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Flexible Riser Global Analysis for Very Shallow Water

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30 ECTS thesis submitted as part of fulfillment of a Master degree in
Offshore Technology (Subsea Technology)

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Abstract

Flexible risers are widely used for a range of water depths and can accommodate large floater motions when using a buoyant system. A wide range of buoyancy solutions have been developed for very shallow water (e.g. 30-50 m), shallow water (e.g. 90-110 m) and semi-deep water (e.g. 300-400 m) and in the ranges between these depths.

Flexible risers can have different configurations. These different solutions have different characteristics which influence their suitability for a given situation. The pipes should not experience excessive curvature; a limiting value is given by the manufacturer. The system should avoid axial compression in the pipes and contact between the pipes and other structures.
This thesis will focus on the challenges and solutions for very shallow water depths (less than 50 m).

This thesis will consider the design of dynamic, flexible unbounded riser pipes connecting a subsea pipeline to an FSO turret. The following work will be presented:

- Study of flexible riser technology, especially comparing different very shallow water buoyancy systems.
- Methodology of design of flexible riser
- Parameters effect on flexible riser design
- A case study of a typical very shallow water project using dynamic flexible risers:
    i. Presenting relevant input data for designing the risers.
    ii. Static and dynamic design and analysis, taking FSO motions and hydrodynamics into account and checking against relevant design codes.

Modeling and Dynamic analysis will be performed by using FE software OrcaFlex.

Irregular waves are taken into account for the dynamic analysis. The wave spectra will be investigated based on location.

Acknowledgement

First of all, I would like to express my deepest appreciation to Professor Ove Tobias Gudmestad for his guide and help through learning process of master study in University of Stavanger and also for the useful comments, remarks and engagement for this master thesis.
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Sadjad Karegar

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Abbreviations

API	American Petroleum Institute
DAF	Dynamic Amplification Factor
DNV	Det Norske Veritas
FE	Finite Element
FSO	Floating Storage and Offloading
ISO	International Organization for Standardization
MBR	Minimum Bending Radius
MWA	Mid Water Arch
PLEM	Pipeline End Manifold
PLET	Pipeline End Termination
RAO	Response Amplitude Operator
STL	Submerged Turret Loading
TDP	Touch Down Point

1. Introduction

1.1 Background

Flexible pipe as a marine product was introduced to the offshore market in the early seventies. The flexible risers were first specified and installed in the Enchova field offshore Brazil in 1978, [6].

Flexible risers are important components for offshore developments because they provide the means of transferring fluids or power between subsea units and floating structures, [6]. These risers can accommodate big motions from floating structure and also can resist hydrodynamic loadings such as waves and currents. They have high axial stiffness and low bending stiffness; these properties increase the ability of the flexible riser to handle large deformations. This large deformation can be generated by ocean currents and waves or motions of floating structure.

For design of flexible risers, complex loadings and motions should be considered. Design of the system should foresee large deflections of structures subject to the dynamic boundary conditions and those non-linear hydrodynamic loadings.

The behavior of flexible riser near the end connectors at seabed or at a floating structure is very important and is dependent to local structural stiffness properties, [6], see Figure 1-1.

The configuration of flexible riser is very important issue. There are many parameters which affect on the flexible riser configuration.

Different analyses must be performed by a suitable software package. The software should be fast enough to combine all the different parameters to enable the engineers to assess the effects of those parameters on the system.

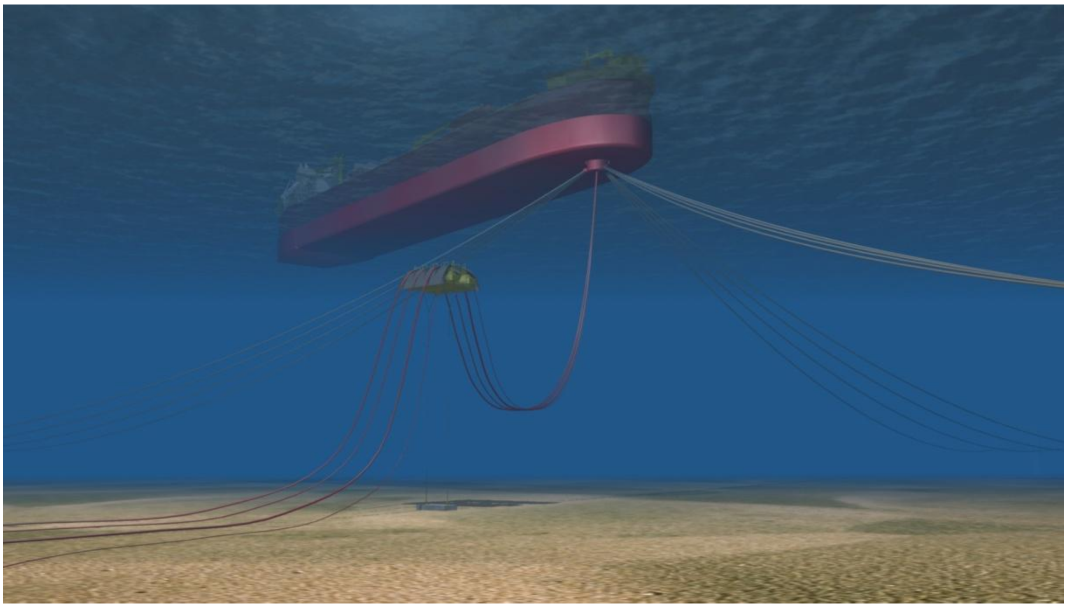


Figure 1-1 Typical Flexible Riser Configuration

1.2 Scope of Work

Due to the advantages of FPSO's they are being used in very shallow waters (less than 50m water depth is current practice in Vietnam now days). The design of a flexible riser in this very shallow water has high challenges. These challenges are connected to mooring and riser design and also to the capacity of FPSO contractors. The Design will become even more challengeable if it combines with harsh environment and significant vessel motions, [7].

In this paper different challenges that we face to design a flexible riser and different parameters which will affect the flexible riser design in very shallow water especially meteocean data will be discussed.

In this paper the configuration of dynamic flexible riser for very shallow water will be defined. The optimum riser configuration in terms of buoyancy elements and weight elements will be analyzed and determined. A design load case matrix with corresponding to sea states and floater conditions will be established.

The dynamic riser analyses will be performed with the computer program OrcaFlex.

A case study will also be presented that will explain how we can reach the specific chosen solution.

1.3 Thesis Organization

The following are to be undertaken in the thesis Scope:

Chapter 1: Introduction.

Chapter 2: Discusses different component which necessary for design and fabrication of flexible riser.

Chapter 3: Discusses different configuration of flexible risers and possible configuration in very shallow water.

Chapter 4: Discusses parameters which will affect the dynamic design of flexible risers in very shallow water including weather, hydrodynamic loads and other factors.

Chapter 5: Discusses Design methodology and steps for global design of flexible pipes in very shallow water and Discuss base case matrixes and sensitivity matrix to be used for design.

Chapter 6: Case study: Design basis.

Chapter 7: Static Analysis using OrcaFlex software

Chapter 8: Dynamic Analysis using OrcaFlex software.

Chapter 9: Provides Conclusions.

Chapter 10: Provides Recommendations and further works.

2. Flexible Riser Components

2.1 Flexible Pipe Description

Generally a flexible pipe combines high axial tensile stiffness with low bending stiffness. This can be achieved by a composite pipe wall construction. This is more applicable to unbonded flexible pipes rather than bonded flexible pipes.

These pipes have much less allowable radius of curvature than steel pipe with the help of helical armoring layers and polymer sealing layers. Generally, a flexible pipe is designed specifically for each application, although they may be grouped according to specific designs. The pipe can be optimized for each application, [4].

2.2 Unbonded Flexible Pipe Structure

A typical cross-section of a flexible pipe is shown in Figure 2-1. The main layers identified are as follows, [4]:

a. Carcass: This is an interlocked metallic layer which provides resistance against external pressure.

b. Internal sheath: This is an extruded polymer layer which provides an internal fluid containment barrier.

c. Pressure armor: This is an interlocked metallic layer which resist against hoop pressure.

d. Tensile armors: The tensile armor layers typically use flat, round, or shaped metallic wires, in two or four layers crosswound at an angle between 20 degrees and 60 degrees.

e. External Sheath: This is a barrier for external fluid.

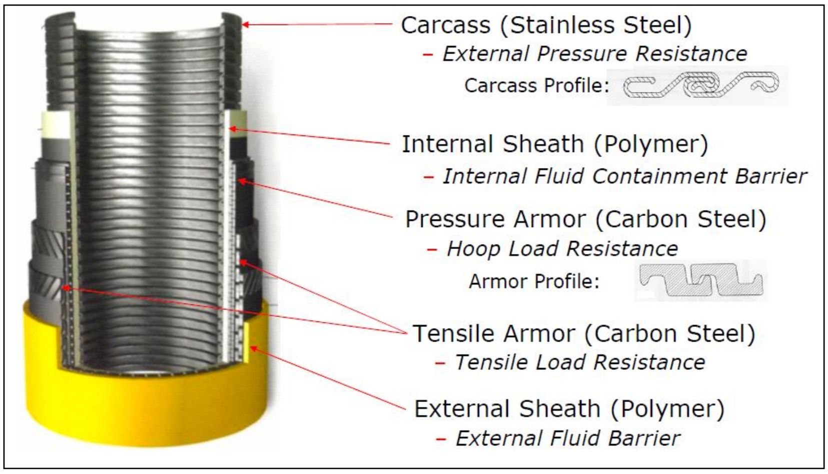


Figure 2-1 Schematic of Typical Flexible Riser Cross Section

2.3 End Fittings

The terminations of a flexible pipe are named as end fittings. The purposes of a flexible pipe end fitting are as follows, [4]:

a. To provide a pressure tight transition between the pipe body and the connector.

b. To terminate all the strength members in the flexible pipes so that axial loads and bending moments can be transmitted into the end connector without affecting on the fluid-containing layers.

An end connector may be an integral part of or attached to the End Fitting. A variety of end connectors exists, such as bolted flanges, clamp hubs, diverless connectors or welded joints. The selection of connector depends on operational and service requirements. A typical unbonded pipe end fitting is illustrated in Figure 2-2.

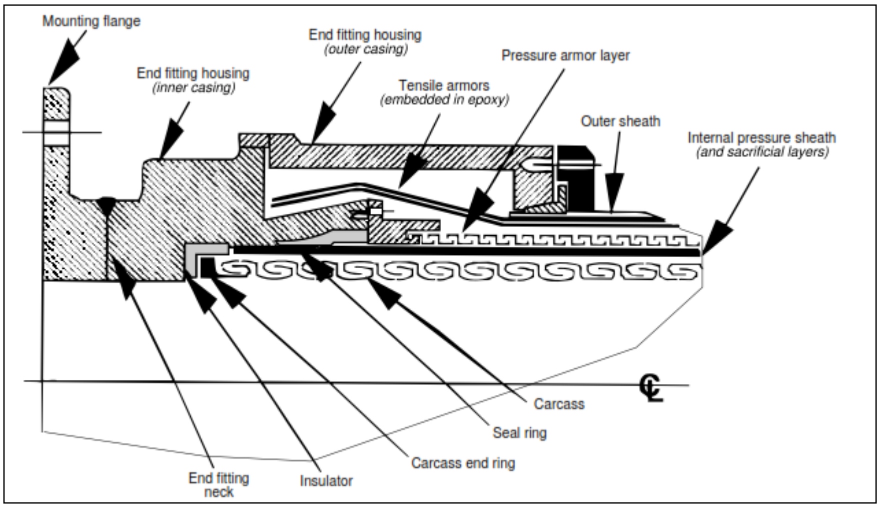


Figure 2-2 Example of and Unbonded Flexible Pipe End Fitting, [4]

2.4 Ancillary Components

2.4.1 Bend Limiters

Bend limiters are designed to give no sharp bending in the pipe for the area close to the end Fitting. For further distances from the end fitting the bending is allowed to increase with a smooth variation of bending moment. This should be within Minimum Bending Radius (MBR) criteria for the flexible pipe, [4].

Two types of bend limiters in common use are bend stiffeners and bellmouths. Bend stiffeners and bellmouths are generally used for dynamic applications; they may also be used in static applications. Bend limiters are shown schematically in Figure 2-3.

