYNMOD modules
- Prepare a plot file (IFNPLO) for later use by the plot module (PLOMOD)

OUTMOD is the last step of RIFLEX analysis and the outputs from this analysis are used to evaluate the SCR performance. Some important outputs are Von Mises stress for strength design check and fatigue life for fatigue analysis check.

APPENDIX B CALCULATIONS

B.1 Riser Wall thickness Sizing – API RP 2RD



Riser wall thickness sizing - API RP 2RD

Inner diameter	$ID := 10in$	
wall thickness	$t := 13.3mm$	
corrosion allowance	$t_{corr} := 3mm$	
corrected wall thickness	$t_2 := t - t_{corr}$	$t_2 = 10.3\,mm$
Outside diameter	$D := ID + 2 \cdot t_2$	$D = 0.275\,m$
Modulus of elasticity	$E := 207000MPa$	
Poisson's ratio	$\nu := 0.3$	
Specified minimum yield stress	$\sigma_y := 448MPa$	
Cross sectional area of pipe	$A := \frac{\pi}{4} \cdot D^2$	$A = 0.059\,m^2$
Cross sectional area of wall	$a := \pi \cdot \frac{\left[D^2 - \left(D - 2 \cdot t_2\right)^2\right]}{4}$	$a = 8.552 \times 10^{-3}\,m^2$
Effective tension on tubular	$T_e := 1300kN$	
Unit weight of water	$G := 1025 \frac{kg}{m^3}$	
Water depth	$H := 1000m$	
Maximum water depth	$H_{max} := 1020m$	

Hydrostatic Collapse Design Check

Internal pressure	$P_i := 0bar$	
Net external pressure	$P := G \cdot H_{max} \cdot g - P_i$	$P = 10.253\,MPa$
Mean axial stress	$S_a := \frac{\left(T_e - P \cdot A\right)}{a} - P_i$	$S_a = 81.007\,MPa$
Reduced yield stress	$Y_r := \sigma_y \cdot \left[\left[1 - 3 \cdot \left(\frac{S_a}{2 \cdot \sigma_y}\right)^2\right]^{0.5} - \left(\frac{S_a}{2 \cdot \sigma_y}\right)\right]$	$Y_r = 401.97\,MPa$

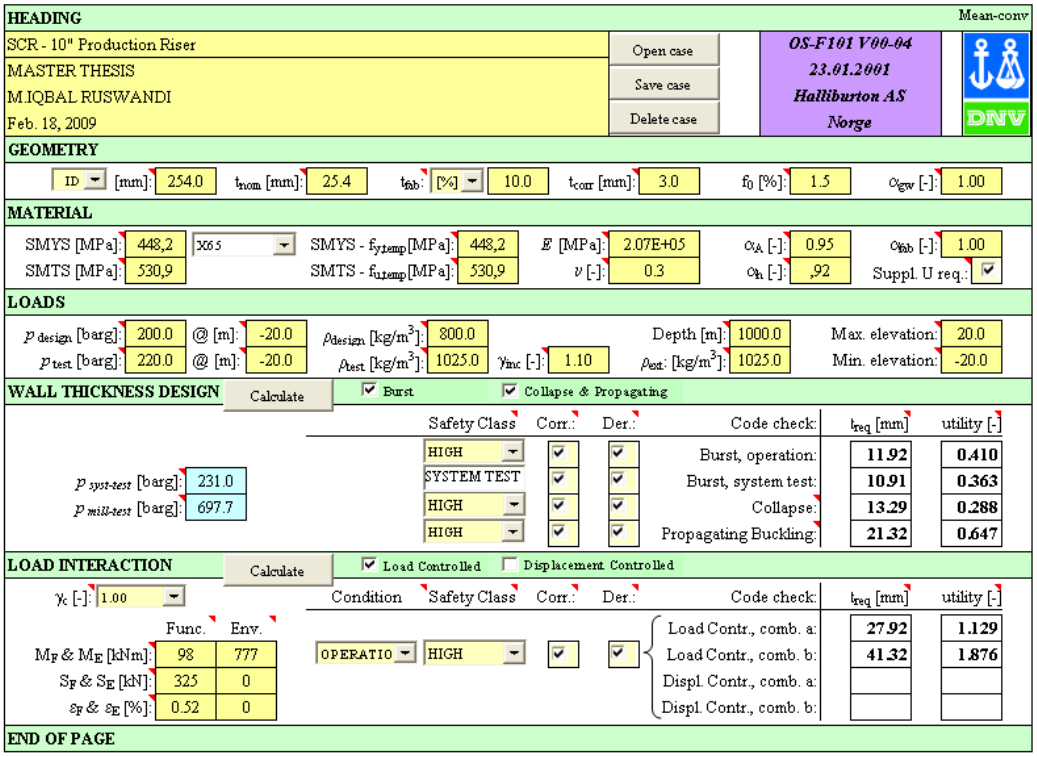
elastic buckling pressure	$P_e := \left[2 \cdot \frac{E}{\left(1-\nu^2\right)}\right] \cdot \left(\frac{t_2}{D}\right)^3$	$P_e = 24.009\,\mathrm{MPa}$
Yield pressure with simultaneous tension	$P_y := 2 \cdot Y_r \cdot \frac{t}{D}$	$P_y = 38.938\,\mathrm{MPa}$
Collapse pressure (round pipe)	$P_o := P_e \cdot P_y \cdot \left(P_e^{\,2} + P_y^{\,2}\right)^{-0.5}$	$P_o = 20.436\,\mathrm{MPa}$
Design factor, Seamless pipe or ERW API pipe		$D_f := 0.75$
Net allowable external design pressure	$P_a := P$	$P_a = 10.253\,\mathrm{MPa}$
Utility ratio	$U := \frac{P_a}{0.67 D_f \cdot P_o}$	$U = 0.998$

Collapse Propagation design check

wall thickness	$t := 20.6\mathrm{mm}$	
corrosion allowance	$t_{corr} = 3\,\mathrm{mm}$	
corrected wall thickness	$t_2 := t - t_{corr}$	$t_2 = 17.6\,\mathrm{mm}$
Design pressure differential	$P_d := P$	$P_d = 10.253\,\mathrm{MPa}$
Predicted propagation pressure	$P_p := 24 \cdot \sigma_y \cdot \left(\frac{t}{D}\right)^{2.4}$	$P_p = 21.473\,\mathrm{MPa}$
Design factor		$D_p := 0.72$
Utility ratio	$U := \frac{P_d}{0.67 \cdot D_p \cdot P_p}$	$U = 0.99$

B.2 SCR Wall Thickness and Buckling Check – LRFD Method

B.2.1 Conventional SCR Configuration 1 (Mean Case)



HEADING Mean-conv

SCR - 10" Production Riser
MASTER THESIS
M.IQBAL RUSWANDI
Feb. 18, 2009

OS-F101 V00-04
23.01.2001
Halliburton AS
Norge

GEOMETRY

ID [mm]: 254.0 — t_{nom} [mm]: 25.4 — t_{fab}: [%] 10.0 — t_{corr} [mm]: 3.0 — f_0 [%]: 1.5 — α_{gw} [-]: 1.00

MATERIAL

SMYS [MPa]: 448,2 — X65 — SMYS - $f_{y,temp}$[MPa]: 448,2 — E [MPa]: 2.07E+05 — α_A [-]: 0.95 — α_{fab} [-]: 1.00
SMTS [MPa]: 530,9 — SMTS - $f_{u,temp}$[MPa]: 530,9 — ν [-]: 0.3 — α_h [-]: ,92 — Suppl. U req.: ☑

LOADS

p_{design} [barg]: 200.0 — @ [m]: -20.0 — ρ_{design} [kg/m^3]: 800.0 — Depth [m]: 1000.0 — Max. elevation: 20.0
p_{test} [barg]: 220.0 — @ [m]: -20.0 — ρ_{test} [kg/m^3]: 1025.0 — γ_{inc} [-]: 1.10 — ρ_{ext}: [kg/m^3]: 1025.0 — Min. elevation: -20.0

WALL THICKNESS DESIGN — ☑ Burst — ☑ Collapse & Propagating

$p_{syst\text{-}test}$ [barg]: 231.0
$p_{mill\text{-}test}$ [barg]: 697.7

Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
HIGH	☑	☑	Burst, operation:	11.92	0.410
SYSTEM TEST	☑	☑	Burst, system test:	10.91	0.363
HIGH	☑	☑	Collapse:	13.29	0.288
HIGH	☑	☑	Propagating Buckling:	21.32	0.647