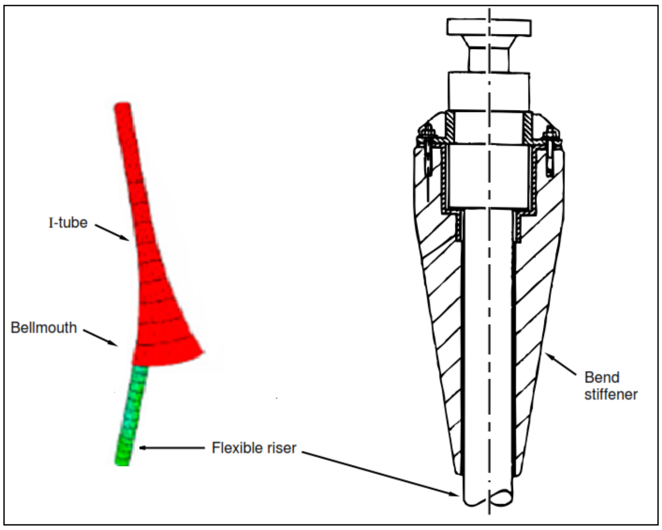


Figure 2-3 Bend Limiters

2.4.2 Subsea Buoys

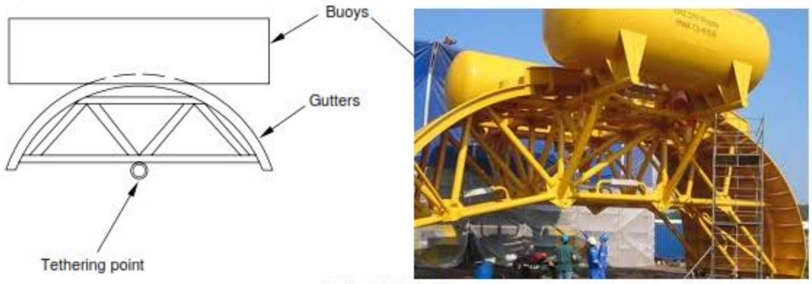
Subsea buoys typically consist of one or more buoyancy tanks supported by a steel structure. Over the structure there are individual gutters (arches) to lay riser on. The buoyancy tanks may be constructed from either steel or syntactic foam modules.

Subsea buoy/arch systems are used to achieve “S configurations”, including, lazy, steep, and reverse configurations. For flexible riser configurations refer to Section 3.

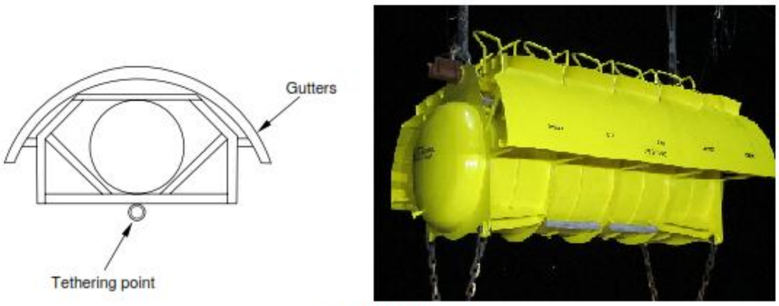
The subsea buoy/arch system is held in place by a riser base or an anchoring system. A bouy is connected to the riser base or anchor by tethers (in the case of lazy-S configuration) or by flexible risers (for steep-S configuration). The subsea buoy/arch systems are designed to typically support two to six risers, though there is no theoretical limit on the number, [4].

As an alternative, the S configuration may be achieved by using a fixed support instead of a floating buoy. The main disadvantage of this system is the reduction in compliancy of the riser system.

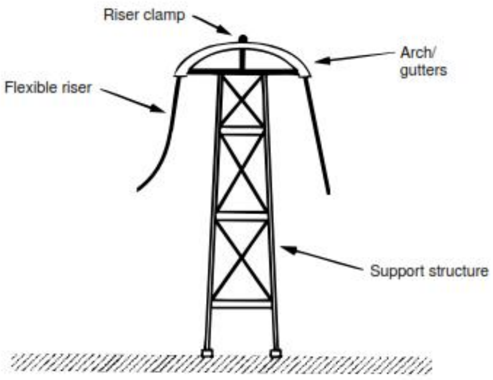
Typical systems of subsea buoys are shown in Figure 2-4.



Option 1–Twin Buoys



Option 2–Single Buoy



Option 3–Fixed Arch

Figure 2-4 Subsea Buoy/Arch System, [4]

2.4.3 Buoyancy Modules

Buoyancy modules are used to make the selected shape of the riser configurations (lazy, steep, and pliant wave configuration). A larg numbers of modules (e.g., 30) are required to make the wave configuration. Their length and diameter is about two to three times the pipe OD. This depends on buoyancy and installation requirements.

The number of modules is largely based on riser weight, water depth, offset requirements, and manufacturing /commercial issues.

The buoyancy modules typically consist of two components: an internal clamp and a syntactic foam buoyancy element. The internal clamp bolts directly onto the flexible pipe, and the buoyancy element fits around the clamp. A polymer (e.g., polyurethane) casing provides impact and abrasion resistance. The buoyancy element is generally in two halves and they are securely fastened together. As the modules are individually clamped to the riser, the design should ensure that they do not slide along the pipe or damage it, [4].

The density of the synthetic foam is selected based on the specified water depth and service life. A typical density is 350 kg/m3.

A schematic of a typical module is shown in Figure 2-5.

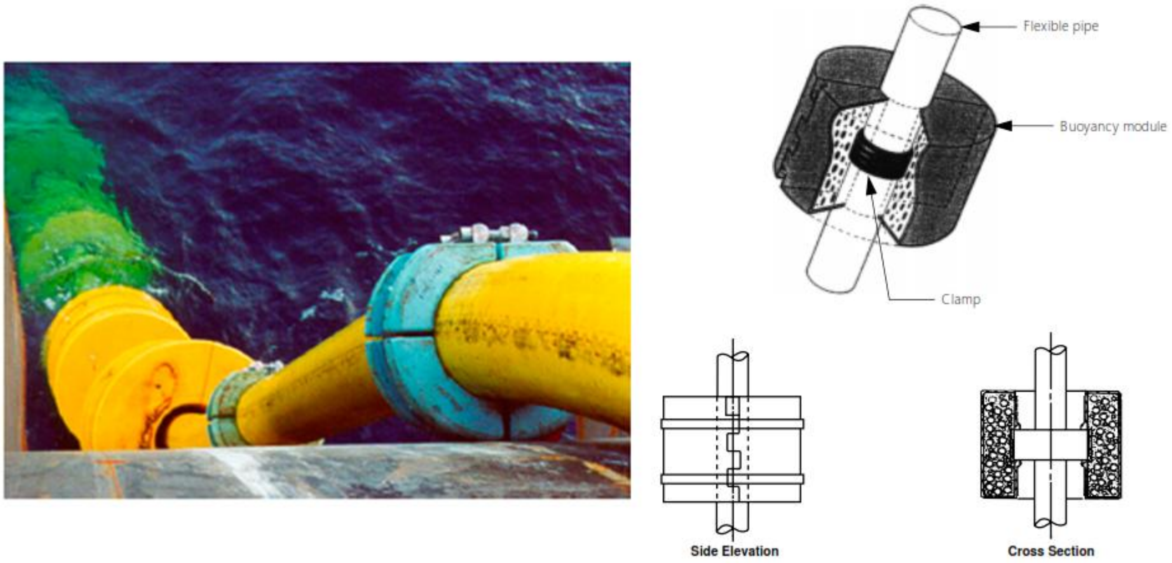


Figure 2-5 Example Buoyancy Module for Wave Configuration,[4]

2.4.4 Riser Bases

Riser bases are used to connect flexible risers to pipelines and may also be required to support subsea buoy/ arch systems (e.g., steep-S configurations). With the lazy S configuration there is no need to use a riser base. The flexible riser will then be directly connected to the PLEM. The PLEM will act as a riser base in this case. More details regarding flexible riser configurations will be discussed in section 3.

The riser base may be a gravity structure, a piled structure, or a suction/anchor pad. Selection of gravity based or piled structure depends on the applied loads and soil conditions.

A typical riser base structure is shown in Figure 2-6.

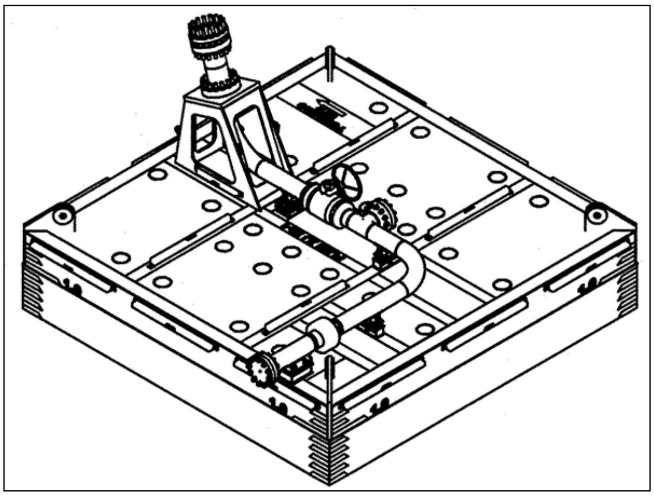


Figure 2-6 Example of a Typical Riser Base

2.4.5 Riser Hang-Off and Turret Structure

The risers may be connected to a turret with hang-off in the FSO. A solution for the turret system is a STL (submerged turret loading) buoy. Alternatively, an internal turret will be considered. The general arrangement of the STL turret system is indicated in Figure 2-7.

Important considerations in the design of riser hang-off structures include the following:

a. The connection will experience axial, bending and shear loads.

b. The main constraints in the design of the hang-off structure are load limitations, space limitations, etc.

c. Overbending of the riser at the base of a turret is prevented by use of a bend limiter (bend stiffener).

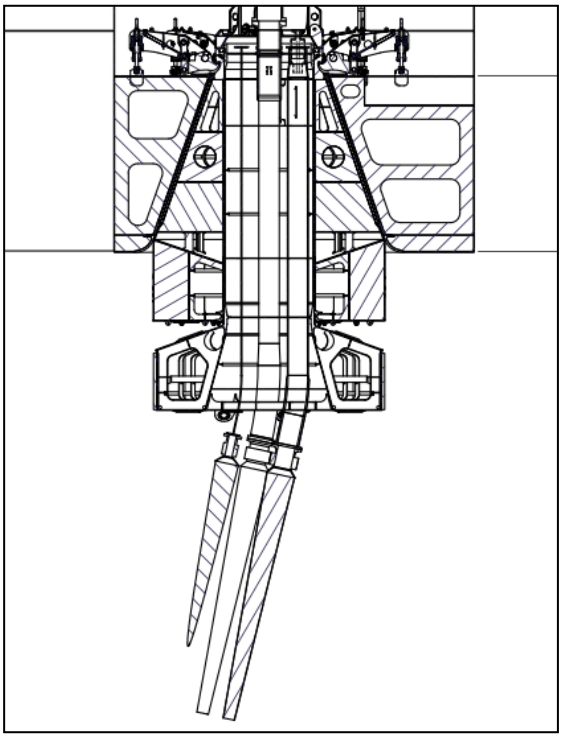


Figure 2-7 Longitudinal Section of Turret System

3. Riser Configurations

3.1 General

A considerable part of a flexible riser system design is the determination of the configuration so that the riser can safely sustain the extreme sea states loadings, [4].

The riser configurations typically used are shown schematically in Figure 3-1. In general the critical sections in the riser configurations are at the top (or bottom), where there are high tensile forces and large curvatures. Also they are critical at the sag bend, where there is large curvature (at low tension); and at the hog of a wave buoyancy section, where there is large curvature (at low tension), [4].

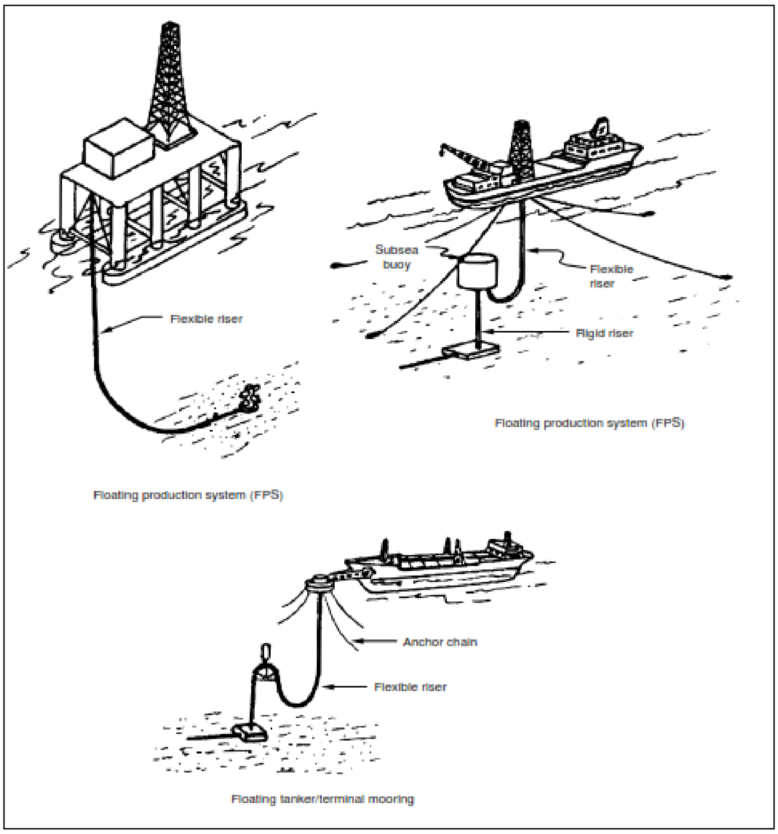


Figure 3-1 Examples of Dynamic Applications for flexible pipes, [4].

Industry practice calls for several types of riser configurations typically used in conjunction with Floating Production/Loading Systems. The standard five configurations generally used are termed: free-hanging catenary, lazy-S, lazy wave, steep-S and steep wave, [8].

Also there are three other wave configurations: Pliant wave, weight added wave and touchdown chain wave (modified pliant wave).

The dynamic response of a particular riser system is directly related to the environmental loadings due to the combined wave-current field flow and the dynamic boundary conditions of the riser top end at the water surface, coupled with the interaction arising from the structural nonlinear behaviour of the riser itself, [8].

3.2 Riser Configurations

3.2.1 Free-hanging catenary

A free hanging configuration is shown in Figure 3-2. This is the simplest configuration for a flexible Riser. This configuration needs minimal subsea infrastructure and is the easiest one to be installed.

Disadvantages with this configuration are:

- Feasibility challenges for high motion floaters.
- Potential snatch loading at touchdown point.
- Potential compression buckling at touchdown point.
- Potential armor wire “birdcaging”.

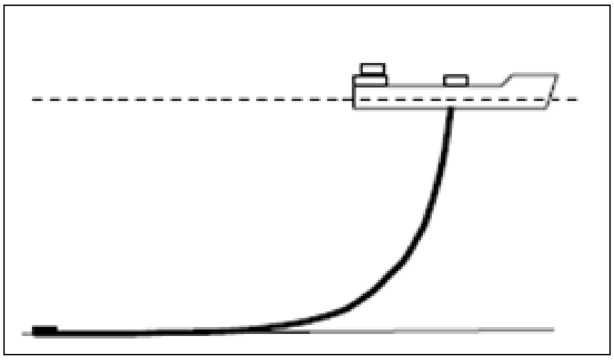


Figure 3-2 Free Hanging Configuration

3.2.2 Lazy-S Risers (Subsea Arch and Buoy)

The Lazy-S configuration includes a buoy or mid water arch as a support for the risers. The configuration is shown in Figure 3-3.This configuration is suitable for small to large water depths with large well head offset from the vessel. With this configuration FSO motions can be decoupled from a fixed subsea structure and it can accommodate large vessel offsets. This configuration can accommodate a large internal fluid density range and can be used when we have a number of flexible riser together.

The disadvantages with this configuration are:

- Complex installation.
- Required mid-water arch with tethers and anchor.
- Response driven by the buoy’s hydrodynamics, complex to model.
- Risk of compression at touchdown point.

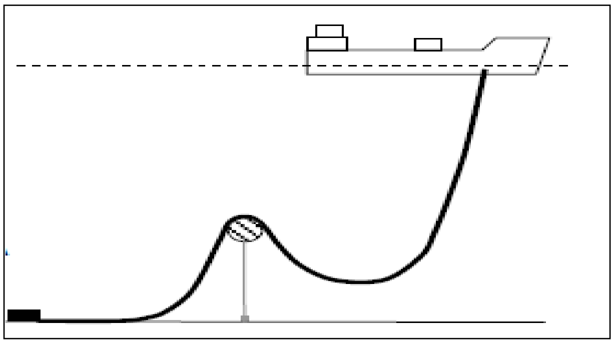


Figure 3-3 Lazy-S Configuration

3.2.3 Steep S

The Steep S configuration includes a buoy or a mid-water arch as a support for risers. The configuration is shown in Figure 3-4. With this configuration FSO motions can be decoupled from a fixed subsea structure and it can accommodate large vessel offsets.it also accommodates large internal fluid density range. This configuration can be used when we have number of flexible riser together.

With this configuration we can control clashing by clamps on mid-water arch.

The disadvantages with this configuration are:

- Complex installation.
- Requires subsea riser base, bend stiffeners and mid-water arch with tethers and anchor.
- Response driven by buoy hydrodynamic, complex to model.
- Risk of compression at riser base.

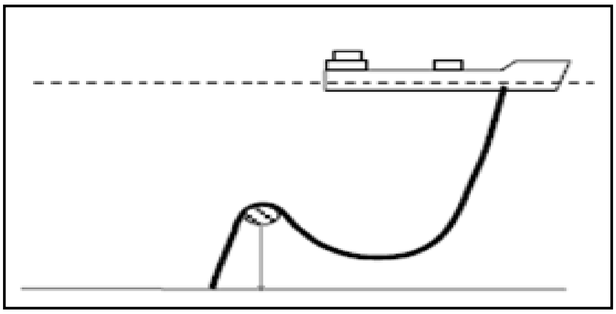


Figure 3-4 Steep S Configuration

3.2.4 Lazy Wave

The Lazy Wave configuration is a commonly used in situations where environmental conditions are up to moderately harsh. The solution consists of distributed buoyancy elements attached on a long section along the riser which makes part of the riser float. The resulting configuration has two sagbends and one hogbend and this prevents much of the wave-induced loads from the FPSO from transferring to the part of the riser on the seabed. The configuration is shown in Figure 3-5.

The disadvantages with this configuration are:

- Internal fluid density significantly affects configuration.
- Large excursions under cross current (clashing).

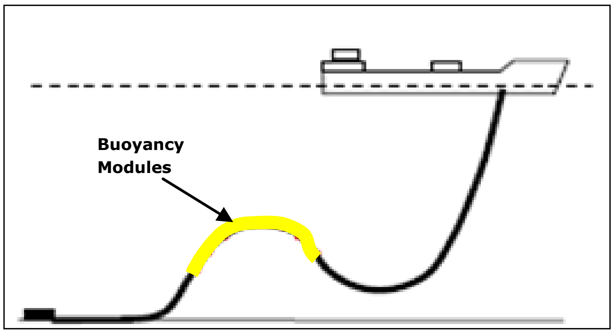


Figure 3-5 Lazy wave Configuration

3.2.5 Steep Wave Risers (Buoyancy modules and a Riser Base)

The Steep Wave configuration has a riser base fixed on the seabed to which the riser is tied in vertically. Near the seabed end of the riser it also has distributed buoyancy (buoyancy modules) attached. This configuration is suitable for shallow to moderate water depths depending on pipe weight and length. The buoyant section de-couples the FSO motions from fixed subsea end. This configuration can accommodate large vessel offsets and internal fluid density range.

The configuration requires a subsea riser base and a bend stiffener.

The configuration is shown in Figure 3-6.

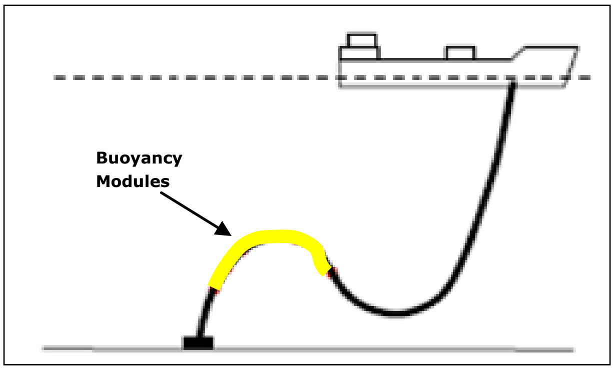


Figure 3-6 Steep Wave Configuration

3.2.6 Pliant Wave

The Pliant Wave configuration has a distributed buoyancy section (buoyancy modules) and is tethered to a gravity anchor near the touchdown point. It has similar characteristics as the Steep Wave solution. It allows for some more movements near the touchdown point compared to the Steep Wave, but it avoids the use of a fixed riser base with a possibly complicated vertical tie-in. This Configuration is not significantly affected by change in the internal fluid density. No subsea bend stiffener is required for this configuration.

A typical configuration challenge with the pliant Wave solution is to avoid high curvature in the section of the riser where it is connected to the anchor.

The disadvantages with this configuration are:

- Hold down tether arrangement and clamp are required.
- More complex make-up and installation.

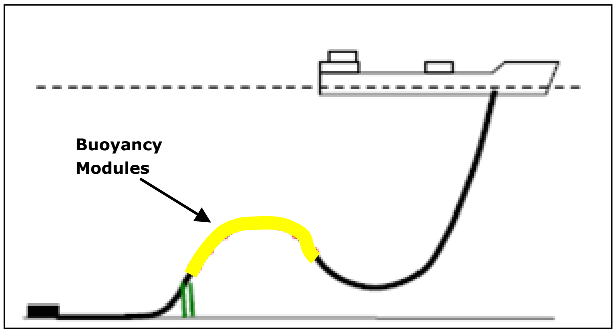


Figure 3-7 Pliant Wave Configuration

3.2.7 Weight Added Wave

The Weight Added Wave configuration is a modification of the Lazy Wave solution. The net buoyancy of the buoyancy modules is increased, and tethers and chains are added to the buoyant section. This results in a more stable configuration in wave movements than the Lazy Wave. The chains also touch the seabed providing a friction force which stabilises the sideways movements.

In this configuration the buoyant section de-couples the FSO motions from the fixed subsea end. This configuration accommodates large vessel offsets. It needs a minimum subsea infrastructure. It also can accommodate an internal fluid density range.

The disadvantages with this configuration are:

- Large excursions under cross current (potential for clashing).
- Experimental solution, lack of track record.

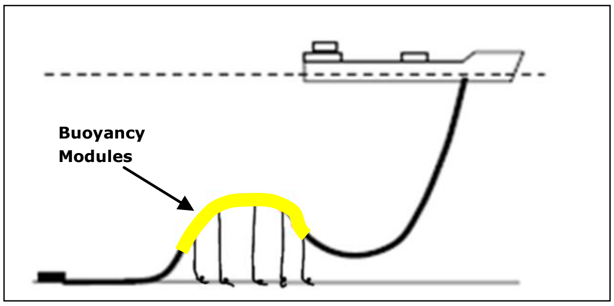


Figure 3-8 Weight Added Wave

3.2.8 Touchdown Chain Added Wave

This configuration is a modified type of a pliant wave configuration. The Touchdown Chain Added Wave configuration has a distributed buoyancy section (buoyancy modules) and is connected to a heavy chain near the touchdown point. It allows for some more movements near the touchdown point compared to the Pliant Wave, but it avoids the use of a fixed gravity anchor. This could make the installation procedure less complex.

The method chosen for finding a system configuration for the Touchdown Chain Wave was to regard the chain as ideally having the same effect on the system as the anchor in the Pliant Wave configuration. So parameters should be adjusted to achieve a mean configuration that resembled the mean Pliant Wave configuration as closely as possible.

This configuration is not significantly affected by a change in the internal fluid density. For this configuration no subsea bend stiffener is required.

The disadvantages with this configuration are:

- Hold down chain arrangement and clamp required.
- More complex make-up and installation.
- Experimental solution, lack of track record.

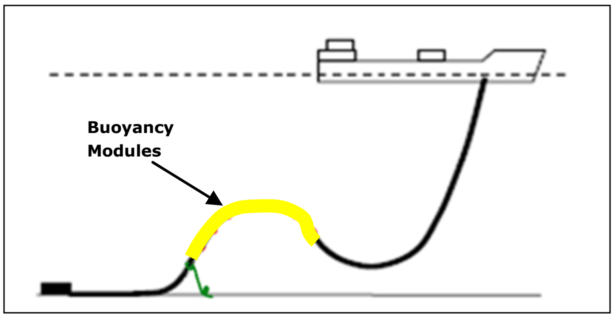


Figure 3-9 Touchdown Chain Added Wave

3.3 Flexible Riser Configurations Selection

Table 3-1 shows the ranking of different configuration with regard to environmental aspects, installation and cost.

The presented matrix is based on IKM Ocean Design in-house data.