LOAD INTERACTION — ☑ Load Controlled — ☐ Displacement Controlled

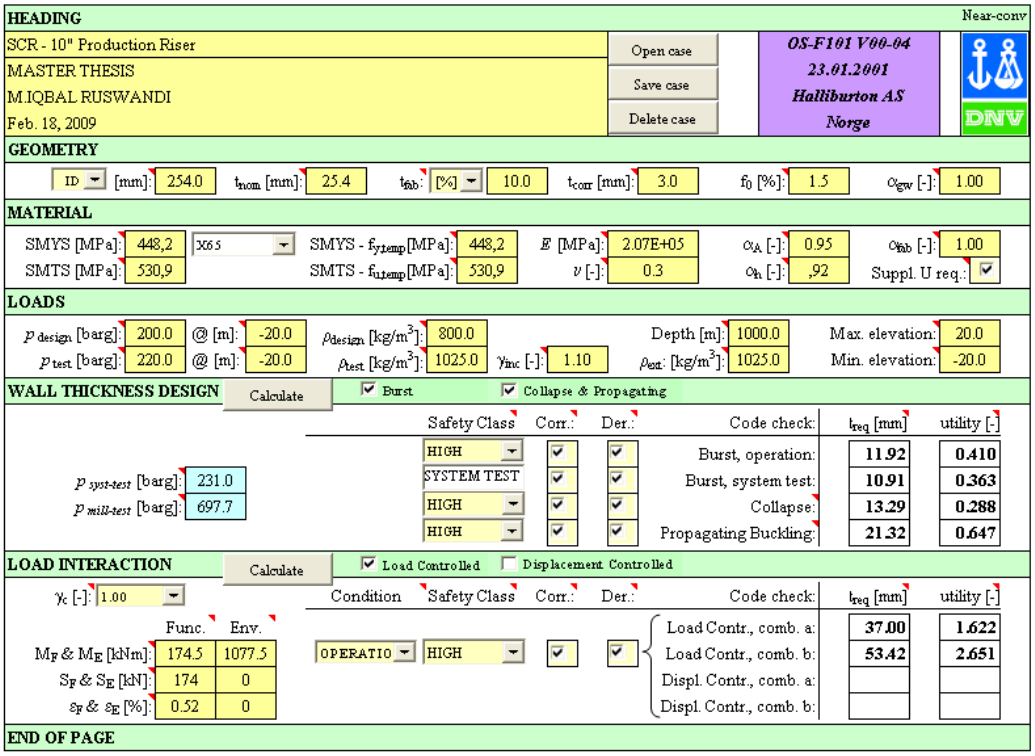
γ_c [-]: 1.00

	Func.	Env.
M_F & M_E [kNm]:	98	777
S_F & S_E [kN]:	325	0
ε_F & ε_E [%]:	0.52	0

Condition	Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
OPERATIO	HIGH	☑	☑	Load Contr., comb. a:	27.92	1.129
				Load Contr., comb. b:	41.32	1.876
				Displ. Contr., comb. a:		
				Displ. Contr., comb. b:		

END OF PAGE

B.2.2 Conventional SCR Configuration 1 (Near Case)



HEADING Near-conv

SCR - 10" Production Riser
MASTER THESIS
M.IQBAL RUSWANDI
Feb. 18, 2009

OS-F101 V00-04
23.01.2001
Halliburton AS
Norge

GEOMETRY

ID [mm]: 254.0 — t_{nom} [mm]: 25.4 — t_{fab}: [%] 10.0 — t_{corr} [mm]: 3.0 — f_0 [%]: 1.5 — α_{gw} [-]: 1.00

MATERIAL

SMYS [MPa]: 448,2 — X65 — SMYS - $f_{y,temp}$[MPa]: 448,2 — E [MPa]: 2.07E+05 — α_A [-]: 0.95 — α_{fab} [-]: 1.00
SMTS [MPa]: 530,9 — SMTS - $f_{u,temp}$[MPa]: 530,9 — ν [-]: 0.3 — α_h [-]: ,92 — Suppl. U req.: ☑

LOADS

p_{design} [barg]: 200.0 — @ [m]: -20.0 — ρ_{design} [kg/m^3]: 800.0 — Depth [m]: 1000.0 — Max. elevation: 20.0
p_{test} [barg]: 220.0 — @ [m]: -20.0 — ρ_{test} [kg/m^3]: 1025.0 — γ_{inc} [-]: 1.10 — ρ_{ext}: [kg/m^3]: 1025.0 — Min. elevation: -20.0

WALL THICKNESS DESIGN — ☑ Burst — ☑ Collapse & Propagating

$p_{syst\text{-}test}$ [barg]: 231.0
$p_{mill\text{-}test}$ [barg]: 697.7

Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
HIGH	☑	☑	Burst, operation:	11.92	0.410
SYSTEM TEST	☑	☑	Burst, system test:	10.91	0.363
HIGH	☑	☑	Collapse:	13.29	0.288
HIGH	☑	☑	Propagating Buckling:	21.32	0.647

LOAD INTERACTION — ☑ Load Controlled — ☐ Displacement Controlled

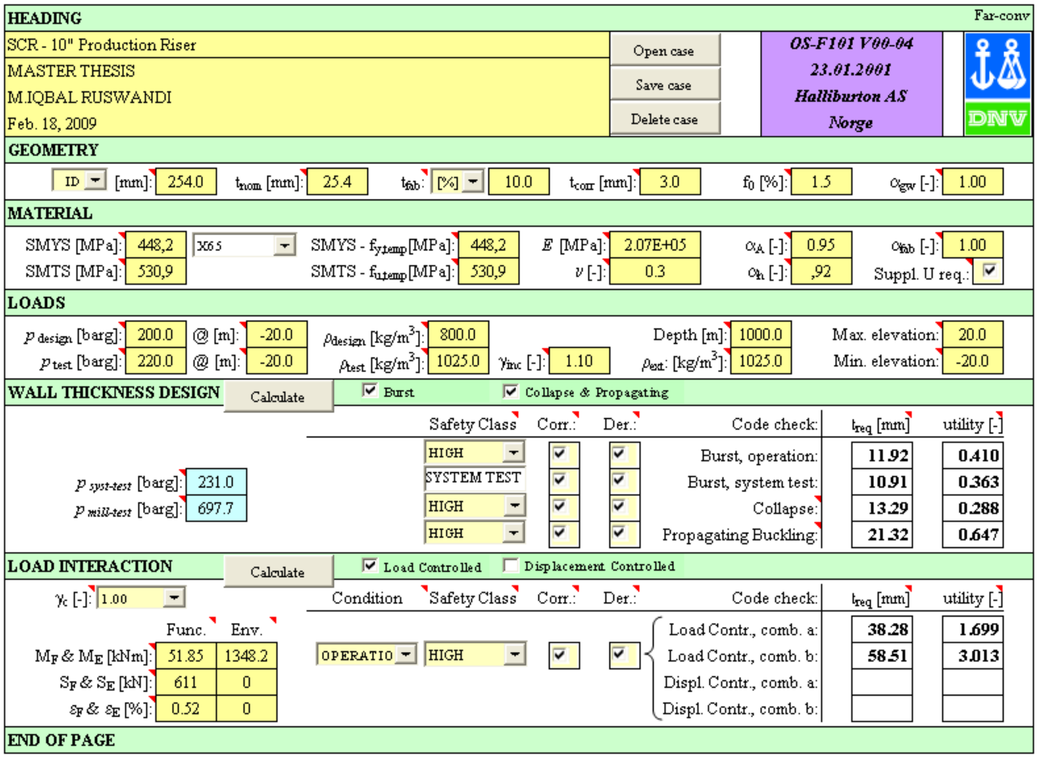
γ_c [-]: 1.00

	Func.	Env.
M_F & M_E [kNm]:	174.5	1077.5
S_F & S_E [kN]:	174	0
ε_F & ε_E [%]:	0.52	0

Condition	Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
OPERATIO	HIGH	☑	☑	Load Contr., comb. a:	37.00	1.622
				Load Contr., comb. b:	53.42	2.651
				Displ. Contr., comb. a:		
				Displ. Contr., comb. b:		

END OF PAGE

B.2.3 Conventional SCR Configuration 1 (Far Case)



HEADING Far-conv

SCR - 10" Production Riser
MASTER THESIS
M.IQBAL RUSWANDI
Feb. 18, 2009

OS-F101 V00-04
23.01.2001
Halliburton AS
Norge

GEOMETRY

ID [mm]: 254.0
t_{nom} [mm]: 25.4
t_{fab}: [%] 10.0
t_{corr} [mm]: 3.0
f_0 [%]: 1.5
α_{gw} [-]: 1.00

MATERIAL

SMYS [MPa]: 448,2 X65
SMTS [MPa]: 530,9
SMYS - $f_{y,temp}$[MPa]: 448,2
SMTS - $f_{u,temp}$[MPa]: 530,9
E [MPa]: 2.07E+05
ν [-]: 0.3
α_A [-]: 0.95
α_h [-]: ,92
α_{fab} [-]: 1.00
Suppl. U req.: ☑

LOADS

p_{design} [barg]: 200.0 @ [m]: -20.0
p_{test} [barg]: 220.0 @ [m]: -20.0
ρ_{design} [kg/m^3]: 800.0
ρ_{test} [kg/m^3]: 1025.0
γ_{inc} [-]: 1.10
Depth [m]: 1000.0
ρ_{ext}: [kg/m^3]: 1025.0
Max. elevation: 20.0
Min. elevation: -20.0

WALL THICKNESS DESIGN Calculate ☑ Burst ☑ Collapse & Propagating

$p_{syst\text{-}test}$ [barg]: 231.0
$p_{mill\text{-}test}$ [barg]: 697.7

Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
HIGH	☑	☑	Burst, operation:	11.92	0.410
SYSTEM TEST	☑	☑	Burst, system test:	10.91	0.363
HIGH	☑	☑	Collapse:	13.29	0.288
HIGH	☑	☑	Propagating Buckling:	21.32	0.647

LOAD INTERACTION Calculate ☑ Load Controlled ☐ Displacement Controlled

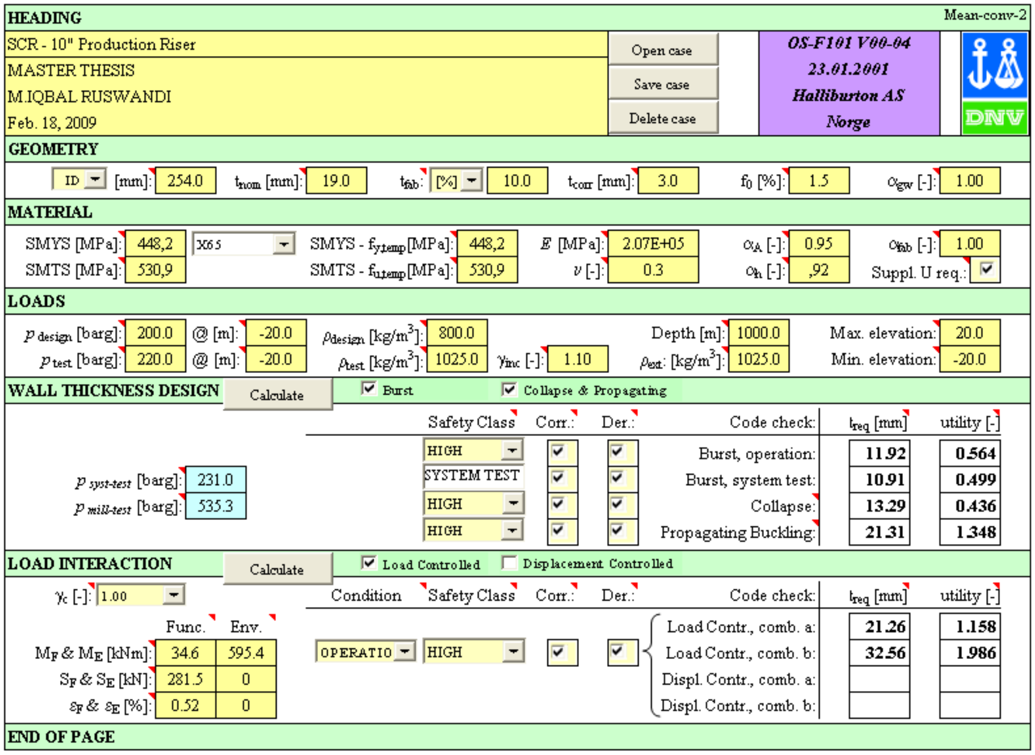
γ_c [-]: 1.00

	Func.	Env.
M_F & M_E [kNm]:	51.85	1348.2
S_F & S_E [kN]:	611	0
ε_F & ε_E [%]:	0.52	0

Condition	Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
OPERATIO	HIGH	☑	☑	Load Contr., comb. a:	38.28	1.699
				Load Contr., comb. b:	58.51	3.013
				Displ. Contr., comb. a:		
				Displ. Contr., comb. b:		

END OF PAGE

B.2.4 Conventional SCR Configuration 2 (Mean Case)



HEADING Mean-conv-2

SCR - 10" Production Riser
MASTER THESIS
M.IQBAL RUSWANDI
Feb. 18, 2009

OS-F101 V00-04
23.01.2001
Halliburton AS
Norge

GEOMETRY

ID [mm]: 254.0
t_{nom} [mm]: 19.0
t_{fab}: [%] 10.0
t_{corr} [mm]: 3.0
f_0 [%]: 1.5
α_{gw} [-]: 1.00

MATERIAL

SMYS [MPa]: 448,2 X65
SMTS [MPa]: 530,9
SMYS - $f_{y,temp}$[MPa]: 448,2
SMTS - $f_{u,temp}$[MPa]: 530,9
E [MPa]: 2.07E+05
ν [-]: 0.3
α_A [-]: 0.95
α_h [-]: ,92
α_{fab} [-]: 1.00
Suppl. U req.: ☑

LOADS

p_{design} [barg]: 200.0 @ [m]: -20.0
p_{test} [barg]: 220.0 @ [m]: -20.0
ρ_{design} [kg/m^3]: 800.0
ρ_{test} [kg/m^3]: 1025.0
γ_{inc} [-]: 1.10
Depth [m]: 1000.0
ρ_{ext}: [kg/m^3]: 1025.0
Max. elevation: 20.0
Min. elevation: -20.0

WALL THICKNESS DESIGN Calculate ☑ Burst ☑ Collapse & Propagating

$p_{syst\text{-}test}$ [barg]: 231.0
$p_{mill\text{-}test}$ [barg]: 535.3

Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
HIGH	☑	☑	Burst, operation:	11.92	0.564
SYSTEM TEST	☑	☑	Burst, system test:	10.91	0.499
HIGH	☑	☑	Collapse:	13.29	0.436
HIGH	☑	☑	Propagating Buckling:	21.31	1.348

LOAD INTERACTION Calculate ☑ Load Controlled ☐ Displacement Controlled

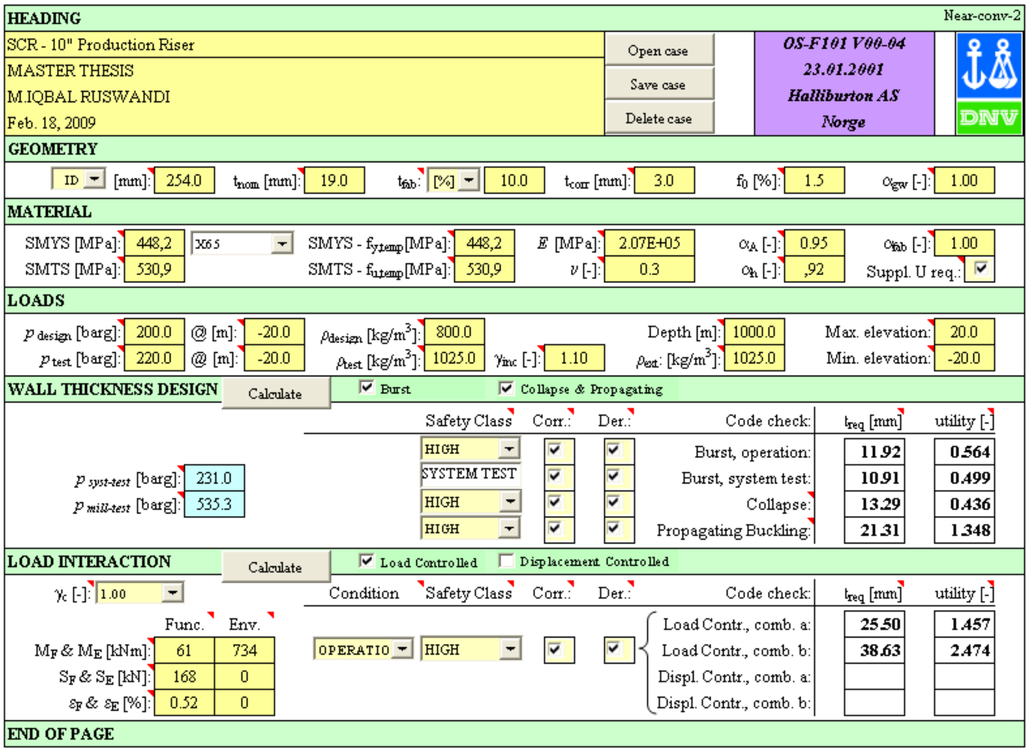
γ_c [-]: 1.00

	Func.	Env.
M_F & M_E [kNm]:	34.6	595.4
S_F & S_E [kN]:	281.5	0
ε_F & ε_E [%]:	0.52	0

Condition	Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
OPERATIO	HIGH	☑	☑	Load Contr., comb. a:	21.26	1.158
				Load Contr., comb. b:	32.56	1.986
				Displ. Contr., comb. a:		
				Displ. Contr., comb. b:		

END OF PAGE

B.2.5 Conventional SCR Configuration 2 (Near Case)



HEADING Near-conv-2

SCR - 10" Production Riser
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Feb. 18, 2009

OS-F101 V00-04
23.01.2001
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Norge

GEOMETRY

ID [mm]: 254.0
t_{nom} [mm]: 19.0
t_{fab}: [%] 10.0
t_{corr} [mm]: 3.0
f_0 [%]: 1.5
α_{gw} [-]: 1.00

MATERIAL

SMYS [MPa]: 448,2
SMTS [MPa]: 530,9
X65
SMYS - $f_{y,temp}$ [MPa]: 448,2
SMTS - $f_{u,temp}$ [MPa]: 530,9
E [MPa]: 2.07E+05
ν [-]: 0.3
α_A [-]: 0.95
α_h [-]: ,92
α_{fab} [-]: 1.00
Suppl. U req.: ☑

LOADS

p_{design} [barg]: 200.0 @ [m]: -20.0
p_{test} [barg]: 220.0 @ [m]: -20.0
ρ_{design} [kg/m^3]: 800.0
ρ_{test} [kg/m^3]: 1025.0
γ_{inc} [-]: 1.10
Depth [m]: 1000.0
ρ_{ext}: [kg/m^3]: 1025.0
Max. elevation: 20.0
Min. elevation: -20.0

WALL THICKNESS DESIGN ☑ Burst ☑ Collapse & Propagating

$p_{syst\text{-}test}$ [barg]: 231.0
$p_{mill\text{-}test}$ [barg]: 535.3

Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
HIGH	☑	☑	Burst, operation:	11.92	0.564
SYSTEM TEST	☑	☑	Burst, system test:	10.91	0.499
HIGH	☑	☑	Collapse:	13.29	0.436
HIGH	☑	☑	Propagating Buckling:	21.31	1.348