Table 3-1 Riser Configuration Selection Matrix

	Free Hanging	Steep-s	Lazy-S	Steep Wave	Lazy Wave	Pliant Wave	Weight Added Wave	Touch down Chain Added Wave
Dynamic behaviour								
Hostile weather, shallow water	Poor	Limited	Good	Good -	Poor	Good	Good -	Good
Hostile weather, deep water	Limited	Good	Good	Good +	Good -	Good +	limited	Good-
Fair weather, Shallow water	Limited	Good -	Good +	Good	Good -	Good	Good -	Good
Fair weather, Deep water	Good	Good	Good	Excellent	Excellent	Excellent	Good	Excellent
Installation ease	Excellent	Poor	Good	Good -	Excellent	Good	Good -	Good
Economic profile								
One line	Excellent	Limited	Good -	Good -	Good +	Excellent	Good -	Good +
Several lines	Excellent	Good -	Good +	Good -	Limited	Good -	Good	Good -
Adaptability - No. Lines	Excellent	Excellent	Excellent	Good -	Limited	Good -	Good	Good -

As we can see from above matrix for shallow water and hostile weather, three configurations are suitable: Lazy-S, pliant wave and touchdown chain added wave.

For Lazy-S configuration as the case is very shallow water (less than 50 m) wave loads may cause roll and impact on MWA and thus slack in one its mooring chains and generating shock and impact load, [7]. Therefore lazy-S configuration is not studied in this thesis.

4. Riser Design parameters

4.1 Internal Fluid Data

Internal fluid parameters should be specified. As relevant, the parameters listed below should be specified, [2]:

Internal Pressure

The following internal pressure shall be specified:

a) Maximum internal pressure including operating, design and incidental pressure with possible pressure profile through service life.

b) Mill and system test pressure requirement.

c) Minimum internal pressure (including vacuum condition if applicable).

Temperature

The following temperatures shall be specified:

a) Operating temperature or temperature profile during service life.

b) Design maximum temperature.

c) Design minimum temperature.

Fluid Composition

This will include produced fluids, injected fluids, exported fluids and continual or occasional chemical treatments. Following shall be specified:

a) All parameters which define service conditions, including partial pressure of H_2S or CO_2.

b) Fluid density range corresponding to relevant pressure and temperature.

c) Fluid description including fluid type and flow regime.

d) Sand or particle erosion data.

4.2 Flexible Riser Components

Flexible riser components are described in section 2.

4.3 Riser Configuration

Riser configuration can be selected based on section 3.

4.4 FSO Data

All data for the floater and station keeping system of relevance for design and analysis of the riser should be specified.

FSO motion characteristic should normally be specified:

a) Vessel data, dimensions, drafts and etc.

b) Extreme vessel offsets

c) First order (RAOs) and second order motions.

d) Vessel motion phase data.

e) Vessel motion reference point.

f) Mooring line configuration data

g) Vessel orientation.

h) Vessel loading condition.

4.5 Environmental Data

All relevant environmental conditions should be specified. As relevant, the parameters listed below should be considered. Combined wind, wave and current conditions should be specified for relevant return periods (e.g. 1, 10 and 100 year return periods), [2].

a) Location: Geographical data for planned fields of operation

b) Water Depth: Design water depth (minimum and maximum),tidal variation, storm surge and subsidence.

c) Seawater Data: Density, pH value and minimum and maximum temperature.

d) Air Temperature: Minimum and Maximum during storage, transportation, installation and operation.

e) Soil Data: Pipe and soil interaction like friction coefficient is required for evaluation of touch down region.

f) Marine Growth: Maximum values and variations along length of riser, such as thickness, density and surface roughness.

g) Current Data: Current velocity as a function of water depth, direction and return period including any known effects of local current phenomena.

h) Wave Data: In terms of significant and maximum wave heights, associated periods, wave spectra, wave spreading functions and wave scatter diagrams as function of direction and return period.

i) Wind Data: Wind velocity as function of direction ,height above water level and return period.

j) Ice: Maximum ice accumulation, or drifting ice berg or ice floes.

k) Earthquake data: Ground motions described by means of spectra or time series.

5. Riser Design Brief and Methodology

5.1 General

The main design stages for the dynamic application are represented in the flowchart shown in Figure 5-1, and are as follows:

a. Stage 1-Material Selection.

b. Stage 2-Cross section configuration design.

c. Stage 3-System configuration design.

d. Stage 4-Dynamic analysis and design.

e. Stage 5-Detail and service life design.

f. Stage 6-Installation design.

Stage 1 and stage 2 are typically performed by a pipe manufacturer of flexible pipe and is not in thescope of this study. This study focuses on the stage 3 and stage 4.

Stage 3 involves selection of the system configuration. This task for dynamic riser involves selecting pipe configuration from available options. Some guidelines for selection of riser configuration are provided in Chapter 3. At this stage it is also required that the effect of ancillary components, such as concentrated or distributed buoyancy, be qualified, [4].

Stage 4 involves in the dynamic design of the riser or riser system. In this stage the dynamic responses of the riser to a series of loadings from functional, environmental and accidental loads on system are studied Other important issues are include possible interference with other system components, top tension, departure angle and curvature, [4].

Stage 5 includes the detailed design of ancillary components, and corrosion protection. Service life analysis (fatigue analysis) is also performed at this stage, this applies to the pipe and components, [4].

Stage 6, installation design, completes the design process. For the risers, the complexity of the system to be installed is generally significantly greater than for a flowline, [4].

for a flowline.

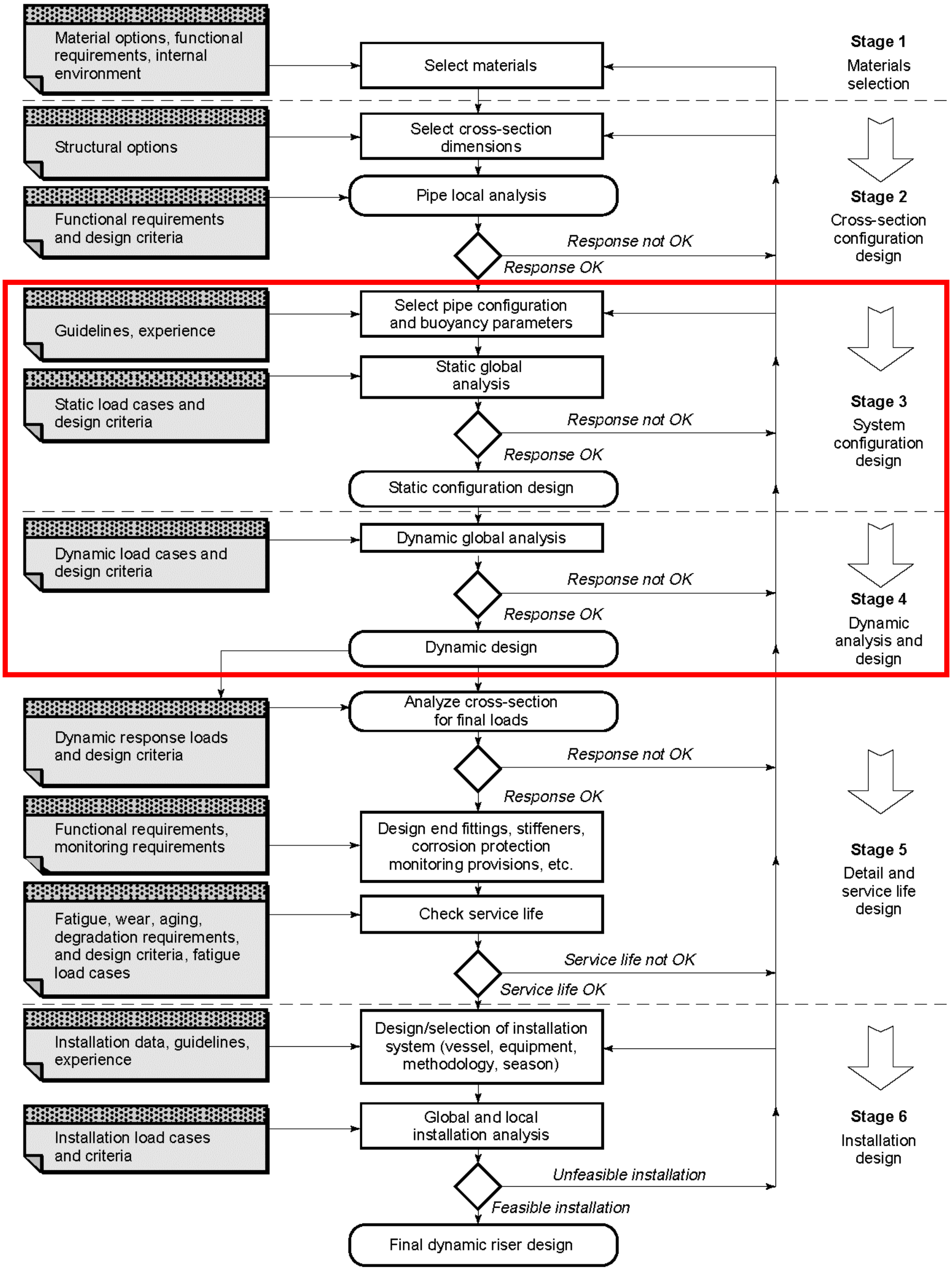


Figure 5-1 Dynamic Application Design Flowchart Ref. [4]

5.2 Software (OrcaFlex) and Finite Element

“OrcaFlex is a fully 3D non-linear time domain finite element program capable of dealing with arbitrarily large deflections of the flexible from the initial configuration. A lumped mass element is used which greatly simplifies the mathematical formulation”, [10].

Figure 5-2 shows OrcaFlex line model. The modal segments only model the axial and torsion property of the line. The mass, weight , buoyancy and etc are lumped to the nodes as indicated by arrows.

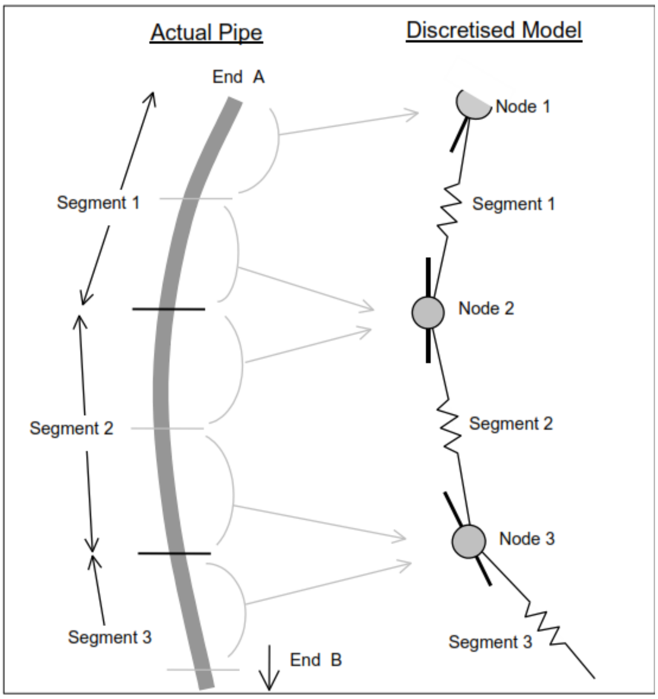


Figure 5-2 OrcaFlex Line Model Based on Lumped Mass Method, [10]

OrcaFlex provides fast and accurate analysis of catenary systems such as flexible risers and umbilical cables under wave and current loads and externally imposed motions. OrcaFlex makes extensive use of graphics to assist understanding. The program can be operated in batch mode for routine analysis work and there are also special facilities for post processing your results including fully integrated fatigue analysis capabilities, [10].

In addition to the time domain features, modal analysis can be performed for either the whole system or for individual lines. RAOs can be calculated for any results variable using the spectral response analysis feature.

OrcaFlex can handle multi-line systems, floating lines and line dynamics after release, etc. Inputs include ship motions, regular and random waves. Results output includes animated replay plus full graphical and numerical presentation.

The program uses lines, 6D buoys, 3D buoys, vessels, tethers, winches, links which can be added into an offshore environment to model the riser systems, including the flexible risers, FSO vessel and mooring lines. Environmental effects such as the seabed profile, different types of wave spectra, wind and currents can be applied to the model.

<u>**Static Analysis:**</u>

Initially the model performs a static calculation, and assuming the model has been made following the correct practice it should converge, which yields a static condition *.dat file that can be used in design.

In OrcaFlex Static equilibrium is determined in a series of iterative stages, [10]:

- At the beginning of the calculation, the positions of the vessels and buoys will be determined by the data.