LOAD INTERACTION ☑ Load Controlled ☐ Displacement Controlled

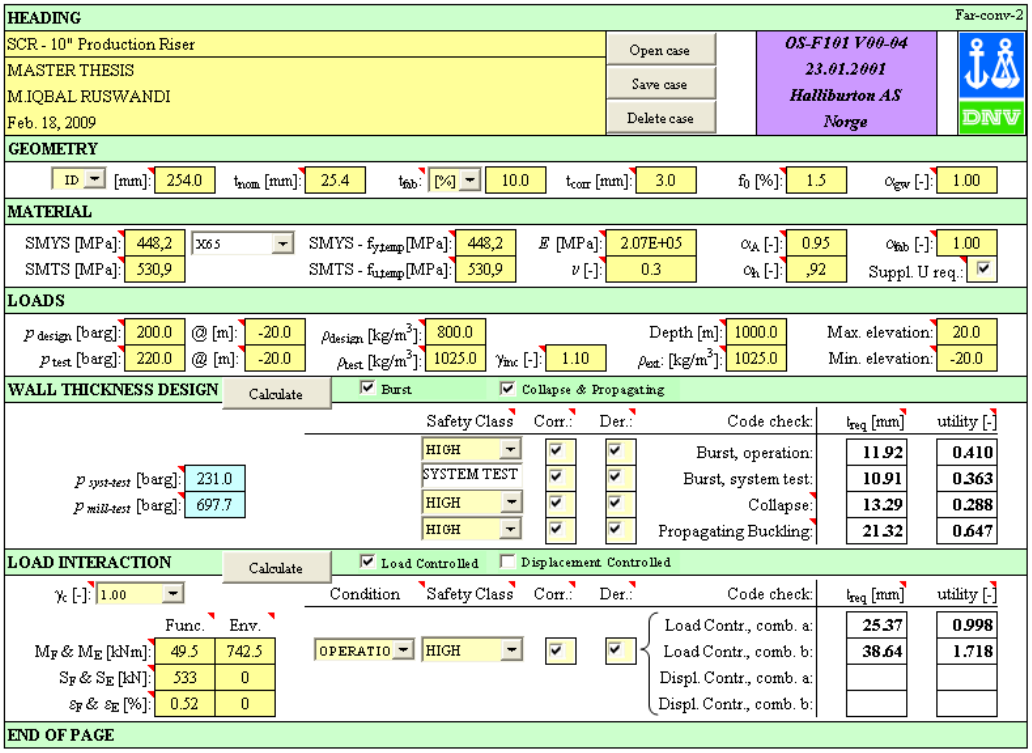
γ_c [-]: 1.00

	Func.	Env.
M_F & M_E [kNm]:	61	734
S_F & S_E [kN]:	168	0
ε_F & ε_E [%]:	0.52	0

Condition	Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
OPERATIO	HIGH	☑	☑	Load Contr., comb. a:	25.50	1.457
				Load Contr., comb. b:	38.63	2.474
				Displ. Contr., comb. a:		
				Displ. Contr., comb. b:		

END OF PAGE

B.2.6 Conventional SCR Configuration 2 (Far Case)



HEADING Far-conv-2

SCR - 10" Production Riser
MASTER THESIS
M.IQBAL RUSWANDI
Feb. 18, 2009

OS-F101 V00-04
23.01.2001
Halliburton AS
Norge

GEOMETRY

ID [mm]: 254.0
t_{nom} [mm]: 25.4
t_{fab}: [%] 10.0
t_{corr} [mm]: 3.0
f_0 [%]: 1.5
α_{gw} [-]: 1.00

MATERIAL

SMYS [MPa]: 448,2
SMTS [MPa]: 530,9
X65
SMYS - $f_{y,temp}$ [MPa]: 448,2
SMTS - $f_{u,temp}$ [MPa]: 530,9
E [MPa]: 2.07E+05
ν [-]: 0.3
α_A [-]: 0.95
α_h [-]: ,92
α_{fab} [-]: 1.00
Suppl. U req.: ☑

LOADS

p_{design} [barg]: 200.0 @ [m]: -20.0
p_{test} [barg]: 220.0 @ [m]: -20.0
ρ_{design} [kg/m^3]: 800.0
ρ_{test} [kg/m^3]: 1025.0
γ_{inc} [-]: 1.10
Depth [m]: 1000.0
ρ_{ext}: [kg/m^3]: 1025.0
Max. elevation: 20.0
Min. elevation: -20.0

WALL THICKNESS DESIGN ☑ Burst ☑ Collapse & Propagating

$p_{syst\text{-}test}$ [barg]: 231.0
$p_{mill\text{-}test}$ [barg]: 697.7

Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
HIGH	☑	☑	Burst, operation:	11.92	0.410
SYSTEM TEST	☑	☑	Burst, system test:	10.91	0.363
HIGH	☑	☑	Collapse:	13.29	0.288
HIGH	☑	☑	Propagating Buckling:	21.32	0.647

LOAD INTERACTION ☑ Load Controlled ☐ Displacement Controlled

γ_c [-]: 1.00

	Func.	Env.
M_F & M_E [kNm]:	49.5	742.5
S_F & S_E [kN]:	533	0
ε_F & ε_E [%]:	0.52	0

Condition	Safety Class	Corr.:	Der.:	Code check:	t_{req} [mm]	utility [-]
OPERATIO	HIGH	☑	☑	Load Contr., comb. a:	25.37	0.998
				Load Contr., comb. b:	38.64	1.718
				Displ. Contr., comb. a:		
				Displ. Contr., comb. b:		

END OF PAGE

APPENDIX C SEA SPECTRUM

There are several spectrum formulas that are used in the design of offshore structures. The most commonly used spectrum formulas are Pierson-Moskowitz model, Bretschneider model, ISSC model, JONSWAP model and less used Ochi-Hubble spectrum model. In this appendix, each of these spectra will be discussed.

C.1 Pierson-Moskowitz Spectrum

The Pierson-Moskowitz (P-M) model is a one-parameter spectrum model. This spectrum assumes a deep sea and a fully developed sea-state. The P-M form was derived from analysis of a sample of 400 spectra measured in the North Atlantic, and is widely used for characterising waves in the open ocean [Barltrop, 1998].

The spectra for fully developed seas may be analytically expressed as:

$$S(\omega) = \alpha g^2 \omega^{-5} exp\left(-1.25\left[{}^{\omega}/_{\omega_0}\right]^{-4}\right)$$

Where

S(ω)= spectral ordinate
α=Philips constant = 0.00810
$\bar{\alpha}$=modified Philips constant
g= acceleration of gravity

The formula is written in terms of the peak frequency ω_o. The frequency corresponds to the frequency at which the energy density spectrum peaks.

C.2 Bretschnerder Spectrum

The Bretschnerder spectrum is a two-parameter family that permits period and wave height to be assigned separately and has the form:

$$S(\omega) = 0.1687 H_s \frac{\omega_s^4}{\omega^5} exp\left(-0.675\left[{}^{\omega}/_{\omega_s}\right]^{-4}\right)$$

Where

$\omega_s = \frac{2\pi}{T_s}$
T_s = significant wave period
$T_s = 0.946 T_0$
T_0 = peak period
H_s = significant wave height

C.3 ISSC Spectrum

The ISSC spectrum has similar form as Bretschnerder spectrum where two-parameter are required as input.

$$S(\omega) = 0.1107 H_s \frac{\bar{\omega}^4}{\omega^5} exp\left(-0.4427\left[{}^{\omega}/_{\bar{\omega}}\right]^{-4}\right)$$

C.4 JONSWAP Spectrum

For the spectra that are found to be more peaky and narrower peak than the Bretschnerder or P-M spectrum, the JONSWAP spectrum is a better model. The

JONSWAP (Joint North Sea Wave Project) spectrum was developed from measurements made off the island of Sylt in the German Bight of the North Sea.

JONSWAP spectrum has five parameters, with only two are generally varied in its application (ω_0 and H_s). The JONSWAP spectrum can be written by modifying the P-M spectrum as:

$$S(\omega) = \bar{\alpha} g^2 \omega^{-5} exp\left(-1.25\left[{}^{\omega}/_{\omega_p}\right]^{-4}\right) \times \gamma^{\left[exp\left(-{(\omega-\omega_p)^2}/{(2\sigma^2\omega_p^2)}\right)\right]}$$

Where:

$$\bar{\alpha} = 5.058\left[\frac{H_s}{(T_p)^2}\right]^2 (1 - 0.287 ln\gamma)$$ - North Sea Application

γ= peakedness parameter

$\gamma = 5$ for ${}^{T_p}/_{\sqrt{H_s}} \leq 3.6$; and

$\gamma = exp\left(5.75 - 1.15\frac{T_p}{\sqrt{H_s}}\right)$ for ${}^{T_p}/_{\sqrt{H_s}} > 3.6$;

σ= 0.07 and 0.09 for $\omega<\omega_p$ and $\omega>\omega_p$ respectively

A suitable parameter for γ is in the range of 2-3 for North Sea application. For a fully developed sea, the JONSWAP spectrum reduces to the Pierson-Moskowitz spectral formulation (γ=1.0). Figure C.1 shows three different gamma values with the same H_s and T_z.

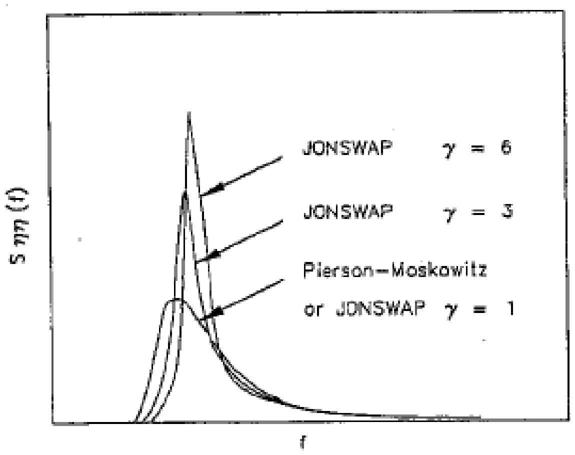


Figure C.1 JONSWAP spectra with three different gamma values

C.5 Ochi-Hubble Spectrum

The Ochi-Hubble spectrum is a six-parameter spectrum describing combination of two superimposed seas- a locally generated sea and a swell. This spectrum was derived from analysis of some 800 spectra measure in the North Atlantic and is illustrated in figure C.2 below for a case in which the two modes are well separated.

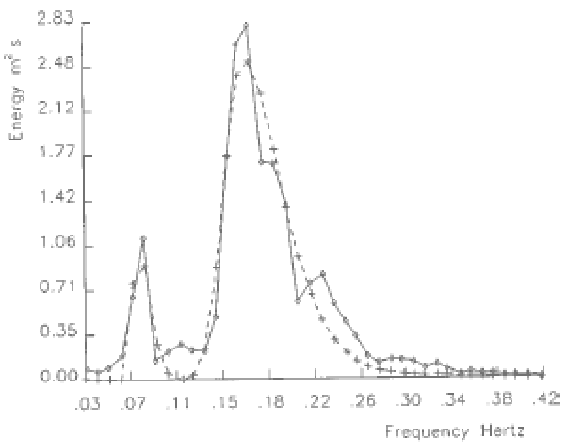


Figure C.2 Sample fitting of bimodal spectrum using Ochi's six parameter formula

This spectrum provides a better method to represent all stages of development of a sea in a storm. The basic form is:

$$S(\omega) = \frac{1}{4}\sum_{j=1}^{2}\frac{\left(\frac{4\lambda_j + 1}{4}\omega_{0j}^{4}\right)^{\lambda_j}}{\Gamma(\lambda_j)} x \frac{H_{sj}^{2}}{\omega^{4\lambda_j+1}} exp\left[-\left(\frac{4\lambda_j + 1}{4}\right)\left[{}^{\omega}/\omega_{0j}\right]^{-4}\right]$$

The swell is a narrow-band wave, which arrives at the site from a distant storm. The three parameters for each of these waves are given individually by significant wave height, peak frequency and a parameter (H_{s1}, ω_{01} and λ_1 and H_{s2}, ω_{02} and λ_2) respectively. The quantity Γ is the Gamma function.

APPENDIX D RIFLEX PROGRAM FILES

D.1 INPMOD

INPMOD for conventional SCR, weight distributed SCR with coating density, weight distributed SCR with clump weight and weight distributed SCR combination are provided in this section. In addition, INPMOD for fatigue analysis is also given.

D.1.1 INPMOD Conventional SCR configuration 1 – Mean Position

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Conventional SCR - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'-----------------------------
  NEW SINGLE RISER
'-----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2       1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0      0      0    GLOBAL
'    x0      y0     z0     x1    y1      z1        rot   dir
     30       0    -500     30    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1       z1     rot   dir
    2930       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI                0.0    0.0     0.0    0.0
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI               -100.0    0.0     0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
```

```
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1       9      0       0
'icmpty  icn1ty  iexwty  nelseg  slgth
  1       0       0        100     200.0
  1       0       0         10     100.0
  1       0       0         75     750.0
  1       0       0        100     100.0
  1       0       0         25      25.0
  1       0       0         50     300.0
  1       0       0        100     250.0
  1       0       0        100     600.0
  1       0       0        100     575.0
'
'                        -----   -------
'                         660     2900.0
'-----------------------------------------------------------------------
' ------     COMPONENT C R S 0                                    ------
'-----------------------------------------------------------------------
'
'
'10" X65 pipe
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  1       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.1   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
'
NEW COMPONENT FLUID
'  icmpty
     99
'
'  rhoi   vveli  pressi  dpress  idir
   0.800   0.0   2.0E4   0.0      2
'
'-----  ENVIRONMENTAL DESCRIPTION                                  -----
'-----------------------------------------------------------------------
'
ENVIronment IDENtification
' Descriptive text one line (A60)
Irregular wave analysis
'idenv
 EXTREM
'
WATErdepth AND WAVEtype
'wdepth  noirw   norw    ncusta
  1000   2       0       2
'
ENVIronment CONStants
'airden  watden  wakivi
 0.0013     1.025   1.188E-6
'
'-----------------------------------------------------------------------
'-----  IRRREGULAR SEASTATE                                        -----
'-----------------------------------------------------------------------
'
NEW IRREGULAR SEASTATE
'   nirwc   iwasp1        iwadr1        iwasp2       iwadr2
    1        9             0            0            0
WAVE SPECTRUM WINDsea
'  Hs   Tp  gamma
   15  16     /
DIRECTION PARAMETERS
'   wadr1    expo1
    0        0
'
NEW IRREGULAR SEASTATE
'   nirwc   iwasp1        iwadr1        iwasp2       iwadr2
    2        9             0            0            0
```

```
WAVE SPECTRUM WINDsea
'  Hs   Tp  gamma
   15  16    /
DIRECTION PARAMETERS
'   wadr1    expo1
    180        0
'
'-----------------------------------------------------------------------
'-----  CURRENT STATE                                              -----
'-----------------------------------------------------------------------
'
NEW CURRENT STATE
' icusta  ncuelv
    1       4
' curelv  curdir  curvel
   0.0    0.0      0.93
 -50.0    0.0      0.68
 -300.    0.0      0.47
 -1000    0.0      0.00
NEW CURRENT STATE
' icusta  ncuelv
    2       4
' curelv  curdir  curvel
   0.0    180.0     0.93
 -50.0    180.0     0.68
 -300.    180.0     0.47
 -1000    180.0     0.00
'-----------------------------------------------------------------------
'-----  SUPPORT VESSEL DATA                                        -----
'-----------------------------------------------------------------------
TRANsfer FUNCtion FILE
'chftra
../../RAO_semi.rif
'
END
```

D.1.2 INPMOD Conventional SCR configuration 1 – Near Position

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Steel Catenary Riser - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'-----------------------------
  NEW SINGLE RISER
'-----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2       1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
'Boundary Conditions  -  top end
```

```
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0     0     0    GLOBAL
'    x0      y0     z0     x1    y1      z1        rot   dir
     0       0    -500    130    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1       z1     rot   dir
    2900       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI              100.0    0.0     0.0    0.0
'
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1       4      0       0
'icmpty  icn1ty  iexwty  nelseg  slgth
  1       0       0         50     100.0
  1       0       0         90     900.0
  1       0       0        100     400.0
  1       0       0        150     1500.0
'
'                        -----   -------
'                         390     2900.0
**** SAME AS MEAN POSITION INPUT ***
'
END
```

D.1.3 INPMOD Conventional SCR configuration 1 – Far Position

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Steel Catenary Riser - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'-----------------------------
  NEW SINGLE RISER
'-----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix   nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2       1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
```

```
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0     0     0    GLOBAL
'    x0      y0     z0     x1    y1      z1        rot   dir
     0       0    -500    -70    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1       z1     rot   dir
    2900       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI              -100.0    0.0     0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1       4      0       0
'icmpty  icn1ty  iexwty  nelseg  slgth
  1       0       0         50     100.0
  1       0       0        120    1200.0
  1       0       0        100     300.0
  1       0       0        130     1300.0
'
'                        -----   -------
'                         390     2900.0
**** SAME AS MEAN POSITION INPUT ***
'
END
```

D.1.4 INPMOD Conventional SCR configuration 2

Only mean position is presented here because typical changes can be found in previous sections for near and far load case.

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Conventional SCR Conf.2 - Strength Design - Mean Position
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'-----------------------------
  NEW SINGLE RISER
'-----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2       1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
```

```
   1       1       2
'
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0     0     0    GLOBAL
'    x0      y0     z0     x1    y1      z1         rot   dir
     30       0    -500     30    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1        z1     rot   dir
    2930       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI                0.0    0.0      0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1      8      0       0
'icmpty  icn1ty  iexwty  nelseg  slgth
  1      0       0        100     200.0
  1      0       0         95     800.0
  1      0       0        100     150.0
  2      0       0         15      25.0
  3      0       0        150     300.0
  3      0       0        100     250.0
  1      0       0        100     600.0
  1      0       0        100     575.0
'
'                        -----   -------
'                         760     2900.0
'-----------------------------------------------------------------------
' ------     COMPONENT C R S 0                                    ------
'-----------------------------------------------------------------------
'
'
'10" X65 pipe
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  1       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.1   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
NEW COMP CRS0
' icmpty  temp
  2       20
' diast    thst   emod     gmod    denst   thex   densx
 0.298    0.022  2.07E8   0.8E8    7.850  0.1   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.498
' tb      ycurmx
  1.0E+4   10.
'
NEW COMP CRS0
' icmpty  temp
  3       20
' diast    thst   emod     gmod    denst   thex   densx
 0.292    0.019  2.07E8   0.8E8    7.850  0.1   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.492
' tb      ycurmx
  1.0E+4   10.
'
' **** SAME AS MEAN POSITION INPUT IN CONFIGURATION 1 ***
'
```

```
END
```

D.1.5 INPMOD Weight Distributed SCR with Coating - Configuration G

Only mean position is presented here because typical change can be found in previous sections for near and far load case.