- The static equilibrium for each line will be calculated; the line ends should be fixed or connected to a buoy or vessel.

- The out of balance on each free body (node, buoy, etc.) will be calculated and a new position for the body will be estimated. This process will be repeated until the out of balance load on each is close to zero (include some tolerances)

Dynamic Analysis:

The next level of the simulation is to run a dynamic simulation, which yields a *.sim file. From this file users can produce graphs giving dynamic information on forces, spatial positions, accelerations and velocity, dynamic response, and other important values.

Calculation method for dynamic analysis in OrcaFlex is based on two complementary dynamic integration schemes: Explicit and Implicit, [10].

The equation of motion OrcaFlex solves is, [10]:

$$M(p,a) + C(p,v) + K(p) = F(p,v,t)$$

where

M(p,a)=system inertia load.

C(p,v)=system damping load.

K(p)=system stiffness load.

F(p,v,t)=external load.

p, v and a =position, velocity and acceleration vectors respectively.

t =the simulation time.

Explicit Scheme

The Explicit scheme is forward Euler with constant time step. At the start of dynamic simulation the initial position and orientation of the all objects will be taken from static analysis. Then the forces and moments acting on each objects and nodes will be calculated. Forces and moments can be, [10]:

- Weight

- Buoyancy

- Hydrodynamic and aerodynamic drag

- Hydrodynamic added mass effects, calculated by using the usual extended form of Morison's Equation with user-defined coefficients:

  $F_w = (\Delta.a_w + C_a.\Delta.a_r) + ½.\rho.C_d.A.V_r|V_r|$

  Where:

  F_w: the fluid force

  Δ : mass of fluid displaced by the body

a_w:fluid acceleration relative to earth

C_a: added mass coefficient for the body

a_r: fluid acceleration relative to the body

ρ : density of water

V_r: fluid velocity relative to the body

C_d: the drag coefficient for the body

A : drag area

- Tension and shear
- bending and torque
- seabed reaction and friction
- contact forces with other objects
- forces applied by links and winches

Then the equation of motion will be formed for each free body and node. These equations require inversion of 3 by 3 or 6 by 6 mass matrices. This equation will be solved for the acceleration vector at the beginning of the time step, for each free body and each node, and then integrated using forward Euler integration. If the position, velocity and acceleration at time step t are Pt, Vt and at respectively, [10]. Then the values at the end of the time step, at time t+1, are given by:

$V_{(t+1)} = V_t + dt.a_t$

$P_{(t+1)} = P_t + dt.V_{(t+1)}$

where dt is the time step.

At the end of each time step, the positions and orientations of all nodes and free bodies are again known and the process is repeated.

Implicit Integration Scheme

For implicit integration OrcaFlex uses the Generalised-α integration scheme as described by Chung and Hulbert. The forces, moments and etc. will be calculated same as for the explicit scheme. Then the system equation of motion will be solved at the end of the time step, [10].

Each implicit time step consumes higher computation time than an explicit time step. Because p, v and a are unknown at the end of the time step and an iterative solution method is required. The implicit scheme is typically stable with longer time steps and often this means that the implicit scheme is faster, [10].

5.3 Global Analyses and Modelling

This section describes the modelling to be used in the global analysis of the riser system.

5.3.1 FE Modelling

Riser FE Modelling

The riser will be modelled as a stack of Line-type elements in OrcaFlex. The drag diameter used for the riser is that of the overall outer diameter of the riser. All normal drag loading is based on this diameter. Properties of the riser are defined in order to reproduce the following:

- Mass per unit length (including the contribution of contained fluid)
- Axial, bending and torsional stiffness.

Riser to turret connection

Bend stiffeners are assumed to be installed on the risers in the area below the turret connection point to avoid violation of the minimum bend radius requirement and the FE model will use a model with bend stiffener.

Turret

The turret is modelled as a rigid circular cylinder rigidly connected to the FSO.

5.3.2 Vessel Motions (RAOs)

Response amplitude operators (RAOs) show the behaviour of the vessel in waves with different periods. The RAO depend on the size, mass, wave and period of waves. RAOS could be separated to rotation and translation. Rotational part includes roll, yaw and pitch. Translation part includes heave, surge and sway. The most important ones are heave and roll motions.

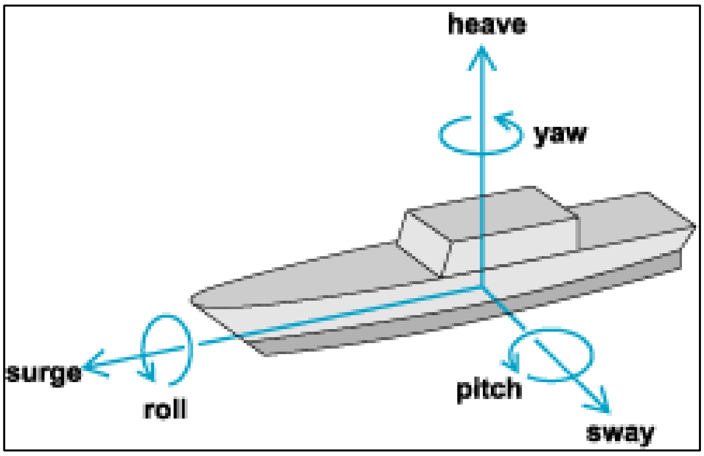


Figure 5-3 The six Degree of motions of a vessel, [12]

Each displacement RAO consists of pairs of numbers that define vessel response to a specific wave direction and period. The pair of numbers are amplitude and phase. The amplitude parameter relates the amplitude of vessel to amplitude of wave. Phase parameter defines the time of vessel motion relate to the wave, [10].

The RAO vary for different types of vessel, and also for a specific type of vessel vary with draught (loaded or ballasted), wave direction, wave period and etc.

RAOs can be obtained from model or specific computer program. The data can be presented in tabular or graphical form.

There are many conventions to define RAOs. The OrcaFlex Convention is to use amplitude of response (in length for translation movements or Degree for rotational movements).per unit wave amplitude. Also use phase lag from the time wave crest passes the RAO origin until the maximum positive excursion is reached, [10]. Mathematically we can say:

$$X = A \cdot RAO \cdot \cos(\omega t + \psi)$$

Where:

X = response

A = wave amplitude

RAO = response amplitude operator

ω = wave frequency (rad/s)

T = time (s)

Ψ = phase angle of response.

The Default RAO conventions in OrcaFlex are:

- Wave directions:
    - Following sea: 0 deg direction of waves is defined as waves propagating along positive x-axis.
    - Beam sea: 90 deg direction of waves is defines as waves propagating along positive y-axis.
    - Head sea: 180 deg direction of waves is defined as waves propagating along negative x-axis.
- The origin of the RAO coordinate system is located along the vessel centreline at amidships in the water plane. The positive x-axis is towards the bow and the positive z-axis is vertically upwards. The positive y-axis is towards the port side of the vessel.

Based on vessel RAOs Rigid body motions will be transferred with OrcaFlex to the riser attachment point. The vessel orientation with respect to the incoming wave direction will be considered and the appropriate RAO will be used.

5.3.3 Boundary Conditions

At the hang-off points on the turret, the bend stiffeners and risers are modelled as being vertically fixed to the bottom of the turret.

The bottom part of the riser lies on the seabed and is connected to the pipeline PLET (Pipeline End Termination). The elements of the risers close to the riser system base are modelled as rigid elements fixed to the seabed.

5.3.4 Meshing & Meshing Refinement

Riser meshes will be suitably graded to ensure that response in critical areas is accurately identified. This will be done by applying a mesh refinement over areas of high loading and where there are changes in geometrical properties such as at the riser top.

5.3.5 Wave Model

In OrcaFlex, different type of wave like regular waves: Single Airy, Stocks 5th order, Cnoidal, or irregular wave theory: JONSWAP, ISSC, Ochi-Hubble and etc can be specified.

Regular Wave Theory:

The simplest wave theory is first order Airy wave (linear wave). It has one frequency component by a sinusoidal wave to describe wave. For linear case wave steepness is so small. The nonlinear terms in the free surface of water are neglected. When waves become large or travel in shallow water higher order wave theories are required, [13].

Stocks wave theory is kind of regular nonlinear wave. In this theory wave steepness (H/L) i small but not as small as first order wave theory. This assumption can be reasonable when wave steepness never exceed 0.1-0.15.this theory is good for deep and intermediate water when depth to wave length ratio (H/L) is higher than 1/8, [13].

Cnoidal wave theory is useful when we are modelling long waves in shallow waters. The Cnoidal wave is a periodic wave that usually has sharp crest with wide troughs. This theory is good when depth to wave length ratio (H/L) is less than 1/8., [13].

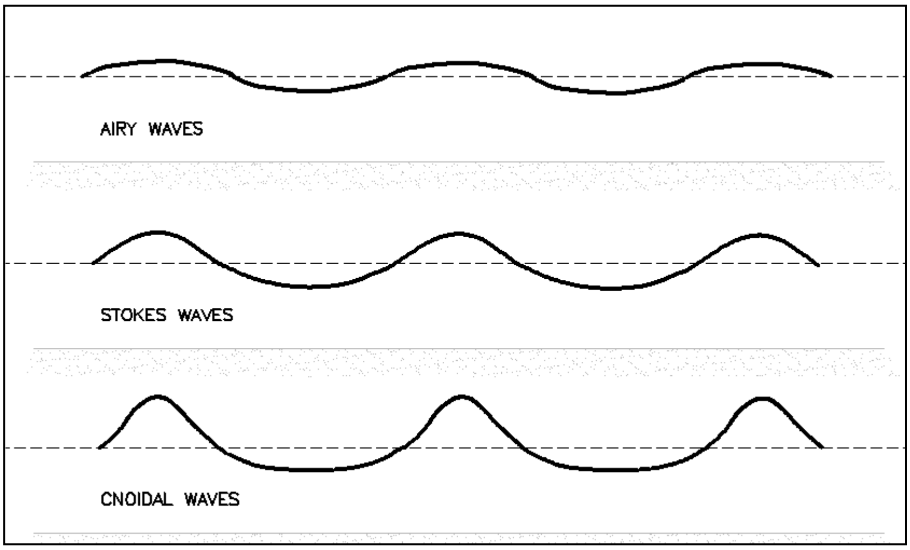


Figure 5-4 Illustration of some Regular Wave

Irregular Wave Theory:

In order to describe real surface f the sea we need a solution. This can be obtained to compose sinusoidal waves which are in consistent with Fourier series analysis. If we consider a certain limited time history of measurement waves, we can consider the time history to be repeated so it will present a periodic motion with period T, [13].

This can be presented in term of frequency content, specifically the distribution of energy as a function of frequency, called the wave spectrum. The energy in harmonic waves is proportional to amplitude squared.

Therefore a random wave record can be presented by a plot of energy versus frequency or ω (rad/s).this indicates the frequencies at which the wave energy is concentrated and those at which there is no wave energy.

Random wave records can be a plot of energy versus ω as shown in Figure 5-5.

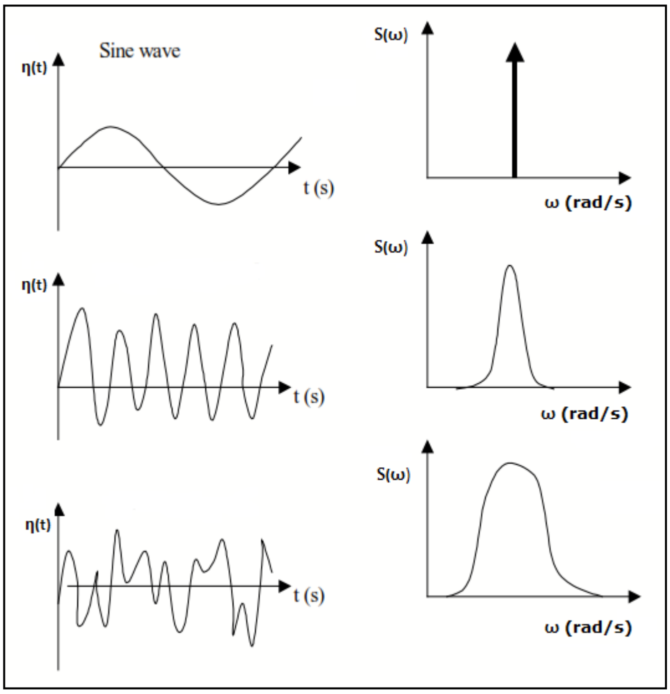


Figure 5-5 Time Histories and corresponding Spectral shapes

From extensive analysis of wave records and by considering the basic physical process involved, several algebraic forms of wave spectra have been developed. The most famous of these is Pierson-Moskowitz wave spectrum. Also JONSWAP Spectrum is similar to Pierson Moskowitz Spectrum.