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Weight Distributed SCR Coating - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'-----------------------------
  NEW SINGLE RISER
'-----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2       1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0     0     0    GLOBAL
'    x0      y0     z0     x1    y1     z1         rot   dir
     0       0    -500     30    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1       z1     rot   dir
    2900       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI                0.0    0.0     0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1      10      0       99
'icmpty  icn1ty  iexwty  nelseg  slgth
'normal coating-1
  1       0       0       100     200.0
  1       0       0        10      85.0
'heavy coating-1
  2       0       0        75     750.0
  2       0       0        50     100.0
```

```
'heavy coating-2
  3       0       0         25      25.0
'light coating
  4       0       0         50     300.0
  4       0       0        100     250.0
  4       0       0        100     300.0
  4       0       0         60     315.0
'normal coating-2
  5       0       0        100     575.0
'
'                        -----   -------
'                                 2900.0
'-----------------------------------------------------------------------
' ------     COMPONENT C R S 0                                    ------
'-----------------------------------------------------------------------
'
'
'10" X65 pipe 100mm coating thickness - Normal coating
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  1       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
'
'10" X65 pipe 100mm coating thickness - Heavy coating-1
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  2       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   2.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
'
'10" X65 pipe 100mm coating thickness - Heavy coating-2
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  3       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   1.500
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
'
'10" X65 pipe 100mm coating thickness - Light coating
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  4       20
' diast    thst   emod     gmod    denst   thex   densx
 0.292    0.019  2.07E8   0.8E8    7.850  0.10   0.670
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.492
' tb      ycurmx
  1.0E+4   10.
'
'10" X65 pipe 100mm coating thickness - Normal coating
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  5       20
' diast    thst   emod     gmod    denst   thex   densx
 0.298    0.022  2.07E8   0.8E8    7.850  0.10   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.498
```

```
' tb      ycurmx
  1.0E+4   10.
'
'10" X65 pipe 100mm coating thickness - Light coating
'-------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  6       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   0.670
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
NEW COMPONENT FLUID
'  icmpty
     99
'
'  rhoi   vveli  pressi  dpress  idir
   0.800   0.0   2.0E4   0.0      2
'
'-----  ENVIRONMENTAL DESCRIPTION                                  -----
'-----------------------------------------------------------------------
'
' **** SAME AS MEAN POSITION INPUT IN CONVENTIONAL SCR ***
'
END
```

D.1.6 INPMOD Weight Distributed SCR with Clump Weight - Configuration F

Only mean position is presented here because typical change can be found in previous sections for near and far load case.

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Weight Distributed SCR Clump Weight - Strength Design - Mean Position
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'----------------------------
  NEW SINGLE RISER
'----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2      1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0     0     0    GLOBAL
'    x0      y0     z0     x1    y1      z1        rot   dir
```

```
     30       0    -500    30    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1        z1     rot   dir
    2930       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI                 0.0    0.0     0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1      70      0       99
'icmpty  icn1ty  iexwty  nelseg  slgth
  2       0       0        100     200.0
  2       0       0         20     208.0
' CLUMP WEIGHT (1-10)-segment 3-12-408m
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
' CLUMP WEIGHT (11-20)-segment 13-22-528m
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
' CLUMP WEIGHT (21-30)-segment 23-32-648m
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
' CLUMP WEIGHT (31-40)-segment 33-42-768m
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
' CLUMP WEIGHT (41-50)-segment 43-52-888m
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
```

```
  2       0      10          2      12.0
' CLUMP WEIGHT (51-60)-segment 53-62-1008m
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          6      12.0
  2       0      10          6      12.0
  2       0      11          6      12.0
  2       0      11          6      12.0
  2       0       0          6      12.0
  5       0       0          6      12.0
' CLUMP WEIGHT (61-62)-segment 63-65-1128m
  5       0       0          6      12.0
  5       0       0          6      12.0
  5       0       0         12      24.0
' NORMAL 22 WT-segment 66-1176m
  5       0       0         10      57.0
' LIGHT 19 WT-segment 67-69-1233m
  1       0       0        100     400.0
  1       0       0        100     250.0
  1       0       0        100     522.0
' NORMAL 22 WT-segment 70-2325m
  5       0       0        100     495.0
'
'                        -----   -------
'                         698     2900.0
'-----------------------------------------------------------------------
' ------     COMPONENT C R S 0                                    ------
'-----------------------------------------------------------------------
'
'
'10" X65 pipe
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  1       20
' diast    thst   emod     gmod    denst   thex   densx
 0.292    0.019  2.07E8   0.8E8    7.850  0.1   0.60
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.492
' tb      ycurmx
  1.0E+4   10.
'
NEW COMP CRS0
' icmpty  temp
  2       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.1   1.0
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
NEW COMP CRS0
' icmpty  temp
  5       20
' diast    thst   emod     gmod    denst   thex   densx
 0.298    0.022  2.07E8   0.8E8    7.850  0.1     0.8
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.498
' tb      ycurmx
  1.0E+4   10.
'-----------------------------------------------------------------------
'External Wrapping - Clump Weight
'-----------------------------------------------------------------------
NEW COMP EXT1
' icmpty
    10
' AMS    AE   RCYR   FRAC
  4.0  0.25  0.335  0.125
' CDX  CDY  AMX  AMY  CDLX  CDLY
   0   0.9  0.0  1.0  0.0    0.0
'
NEW COMP EXT1
' icmpty
    11
```

```
' AMS    AE   RCYR   FRAC
  2.0  0.2  0.335  0.125
' CDX  CDY  AMX  AMY  CDLX  CDLY
   0   0.9  0.0  1.0  0.0    0.0
NEW COMPONENT FLUID
'  icmpty
     99
'
'  rhoi   vveli  pressi  dpress  idir
   0.800   0.0   2.0E4   0.0      2
'
'-----  ENVIRONMENTAL DESCRIPTION                                  -----
'-----------------------------------------------------------------------
'
' **** SAME AS MEAN POSITION INPUT IN CONVENTIONAL SCR ***
'
END
```

D.1.7 INPMOD Weight Distributed SCR Combination B

Only mean position is presented here because typical change can be found in previous sections for near and far load case.

```
' ***   I N P M O D  INPUT FILE   ***
'-----------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Weight Distributed SCR Combination - Strength Design - Mean Position
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'-----------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                 ------
'-----------------------------------------------------------------------
'
'        Super nodes
'        Lines
'        Segments
'        Elements
'----------------------------
  NEW SINGLE RISER
'----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2      1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0     0     0    GLOBAL
'    x0      y0     z0     x1    y1      z1        rot   dir
     30       0    -500    30    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0       y0     z0        x1        y1       z1     rot   dir
    2930       0     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
```

```
  1     SEMI                0.0    0.0     0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'-----------------------------
' ilinty nseg  icnlty  ifluty
  1      43      0       99
'icmpty  icn1ty  iexwty  nelseg  slgth
  5       0       0        100     200.0
  5       0       0         55     500.0
' CLUMP WEIGHT (1-10)-segment 3-12-700m
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
' CLUMP WEIGHT (11-20)-segment 13-22-820m
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0       0          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
' CLUMP WEIGHT (21-30)-segment 23-32-940m
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
  2       0      10          2      12.0
' CLUMP WEIGHT (31-35)-segment 33-37-1060m
  2       0      10          6      12.0
  2       0      10          6      12.0
  2       0      11          6      12.0
  2       0      11          6      12.0
  2       0      11          6      12.0
' NORMAL 25.4 WT-segment 38-1120m
  5       0       0         10       50.0
' LIGHT 19 WT-Segment 39-41-1156m
  1       0       0         60     350.0
  1       0       0        100     200.0
  1       0       0         40     130.0
' NORMAL 22 WT-segment 42-43-1850m
  5       0       0        100     475.0
  5       0       0        100     575.0
'
'                        -----   -------
'                         655     2900.0
'-----------------------------------------------------------------------
' ------     COMPONENT C R S 0                                    ------
'-----------------------------------------------------------------------
'
'
'10" X65 pipe
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  1       20
' diast    thst   emod     gmod    denst   thex   densx
 0.292    0.019  2.07E8   0.8E8    7.850  0.1   0.600
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.492
```

```
' tb      ycurmx
  1.0E+4   10.
'
NEW COMP CRS0
' icmpty  temp
  2       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.1   2.2
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
NEW COMP CRS0
' icmpty  temp
  5       20
' diast    thst   emod     gmod    denst   thex   densx
 0.298    0.022  2.07E8   0.8E8    7.850  0.1     0.8
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.498
' tb      ycurmx
  1.0E+4   10.
'------------------------------------------------------------------------
'External Wrapping - Clump Weight
'------------------------------------------------------------------------
NEW COMP EXT1
' icmpty
    10
' AMS    AE   RCYR   FRAC
  3.0  0.25  0.335  0.125
' CDX  CDY  AMX  AMY  CDLX  CDLY
   0   0.9  0.0  1.0  0.0    0.0
'
NEW COMP EXT1
' icmpty
    11
' AMS    AE   RCYR   FRAC
  2.0  0.2  0.335  0.125
' CDX  CDY  AMX  AMY  CDLX  CDLY
   0   0.9  0.0  1.0  0.0    0.0
NEW COMPONENT FLUID
'  icmpty
     99
'
'  rhoi   vveli  pressi  dpress  idir
   0.800   0.0   2.0E4   0.0      2
'
'-----  ENVIRONMENTAL DESCRIPTION                                  -----
'------------------------------------------------------------------------
'
' **** SAME AS MEAN POSITION INPUT IN CONVENTIONAL SCR ***
'
END
```