Pierson-Moskowitz and JONSWAP Spectrum are defined in DNV-RP-C205, [3]. The formulas are defined as below:

$$S_J(\omega) = A_\gamma S_{PM}(\omega)\ \gamma^{\exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma\ \omega_p}\right)^2\right)}$$

$$S_{PM}(\omega) = \frac{5}{16}\cdot H_S^2\omega_p^4\cdot\omega^{-5}\exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right)$$

Where:

$S_{PM}(\omega) = Pierson - Moskowitz\ spectrum$

$S_J(\omega) = JONSWAP\ Spectrum$

$\omega_p = Peak\ Wave\ Frequency$

$\gamma = non - dimensional\ peak\ shape\ parameter$

$\sigma = Spectral\ width\ parameter\ \sigma = \begin{cases} 0.07 & if\quad \omega \le \omega_P \\ 0.09 & if\quad \omega > \omega_P \end{cases}$

$A_\gamma = 1 - 0.287\ln(\gamma)\ is\ a\ normalizing\ factor$

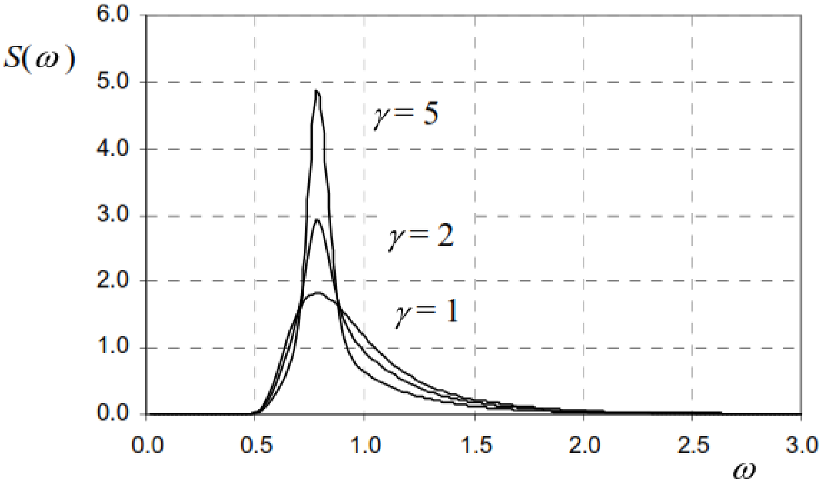


Figure 5-6 JONSWAP Spectrum for Hs=4.0 m, Tp=8.0 s, [3]

Based on DNV-RP-C205, [3] If no particular values are given for peak shape parameter γ, the following value may be applied:

$$\gamma = 5 \quad for \ \frac{T_p}{\sqrt{H_s}} \leq 3.6$$

$$\gamma = \exp\left(5.75 - 1.15\frac{T_p}{\sqrt{H_s}}\right) \quad for \ 3.6 \leq \frac{T_p}{\sqrt{H_s}} < 5$$

$$\gamma = 1 \quad for \ 5 \leq \frac{T_p}{\sqrt{H_s}}$$

$$\frac{T_z}{T_p} = 0.6673 + 0.05037\,\gamma - 0.006230\,\gamma^2 + 0.0003341\,\gamma^3$$

In OrcaFlex, γ and the wave peak period T_p are required to be specified; the other parameters are automatically calculated by OrcaFlex.

5.3.6 Hydrodynamic Coefficients

Values used for the drag coefficients of the riser system will be selected depending upon the mean Reynolds number. Value used for added mass is depending upon

For all riser types and all current profiles used in the detailed extreme, fatigue and interference analysis, the Reynolds Number will be automatically calculated by OrcaFlex along the length of the riser based on riser diameter and wave and current load conditions.

Hydrodynamic coefficient is dependent on below parameters, [2]:

- body shape;
- Reynolds number
- Keulegan Carpenter number KC = $U_M T/D$, where U_M is the free stream velocity amplitude of the oscillatory flow and T is the period of oscillation and D is Diameter.
- Roughness ratio k/D, where k is the characteristicdimension of the roughness on the body;
- Reduced velocity $U/f_n D$, where f_n is the natural frequency of the riser;

- Relative current number U_c/U_M, where U_c is the current velocity and U_M is the velocity of the oscillatory motion.

As the riser cross section is circular based on DNV-RP-C205 drag coefficient can be calculated based on below figures:

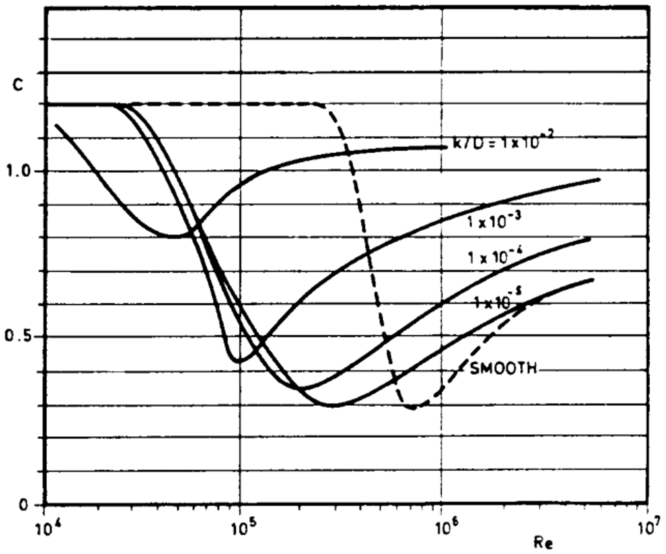


Figure 5-7 Drag coefficient for fixed cylinder for steady flow, for various roughness, [3]

Table 5-1 Surface Roughness, [3]

Material	*k (meters)*
Steel, new uncoated	5×10^{-5}
Steel, painted	5×10^{-6}
Steel, highly corroded	3×10^{-3}
Concrete	3×10^{-3}
Marine growth	5×10^{-3} - 5×10^{-2}

Added mass coefficient can be calculated based on below figure:

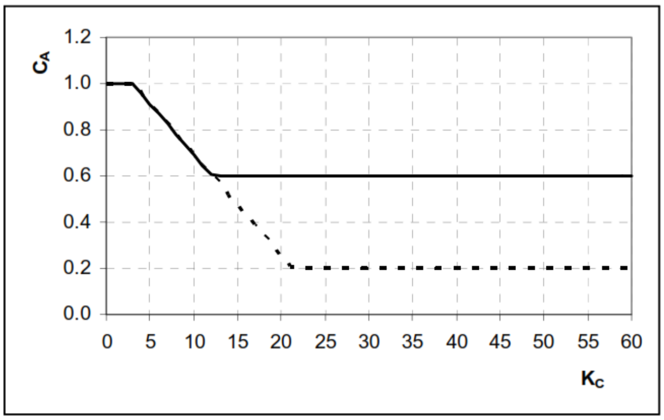


Figure 5-8 Added mass coefficient as function of K_C-number for smooth and rough cylinder, [3]

5.4 Global Analysis and Design

5.4.1 General

This section outlines the methodology to be used for the static and dynamic analysis and design of the riser system.

The main riser analysis is carried out using the non-linear time domain analysis program OrcaFlex.

5.4.2 Design Criteria & Load Case Selection

The riser systems will be assessed under the effects of combined loads in accordance with the Design Requirement in Ref. [5].

Loads are classified as functional and environmental (external) defined as follows, [5]:

a. *Functional loads* are all loads on the riser in operation, including all loads which act on the pipe in still water except wind, wave, or current loads.

b. *Environmental loads* and loads induced by external environmental parameters.

For the riser systems in very shallow waters, Load classes and Load (Service) conditions are listed in Table 5-2. We will consider the following extreme events for the static and dynamic analysis:

- 100-year environmental condition.

When combining waves and currents for 100 year conditions, the following two load combinations should be considered unless more specific data is available:

a. 100-year wave combined with 10-year current.

b. 10-year wave combined with 100-year current.

Table 5-2 Load Combinations of Load Classes, Load (Service) Conditions

Load Conditions **Load Classes**	**Normal Operation**
Functional Loads	
Loads due to weight and buoyancy of riser and internal fluid	X
Internal pressure	Max Operating Pressure
Environmental Loads	
Loads caused by current and wave	100 yr

5.4.3 Static Analysis and Design

The first stage of the analysis will involve a series of static analyses for static configuration design. Input to this stage includes all static loads relating to the system design. The loads considered in the static analysis are generally gravity, buoyancy, internal fluid, vessel offsets and current loads, [4]. The riser system is analyzed under all functional loading. According to Section 5.4.2, the global static analysis load cases related to this stage of design is presented in Table 5-3.

Table 5-3 Static Load Case Matrix

Load Case	Service Conditions	FSO Loading Condition	FSO Offset	Internal Fluid	Current
1	Normal Operation	Ballasted and Loaded	Mean	Operating, Empty and Flooded	None
2			Far		Far 100yr
3			Near		Near 100yr
4			Cross		Cross 100yr

Notes:
1) Near case has the environment and offset orientated along the plane of the riser towards the riser seabed connection.
2) Far case has the environment and offset orientated along the plane of the riser away from the riser seabed connection.
3) Cross case has the environment and offset orientated perpendicular to the plane of the riser.

5.4.4 Dynamic Analysis and Design

After static analysis the next stage in the design procedure is to perform dynamic analyses of the system to assess the global dynamic response. The objective in performing this analysis is to predict the lifetime maximum or extreme response of the flexible riser system. These load cases combine different wave and current conditions, vessel positions and motions, riser content conditions to provide an overall assessment of riser suitability in operation and extreme environmental condition, [4].

Either regular waves or irregular seas can be used for dynamic analysis. The regular wave is recommended for preliminary sizing of the riser configuration. The critical results from regular waves should be verified with irregular waves, [4].

Irregular Wave Extreme Analysis

For dynamic analyses irregular wave is considered. A Three-hour design storm duration is considered. To account for this, the dynamic analyses are run in a 180 s time frame around the maximum wave height found in a three-hour section of the irregular wave spectrum (see Figure 5-9).

Load cases for this stage include all dynamic loads for the global system design. The riser system is again analyzed under all functional and environmental loading combinations. Table 5-4 shows the dynamic analysis load cases.

Table 5-4 Dynamic Load Case Matrix

Load Case	Service Conditions	FSO Loading Condition	FSO Offset	Internal Fluid	Wave and Current
1	Normal Operation	Ballasted and Loaded	Far	Operating, Empty and Flooded	Far 100yr
2			Near		Near 100yr
3			Cross		Cross 100yr

Note:

1) The combinations of waves and currents for 100 year conditions refer to Section 5.4.2.

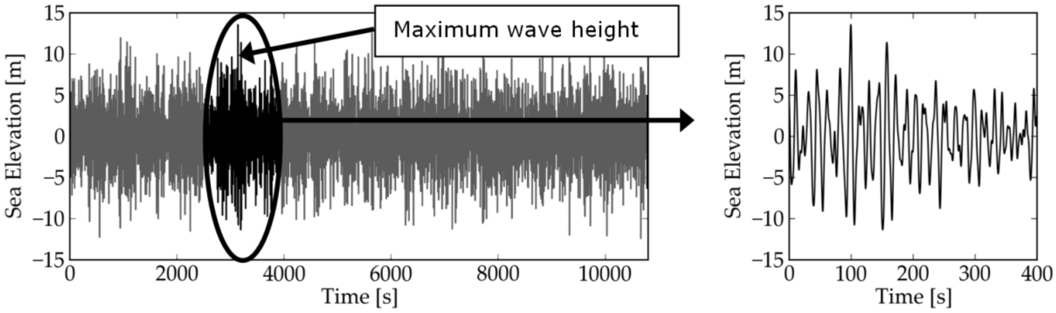


Figure 5-9 Selection of Time Frame for Dynamic Analysis, [10]

5.4.5 Analysis Output

With regard to riser behaviour in very shallow water each extreme analysis load case will output and tabulate the following against input conditions:

- Max/min riser effective axial tension and the associated bending moment at turret hang-off.
- Max/min effective axial tension along the whole riser.
- Max/min effective tension at riser connection to PLET .
- Max/min effective tension on tether connecting riser to seabed.
- Minimum bending radius.
- Rise clearance from surface.
- Riser clearance from Seabed.