D.1.8 INPMOD Fatigue Analysis - Weight Distributed SCR

Only weight distributed SCR with coating is presented here.

```
' ***   I N P M O D  INPUT FILE   ***
'------------------------------------------------------------------------
'
INPMod IDENtification TEXT  3.2
'
Weight Distributed SCR coating – Fatigue Analysis
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
UNIT NAME SPECification
' UTime    ULength  UMass      UForce       GRAV     GCONS
  s        m        MG         KN           9.81     1.0
' seconds  meter    Megagrams  kiloNewtons  m/s^2
'------------------------------------------------------------------------
'----- RISER SYSTEM SPECIFICATION                                  ------
'------------------------------------------------------------------------
'
'        Super nodes
```

```
'        Lines
'        Segments
'        Elements
'-----------------------------
  NEW SINGLE RISER
'-----------------------------
'iatyp  idris
 AR     LONG
 ARBITRARY SYSTEM AR
' nsnod     nlin   nsnfix  nves  no-of rigid-snodes
   2         1      2       1         0
'ibtang   zbot  ibot3D
   1      -1000    0
'Seafloor support conditions
'   stfbot     stfaxi     stflat    friaxi     frilat
   6.0E3      1.0E2       1.0E0      0.5         0.5
'  ilinty  isnod1  isnod2
   1       1       2
'
'Boundary Conditions  -  top end
' isnod   ipos   ix     iy    iz     irx    iry    irz
    1        1      1      1     1      0      0      0    GLOBAL
'    x0      y0     z0     x1    y1      z1        rot   dir
     30       2    -500     30    2.0    -20         75.0
'
'Boundary Conditions  -  lower end
' isnod   ipos   ix     iy    iz     irx    iry    irz
   2       0      1      1     1      1      1      1    GLOBAL
'    x0        y0     z0        x1        y1       z1     rot   dir
    2930       2     -500     2400      2.0      -1000
'
'
' xg, yg, zg: Coordinates for vessel contact
' ives  idhftr               xg     yg     zg   headng
  1     SEMI                0.0    0.0     0.0    0.0
'
'-----------------------------------------------------------------------
'----- LINE DATA                                                   -----
'-----------------------------------------------------------------------
NEW LINE DATA
'----------------------------
' ilinty nseg  icnlty  ifluty
   1       8      0       99
'icmpty  icn1ty  iexwty  nelseg  slgth
'normal coating-1
  1       0       0        100     200.0
  1       0       0         10      85.0
'heavy coating-1
  2       0       0         85     850.0
'heavy coating-2
  3       0       0         25      25.0
'light coating
  4       0       0         45     450.0
  4       0       0        100     150.0
  4       0       0         55     565.0
'normal coating-2
  5       0       0         57     575.0
'                        -----   -------
'                          477    2900.0
'-----------------------------------------------------------------------
' ------     COMPONENT C R S 0                                   ------
'-----------------------------------------------------------------------
'
'
'10" X65 pipe 100mm coating thickness - Normal coating
'-------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  1       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
'
```

```
'10" X65 pipe 100mm coating thickness - Heavy coating-1
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  2       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   2.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
'
'10" X65 pipe 100mm coating thickness - Heavy coating-2
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  3       20
' diast    thst   emod     gmod    denst   thex   densx
 0.298    0.022  2.07E8   0.8E8    7.850  0.10   1.500
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.498
' tb      ycurmx
  1.0E+4   10.
'
'
'10" X65 pipe 100mm coating thickness - Light coating
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  4       20
' diast    thst   emod     gmod    denst   thex   densx
 0.292    0.019  2.07E8   0.8E8    7.850  0.10   0.670
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.492
' tb      ycurmx
  1.0E+4   10.
'
'10" X65 pipe 100mm coating thickness - Normal coating
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  5       20
' diast    thst   emod     gmod    denst   thex   densx
 0.298    0.022  2.07E8   0.8E8    7.850  0.10   0.800
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.498
' tb      ycurmx
  1.0E+4   10.
'
'10" X65 pipe 100mm coating thickness - Light coating
'------------------------------------------------------
NEW COMP CRS0
' icmpty  temp
  6       20
' diast    thst   emod     gmod    denst   thex   densx
 0.3048    0.0254  2.07E8   0.8E8    7.850  0.10   0.670
' cqx  cqy  cax   cay  clx  cly  icode  d
  0.0  0.9  0.0   1.0  0.0  0.0    2   0.5048
' tb      ycurmx
  1.0E+4   10.
'
NEW COMPONENT FLUID
'  icmpty
     99
'
'  rhoi   vveli  pressi  dpress  idir
   0.800   0.0   2.0E4   0.0      2
'
'-----  ENVIRONMENTAL DESCRIPTION                                  -----
'-----------------------------------------------------------------------
'
ENVIronment IDENtification
' Descriptive text one line (A60)
Irregular wave analysis
'idenv
 EXTREM
```

```
'
WATErdepth AND WAVEtype
'wdepth  noirw   norw    ncusta
  1000   1       0       2
'
ENVIronment CONStants
'airden  watden  wakivi
 0.0013     1.025   1.188E-6
'
'-----------------------------------------------------------------------
'-----  IRRREGULAR SEASTATE                                        -----
'-----------------------------------------------------------------------
'
NEW IRREGULAR SEASTATE
'   nirwc   iwasp1        iwadr1        iwasp2       iwadr2
    1        9              0            0            0
WAVE SPECTRUM WINDsea
'  Hs   Tp      gamma
  xxxhs xxxtp     /
DIRECTION PARAMETERS
'   wadr1    expo1
  xxxdir        0
'
'
'-----------------------------------------------------------------------
'-----  CURRENT STATE                                              -----
'-----------------------------------------------------------------------
'
NEW CURRENT STATE
' icusta  ncuelv
    1       4
' curelv  curdir  curvel
   0.0    0.0      0.93
 -50.0    0.0      0.68
 -300.    0.0      0.47
 -1000    0.0      0.00
NEW CURRENT STATE
' icusta  ncuelv
    2       4
' curelv  curdir  curvel
   0.0    180.0     0.93
 -50.0    180.0     0.68
 -300.    180.0     0.47
 -1000    180.0     0.00
'-----------------------------------------------------------------------
'-----  SUPPORT VESSEL DATA                                        -----
'-----------------------------------------------------------------------
TRANsfer FUNCtion FILE
'chftra
../../RAO_semi.rif
'
END
```

D.2. STAMOD

STAMOD input variation is only affected by vessel position. The wave direction and vessel position is combined such that it results in worst situation. Therefore, there are only twodifferent STAMODs; near, far load case. STAMOD for Mean load case is similar to near load case.

D.2.1 STAMOD Near Load Case

```
'
' ***   S T A M O D  INPUT  FILE   ***
'
STAMod CONTrol INFOrmation   3.2
'
'Three lines of identification text (A60)
'
Steel Catenary Riser - Strength Design – Near Load Case
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'---
'irunco  idris   ianal     iprdat    iprcat    iprfem   iprform   iprnor
   1     LONG      1         5         5         5        1         1
'---
RUN IDENtification
'idres
SHAPE
'---
ENVIronment REFErence IDENtifier
'idenv
 EXTREM
'---
STATic CONDition INPUt
'nlcomp  icurin  curfac  lcons
 0        1       1.0     0
'---
COMPutational PROCedure
FEM
FEM ANALysis PARAmeters
'
LOAD GROUP DATA
' nstep  maxit      racu
  10       50      1.E-5
' lotype
   VOLU
'
LOAD GROUP DATA
' nstep  maxit      racu
   100     50      1.E-5
' lotype
   DISP
'
LOAD GROUP DATA
' nstep  maxit      racu
   10     50      1.E-5
' lotype
   FRIC
'
LOAD GROUP DATA
' nstep  maxit      racu
   10     50      1.E-5
' lotype
  CURR
'--------------------------------------------------------
 END
'--------------------------------------------------------
'  --
PARAMETRIC VARIATION DEFINITION
'  nstvar  iofpos  icuvar  ifovar  maxipv  racupv
    10        1      0        0       1      0.00001
STATIC OFFSET INCREMENT
' iref  dxoff  dyoff  dzof  irot  drot
   -1   0.2     0.0   0.0    0   0.0
'  -1  1.9775 3.42513   0.0    0   0.0
STAMOD PRINT CONTROL
' istep  isfor  ispos
```

```
   10      0      1
'
END
```

D.2.2 STAMOD Far Load Case

```
'
' ***   S T A M O D  INPUT  FILE   ***
'
STAMod CONTrol INFOrmation   3.2
'
'Three lines of identification text (A60)
'
Steel Catenary Riser - Strength Design – Far Load Case
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'---
'irunco  idris   ianal     iprdat    iprcat    iprfem   iprform   iprnor
   1     LONG      1         5         5         5        1         1
'---
RUN IDENtification
'idres
SHAPE
'---
ENVIronment REFErence IDENtifier
'idenv
 EXTREM
'---
STATic CONDition INPUt
'nlcomp  icurin  curfac  lcons
 0        2       1.0     0
'---
COMPutational PROCedure
FEM
FEM ANALysis PARAmeters
'
LOAD GROUP DATA
' nstep  maxit      racu
  10       50      1.E-5
' lotype
   VOLU
'
LOAD GROUP DATA
' nstep  maxit      racu
   100     50      1.E-5
' lotype
   DISP
'
LOAD GROUP DATA
' nstep  maxit      racu
   10     50      1.E-5
' lotype
   FRIC
'
LOAD GROUP DATA
' nstep  maxit      racu
   10     50      1.E-5
' lotype
  CURR
'---------------------------------------------------------
 END
'---------------------------------------------------------
'  --
PARAMETRIC VARIATION DEFINITION
'  nstvar  iofpos  icuvar  ifovar  maxipv  racupv
    10        1      0        0       1      0.00001
STATIC OFFSET INCREMENT
' iref  dxoff  dyoff  dzof  irot  drot
   -1   0.2     0.0   0.0    0   0.0
'  -1  1.9775 3.42513  0.0    0   0.0
STAMOD PRINT CONTROL
' istep  isfor  ispos
   10      0      1
'
END
```

D.3 DYNMOD

DYNMOD input variation is also affected by vessel position. The wave direction and vessel position is combined such that it results in worst situation. Therefore, there are only two different DYNMODs; near, far load case. DYNMOD for Mean load case is similar to near load case.