6. Case Study: Design Basis

6.1 Project Description

The field selected is located in Vietnam at a water depth of 49m. The flexible risers will connect the FPSO to a PLET on the seabed, [7].

A summary of main characteristics for the riser is given in Table 6-1.

Table 6-1 Summary of Line Data for the Riser

Dimension	10" Riser
ID (m)	0.250
OD (m)	0.400
Weight in air, empty (kg/m)	250
Minimum bending radius in service (m)	4
Allowable tension (kN)	2700
Axial stiffness (MN)	550
Bending stiffness (kNm^2)	150
Torsional stiffness (kNm^2)	90

The weights for different fluid content are provided in Table 6-2.

Table 6-2 Summary of Weight/Diameter Ratios for the

Configuration	Weight (kg/m)
Submerged, empty	118
Submerged, full of water	165.9
Submerged, full of product (min density)	121.6

A summary of fluid data is given in Table 6-3 below, [7]:

Table 6-3 Fluid Data for the Riser

Pipeline Service	Fluid Density (kg/m^3)	
	Operating (Min-Max)	Hydrotest
10" Production Riser	77-374	1025

6.2 Bend stiffener data

Bend Stiffeners are required for dynamic applications, the Bend Stiffener will be attached to theflexible at riser and turret connections.

Bend stiffener data considered for this case study are presented in below table:

Table 6-4 Bend Stiffener Properties

	Length (m)	Material	Density (kg/m^3)	Modulus of Elasticity (kPa)	Radius (m)
Bend Stiffener	5	Poly-Urethane	1158	220E3	0.40 -0.70

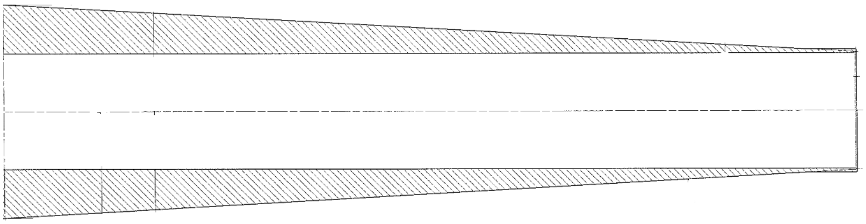


Figure 6-1 Bend Stiffener

6.3 Vessel Data

6.3.1 Vessel Loading Conditions

The following vessel loading configurations will be considered for riser global analysis:

- Ballast condition.
- Loaded condition.

Vessel properties each of these cases are given in Table 6-5.

Table 6-5 Vessel Description

Vessel Particular	Unit	Ballast Condition	Intermediate Condition	Loaded Condition
Length over all	m	260		
Length between perpendiculars	m	245		
Breadth moulded	m	40		
Draught	m	8	11	15
Trim	(°)	-0.8	-2	-0.2

6.3.2 Vessel Offset

Vessel allowable offsets are extremely challenging. Table 6-6 presents 1 year and 100 year return periods in loaded and ballasted condition, [7].

Table 6-6 Vessel Offset Data, [7]

		FPSO Excursions (m)	
Return Period	Loading Condition	Near/Far	Trans
1 yr	All	10	
100 yr	Ballasted	15	20
100 yr	Fully loaded	15	20

6.3.3 Vessel RAO

The FSO vessel will experience motions due to wind, current and high and low frequency wave loads. Only the high frequency wave-induced motion is described by the displacement RAOs. The wind loads and the low frequency wave loads are accounted for by using the maximal FSO vessel offsets.

RAOs data and graphs used for this study are presented in Appendix A.

6.4 Environmental Data

6.4.1 Wave and Current

The extreme weather conditions are important in the global analysis of the riser. Table 6-7 below summarize current and wave data for Block Hanoi Trough in Vietnam waters, [9].

Irregular extreme wave will be used to model wave, Pierson-Moskowitz wave spectrum is used as irregular wave model.

Table 6-7 Extreme Wave Data, [9]

	Return Period	H_s (m)	H_{max}(m)	T_s (s)	Tz (s)
Typhoon	1 yr	8	13.5	10.4	8.6
	10 yr	12.5	20.9	13.3	11.1
	100 yr	14.9	24.9	14.7	12.2
Non-Typhoon	1 yr	2.7	4.5	6.6	5.5
	10 yr	5.1	8.5	8.8	7.3
	100 yr	7.3	12.3	10.4	8.6

Table 6-8 Extreme Current Data, [9]

	Return Period	Speed (m/s)	Direction (^{o})
Typhoon	1 yr	1.72	225
	10 yr	2.32	247.5
	100 yr	2.75	247.5
Non-Typhoon	1 yr	0.57	225
	10 yr	0.85	225
	100 yr	1.1	225

6.4.2 Seabed Frictional Coefficients

The seabed friction Coefficient of 0.7 is used in the OrcaFlex analysis.

6.5 Hydrodynamic Coefficients of Riser

6.5.1 Drag Coefficient

With reference to section 5.3.6 the roughness for flexible pipes is selected as:

K=5.0E-05 K/D=1.0E-04

Based on outer diameter of pipe and 100 year current Reynolds number is approximately 6.0E+5.

From section 5.3.6 for pipe with marin growth and graph related to K/D=1.0E-04 the drag coefficient considered is 1.05 in the analysis (C_D=1.05).for smooth pipe drag coefficient is 0.6.

6.5.2 Added Mass Coefficient

Based on DNV-RP-C205, [3] the added mass is a function of Keulegan-Carpenter number.

KC = UMT/D

In wave zone: KC = πH/D

H_{max} = 24.9, D=0.4 => K_C =195

The Keulegan-Carpenter number was taken to be high, so based on the graph in section 5.3.6 an added mass coefficient of, [3]:

- 0.6 was used for the smooth pipe (no marine growth), and
- 0.2 was used for rough pipe (with marine growth).

7. Static Analysis

The first stage of the analysis will involve a series of static analyses for static configuration design. Input to this stage includes all static loads relating to the system design. The loads considered in the static analysis are generally gravity, buoyancy, internal fluid, vessel offsets and current loads, [4].

Based on above, Table 7-1 has different cases been defined to find best solution configuration for Riser.

The currents in the same direction of vessel heading are defined as far current. The currents in opposite direction of vessel heading defined as near current. The currents 90 degree with vessel heading is defined as cross currents.

In this section two types of configurations will be studied: Pliant wave configuration and touchdown added chain wave configuration.

Table 7-1 Static Analyses Matrix

Load Case	Service Conditions	FSO Loading Condition	Internal Fluid	FSO Offset	Current
1	Normal Operation	Ballasted	Empty	Mean	None
2				Far	Far 100yr
3				Near	Near 100yr
4				Cross	Cross 100yr
5	Normal Operation	Ballasted	Operating	Mean	None
6				Far	Far 100yr
7				Near	Near 100yr
8				Cross	Cross 100yr
9	Normal Operation	Ballasted	Flooded	Mean	None
10				Far	Far 100yr
11				Near	Near 100yr
12				Cross	Cross 100yr
13	Normal Operation	Loaded	Empty	Mean	None
14				Far	Far 100yr
15				Near	Near 100yr
16				Cross	Cross 100yr
17	Normal Operation	Loaded	Operating	Mean	None
18				Far	Far 100yr
19				Near	Near 100yr
20				Cross	Cross 100yr
21	Normal Operation	Loaded	Flooded	Mean	None
22				Far	Far 100yr
23				Near	Near 100yr
24				Cross	Cross 100yr

7.1 Model Description

The riser has been modelled based on water depth, vessel data, riser base connection, buoyancy section and etc.

The preliminary lazy wave model is based on empty condition. This preliminary configuration is optimized based on operational and flooded condition.

Figure 7-1 shows the riser configuration and components for static design. This model is just to show that how the configuration will look without tether and chain. The location of tether and chain will be selected based on touchdown location.

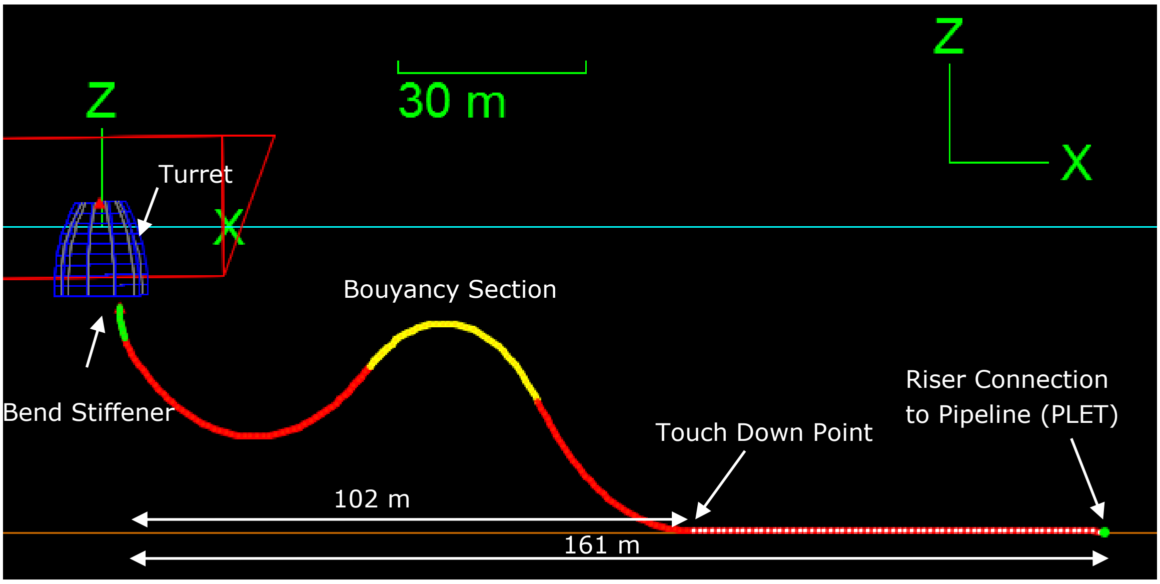


Figure 7-1 Configuration and Components for 10” Riser Modelling

7.2 Pliant Wave Configuration

The Pliant Wave configuration has a distributed buoyancy section (buoyancy modules) and is tethered to a gravity anchor near the touchdown point. It has similar characteristics as the Steep Wave solution. It allows for some more movement near the touchdown point compared to the Steep Wave, but it avoids the use of a fixed riser base with a possibly complicated vertical tie-in.

A typical configuration challenge with the Pliant Wave solution is to avoid high curvature in the section of the riser where it is connected to the anchor.

The following parameters are studied:

- Horizontal distance from turret connection to anchor.
- Length of floating section of riser line.
- Length of buoyant section.
- Buoyancy factor.
- Anchor connection point.

The mean configuration described in Figure 7-2 and Table 7-2 is found for the 10” line Pliant Wave configuration, and will be used in further steps of the analysis.

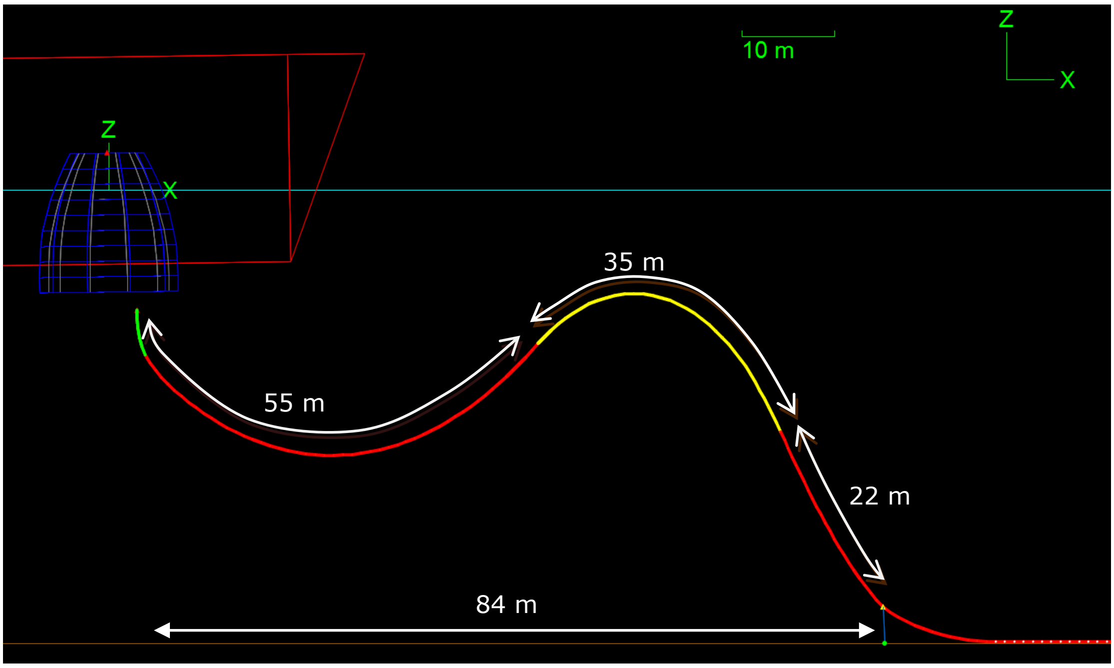


Figure 7-2 Mean Configuration of the 10” Riser Pliant Wave Solution-Empty

Table 7-2 System Configuration Details for 10” Riser Pliant Wave

Dimension	Value
Horizontal distance from turret connection to gravity anchor	84 m
Riser arc length from turret connection to anchor tether connection	112 m
Arc length from turret connection to start of buoyant section	55 m
Arc length of buoyant section	35 m
Net buoyancy of buoyant section	276 kg/m

Figure 7-3 shows the riser configuration with far offset of vessel including far current for 100 years return period.