D.3.1 DYNMOD Near Load Case

```
'
' ***   D Y N M O D  INPUT  FILE   ***
'---                                                --- A1
DYNMod CONTrol INFOrmation  3.2
'
'Three lines of identification text (A60)
'
Steel Catenary Riser - Strength Design – Near Load Case
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
'---     (2=reg, 3=irreg)
'irunco  ianal   idris   idenv   idsta   idirr   idres
 1       3      LONG    EXTREM  SHAPE   IRR_1    REG_1
'
'REGULAR WAVE ANALYSIS
' nper  nstppr  irwcn  imotd
'   5      200     1      1
'
'REGULAR WAVE LOADING
'  iwtyp  isurf  iuppos
'     2      /       1
'
'REGWAVE PRINT OPTIONS
' nprend  nprenf  nprenc
'     1       1       1
'
'---                                                --- A2
 IRREGULAR TIMESERIES PARAMETERS
' linear + wave spreading
' irand   mhf   dthf
   478941 10800   0.33
'
 IRREGULAR RESPONSE ANALYSIS
' ircno   time      dt    irwav   irmot   irlfm   tbeg   iscale
    1    10800    0.11     2       2      NONE
'     1   200  0.033     2       2      NONE      400
'     1   100  0.011     2       2      NONE      7110
'
'
 IRREGULAR WAVE PROCEDURE
' Iuppos    icosim  kinoff   chstep   nodstp   zlower   zupper
     1         1      0        NODE      1      -500      0.0
'
 IRREGULAR FOURIER PRINT
' ipmoti  ipwafo  iphfts  iplfts  iptomo  ipveac
    0       0       0       0       0       1
'-------------------------------------------------------------------------------
          TIME DOMA PROC
'-------------------------------------------------------------------------------
'   itdmet  inewil  idisst  iforst  icurst
       2       1       1       1       0
'   betin   gamma   tetha   a1      a2     a1t     a1to    a1b     a2t     a2to    a2b
    4.000    .500   1.000    .000    .0127    .000    .000    .000    .000    .000
.000
'   indint  indhyd  maxhit  epshyd  ntramp  indrel  iconre  istepr  ldamp
       1       1       5     .01     10       0       0       0       0
  NONLINEAR INTEGRATION PROCEDURE
' ITFREQ  ISOLIT  MAXIT  DACCU  ICOCOD
    1       1      20   1.0E-10     1    8
'
'---                                             --- E6
DISPLACEMENT  RESPONSE  STORAGE
'idisp   nodisp
  1       7
'ilin    iseg    inod
```

```
  1       1       ALL
  1       2       ALL
  1       3       ALL
  1       4       ALL
  1       5       ALL
  1       6       ALL
  1       7       ALL
'
'---                                             --- E7
FORCE RESPonse  STORage
'ifor    nofor
  1       7
'ilin    iseg    inod
  1       1       ALL
  1       2       ALL
  1       3       ALL
  1       4       ALL
  1       5       ALL
  1       6       ALL
  1       7       ALL
'---                                             --- E8
' CURVature RESPonse STORage
'icurv   nocurv
'  2       2
''ilin    iseg    inod
' 1       1       ALL
' 1       6       ALL
'---                                             --- E6
ENVElope CURVe SPECification
'ienvd   ienvf   ienvc   tenvs   tenve   nprend  nprenf  nprenc
 1         1       1       0.     1.E6    1       1       1
'---                                             --- E7
END
```

D.3.1 DYNMOD Far Load Case

```
'
' ***   D Y N M O D  INPUT  FILE   ***
'---                                                --- A1
DYNMod CONTrol INFOrmation  3.2
'
'Three lines of identification text (A60)
'
Steel Catenary Riser - Strength Design – Far load case
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
'---     (2=reg, 3=irreg)
'irunco  ianal   idris   idenv   idsta   idirr   idres
 1       3      LONG    EXTREM   SHAPE   IRR_1    REG_1
'
'REGULAR WAVE ANALYSIS
' nper  nstppr  irwcn  imotd
'   5      200     1      1
'
'REGULAR WAVE LOADING
'  iwtyp  isurf  iuppos
'     2      /       1
'
'REGWAVE PRINT OPTIONS
' nprend  nprenf  nprenc
'     1       1       1
'
'---                                                --- A2
 IRREGULAR TIMESERIES PARAMETERS
' linear + wave spreading
' irand   mhf   dthf
   478941 10800   0.33
'
 IRREGULAR RESPONSE ANALYSIS
' ircno   time     dt    irwav   irmot   irlfm   tbeg   iscale
    2    10800    0.11     2       2      NONE
'     2   200  0.033     2       2      NONE      400
'     2   100  0.011     2       2      NONE      7110
'
'
```

```
 IRREGULAR WAVE PROCEDURE
' Iuppos    icosim  kinoff   chstep   nodstp   zlower   zupper
     1        1      0        NODE      1      -500      0.0
'
 IRREGULAR FOURIER PRINT
' ipmoti  ipwafo  iphfts  iplfts  iptomo  ipveac
    0       0       0       0       0       1
'-------------------------------------------------------------------------------
           TIME DOMA PROC
'-------------------------------------------------------------------------------
'   itdmet  inewil  idisst  iforst  icurst
       2       1       1       1       0
'   betin   gamma   tetha   a1      a2     a1t     a1to    a1b     a2t     a2to    a2b
    4.000    .500   1.000    .000    .0127    .000    .000    .000    .000    .000
.000
'   indint  indhyd  maxhit  epshyd  ntramp  indrel  iconre  istepr  ldamp
       1       1       5     .01     10       0       0       0       0
  NONLINEAR INTEGRATION PROCEDURE
' ITFREQ  ISOLIT  MAXIT  DACCU  ICOCOD
    1       1      20   1.0E-10     1    8
'
'---                                             --- E6
DISPLACEMENT  RESPONSE  STORAGE
'idisp   nodisp
  1       9
'ilin    iseg    inod
  1       1       ALL
  1       2       ALL
  1       3       ALL
  1       4       ALL
  1       5       ALL
  1       6       ALL
  1       7       ALL
  1       8       ALL
  1       9       ALL
'
'---                                             --- E7
FORCE RESPonse  STORage
'ifor    nofor
  1       9
'ilin    iseg    inod
  1       1       ALL
  1       2       ALL
  1       3       ALL
  1       4       ALL
  1       5       ALL
  1       6       ALL
  1       7       ALL
  1       8       ALL
  1       9       ALL
'---                                             --- E8
' CURVature RESPonse STORage
'icurv   nocurv
'  2       2
''ilin    iseg    inod
' 1       1       ALL
' 1       6       ALL
'---                                             --- E6
ENVElope CURVe SPECification
'ienvd   ienvf   ienvc   tenvs   tenve   nprend  nprenf  nprenc
 1         1       1       0.     1.E6    1       1       1
'---                                             --- E7
END
```

D.4 OUTMOD

There are three different OUTMOD input.

- OUTMOD to derive time series in strength analysis
- OUTMOD to derive Von Mises stress curve in strength analysis
- OUTMOD to derive fatigue damage/life in fatigue analysis

D.4.1 OUTMOD – time series

In this example, OUTMOD is used to extract results for riser segment 4.

```
OUTMOD IDENTIFICATION TEXT  3.2
Steel Catenary Riser - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
NEW PLOT FILE
'----------------------------------------------------
DYNDisp TIME SERIes
'----------------------------------------------------
' iop  idof  it1   nts    nnelc
   1     3    1   10000000  1
' iline  iseg  ielm
    1      4   ALL
'----------------------------------------------------
TOTForce TIME SERIES
'----------------------------------------------------
' iop  idof  it1   nts    nnelc
    1    1   1  10000000    1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
    1      4    ALL
'    1      5    ALL
STARTIMES FILE
PLOT
'
'
TOTForce TIME SERIES
' iop  idof  it1   nts    nnelc
    1    3   1  10000000    1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
    1      4    ALL
'    1      5    ALL
STARTIMES FILE
PLOT
'
'
TOTForce TIME SERIES
' iop  idof  it1   nts    nnelc
    1    5   1  10000000    1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
    1      4    ALL
'    1      5    ALL
STARTIMES FILE
PLOT
'
'
STRESS TIME SERIES
' iop  idof   it1       nts      isubst    nnelc
    1   7      1     1000000      0         1
' theta   inex   ioppre
   90      2     -1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
```

```
    1      4    ALL
'    1      5    ALL
STARTIMES FILE
PLOT
'
'
'STRESS TIME SERIES
' iop  idof   it1       nts      isubst    nnelc
'    1   7      1     1000000      0         1
' theta   inex   ioppre
'   270      2     -1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
'    1      4    ALL
'STARTIMES FILE
'PLOT
'
'
STRESS TIME SERIES
' iop  idof   it1       nts      isubst    nnelc
    1   4      1     1000000      0         1
' theta   inex   ioppre
   90      2     -1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
    1      4    ALL
'    1      5    ALL
STARTIMES FILE
PLOT
'
'
'STRESS TIME SERIES
' iop  idof   it1       nts      isubst    nnelc
'    1   4      1     1000000      0         1
' theta   inex   ioppre
'   270      2     -1
' iline  iseg  ielm
'    1      1    ALL
'    1      2    ALL
'    1      3    ALL
'    1      4    ALL
'STARTIMES FILE
'PLOT
'
END
```

D.4.2 OUTMOD – Von Mises stress curve

```
OUTMOD IDENTIFICATION TEXT  3.2
Steel Catenary Riser - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
NEW PLOT FILE
'
STRESS ENVELOPE CURVE
' iline  idof1  idof2
     1     4
' tsta   tend  iop  dur
   10  1000000  1
'  npcs  iopr  theta  inex  iopre
   36     0     0.0   2     -1
' iopstr
     0
PLOT
'
STRESS ENVELOPE CURVE
' iline  idof1  idof2
     1     7
' tsta   tend  iop  dur
   10  1000000  1
'  npcs  iopr  theta  inex  iopre
```

```
   36     0     0.0   2     -1
' iopstr
     0
PLOT
'
END
```

D.4.3 OUTMOD – Fatigue Damage/Life

```
OUTMOD IDENTIFICATION TEXT  3.2
'
'Three lines of identification text (A60)
'
Steel Catenary Riser - Strength Design
10inch pipe (X65)
Iqbal Ruswandi - Feb 2009
'
TIMEDOMAIN FATIGUE DAMAGE
' nsect  npcs ioppr  tbeg  tend
  0      16    16     0   2700
' DSCFA  DSCFY  DSCFZ  ASI        WST
  1.05    1.05    1.05
' nosl   limind  fatlim  rfact
  2      0       0.0     0.001
' rm1    rc1    -    DnV C-Curve in SW
  -3.0   12.192  -5   7
'
PRINT
END
```