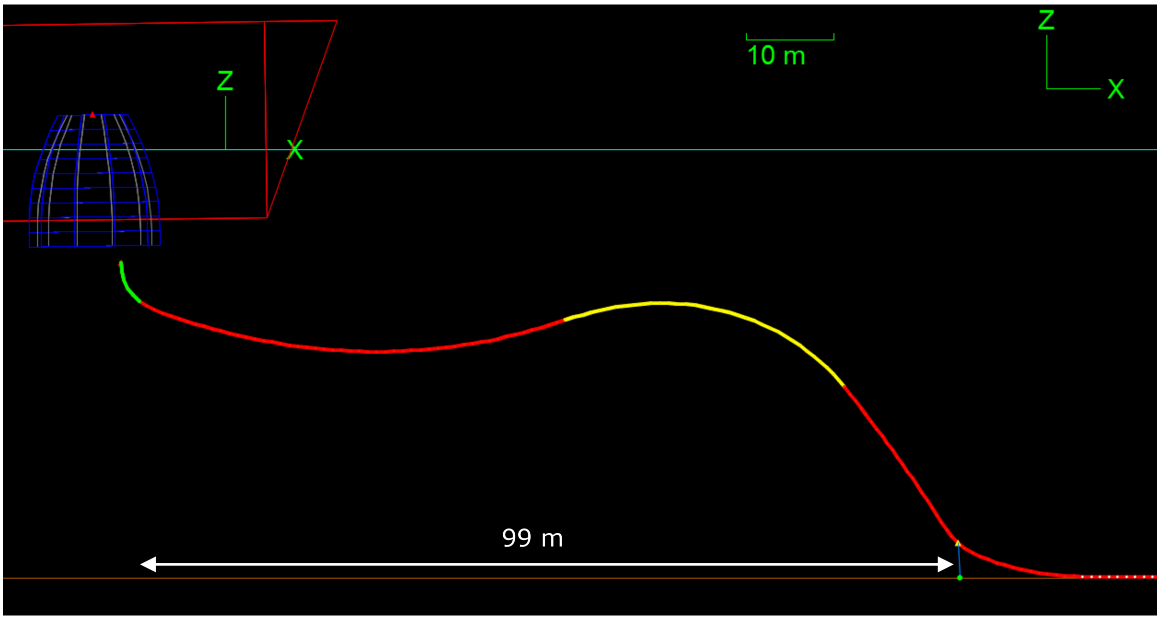


Figure 7-3 Far Configuration of the 10” Riser Pliant Wave Solution-Empty-Far Cuurrent

Figure 7-4 shows riser configuration with near offset of vessel including near current for 100 years return period.

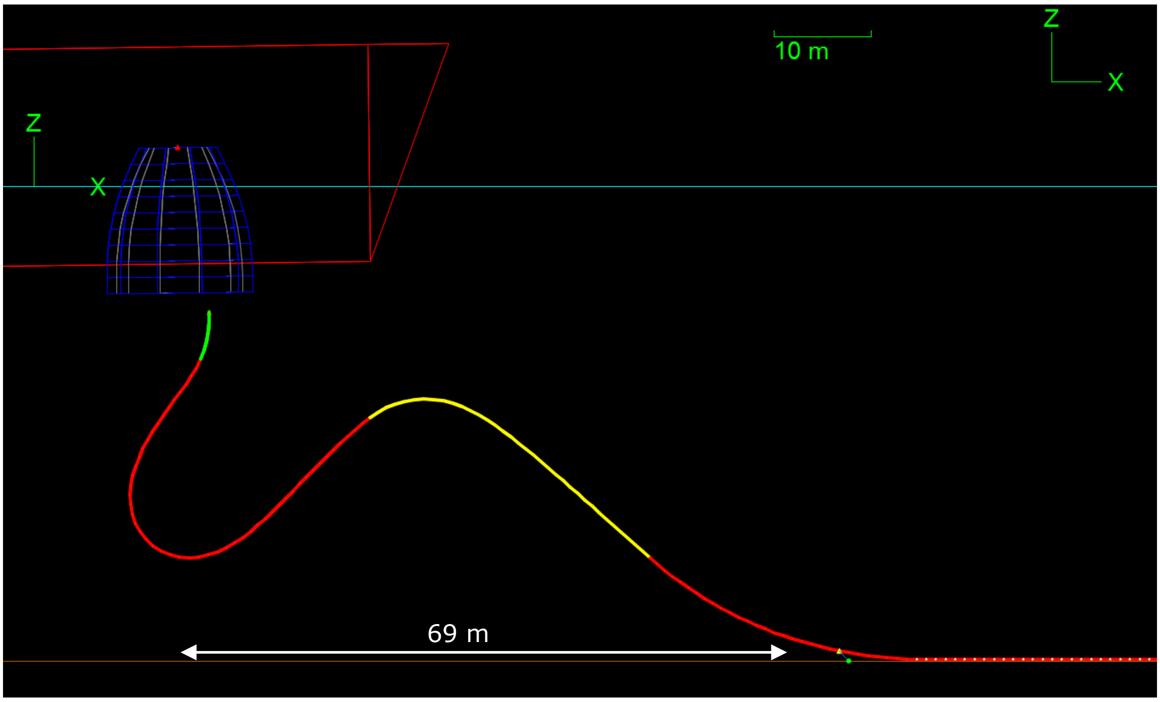


Figure 7-4 Near Configuration of the 10” Riser Pliant Wave Solution-Empty-Near Current

Figure 7-5 shows riser configuration with cross offset of vessel including cross current of 100 years return period.

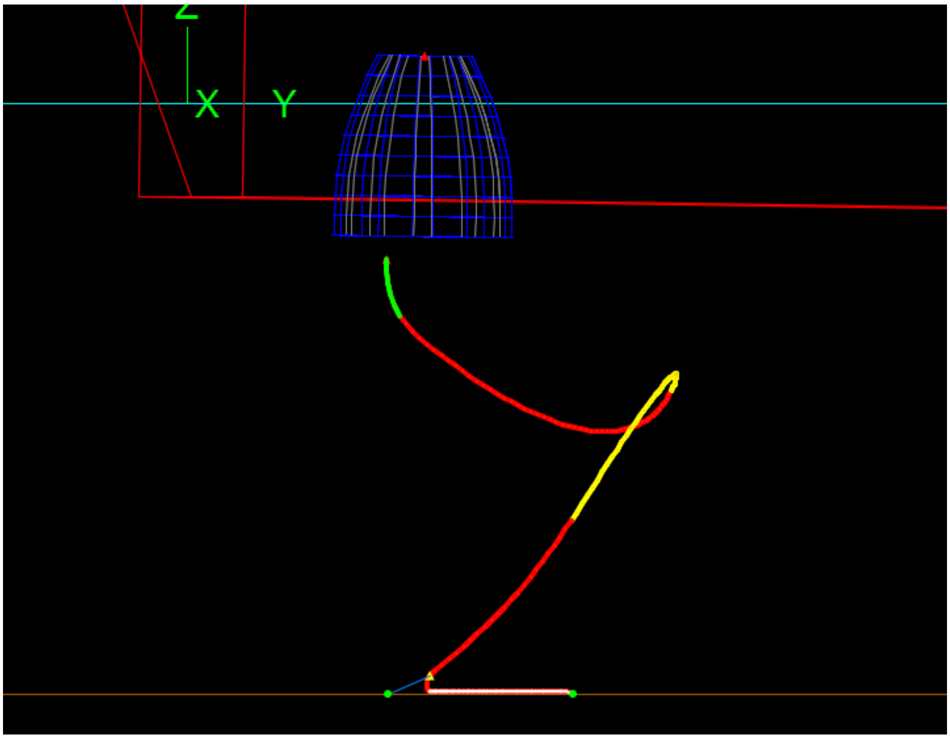


Figure 7-5 Cross Configuration of the 10" Riser Pliant Wave Solution-Empty-Cross Current

The following results were extracted for the static configuration in each case:

- Minimum bending radius along the riser line.
- Minimum bending radius at tether connection.
- Riser line tension at turret connection point.
- Riser line tension at tether connection point.
- Riser line tension at riser base connection point.
- Tether Tension.
- Riser line Moment at turret connection point.
- Riser line clearance from surface.
- Riser line clearance from seabed.

Summary of above results are listed in Table 7-3.

Table 7-3 Static Analyses Results-Pliant Wave Configuration

Load Case	Minimum Bending Radius (m)	Riser tension at Turret (kN)	Riser Line Tension at tether connection(kN)	Tether Tension (kN)	Moment at turret connection (kN.m)	Riser line Tension at PLET (kN)	Surface Clearance (m)	Sea Bed Clearance (m)
1	6.9	40	66.1	19.5	9	33	11.3	20.7
2	4.9	79	102	49.1	24.7	41.6	16.8	26.8
3	5.7	33.7	66.2	0	9.8	58.9	22	11
4	4.8	55.1	85.1	131.3	16.1	79.0	21.1	21.1
5	6.9	40.3	66.5	19.5	8.9	33.0	11.3	20.7
6	5.2	63.5	90	49.5	20.5	41.6	17.9	24.5
7	6.7	35.2	66.5	0	3.2	58.9	13.7	12.11
8	4.9	56.7	83.9	129.5	16.1	77.8	22.7	21.1
9	11.3	62.3	49.8	0	6.5	30	20.15	11.8
10	7.1	75.1	68.1	10.8	16.2	35.5	23.9	17.6
11	6.5	60.1	51.9	0	4.1	49.2	25.0	4.7
12	7.7	78.5	73.3	106.3	14.8	55.9	29.7	15.4
13	5.4	35.4	64.5	18.7	9.5	33.2	12.5	16.4
14	4.8	55.6	83.1	41.4	20.3	37.7	19.5	20.7
15	6.01	30.4	66.6	0	3.3	60.2	14.5	8.2
16	4.9	50.7	80.8	125.8	16.3	77.0	24.1	16.4
17	6.3	36.7	62.9	15.9	9.11	33	13.8	15.2
18	4.9	56.2	81.1	38.4	19.9	37.1	19.53	19.53
19	6.1	31.5	65.4	0	3.2	59.1	14.11	7.5
20	5.1	52.2	79.8	123.8	16.1	75.5	24.6	16.1
21	10.9	59.1	46.4	0	6.5	29.2	23.1	6.7
22	6.9	69.8	59.8	0	15.5	30.3	27.3	11.3
23	6.1	53.9	50.7	0	4.1	42.4	26.6	0
24	6.6	73.3	68.9	101.3	14.8	54.0	32.4	10.6

From a list of reasonable cases, followings are considered for the configuration:

- Bending radius is given as priority for design, especially at tether connection.
- A longer riser will accommodate vessel offset better, but will also increase the drag area causing larger out-of-plane excursions and also make it more close to surface.
- Buoyant sections that float too high in the water are more likely to have interference with the hull also to have larger current forces, causing larger out-of-plane excursions.

Summary of results are:

- Bending radius for all cases is within the MBR limit.
- The tensions reported at the turret, tether and PLET location are in a reasonable limit. Tension data can be used to check with dynamic condition and report dynamic amplification factor (DAF).
- Tether Tension reported can be used for tether design. Also it can be used to check dynamic amplification factor (DAF).

- The biggest challenge for very shallow water is the surface and seabed clearances. Different cases show that there is a limited clearance with surface and bottom and it may cause problems during dynamic motions. One case shows that in temporary condition (water filled)the riser will touch the seabed. This condition will happen during near position of vessel and near current (100 years return period). This condition can be studied with a more real condition for current.

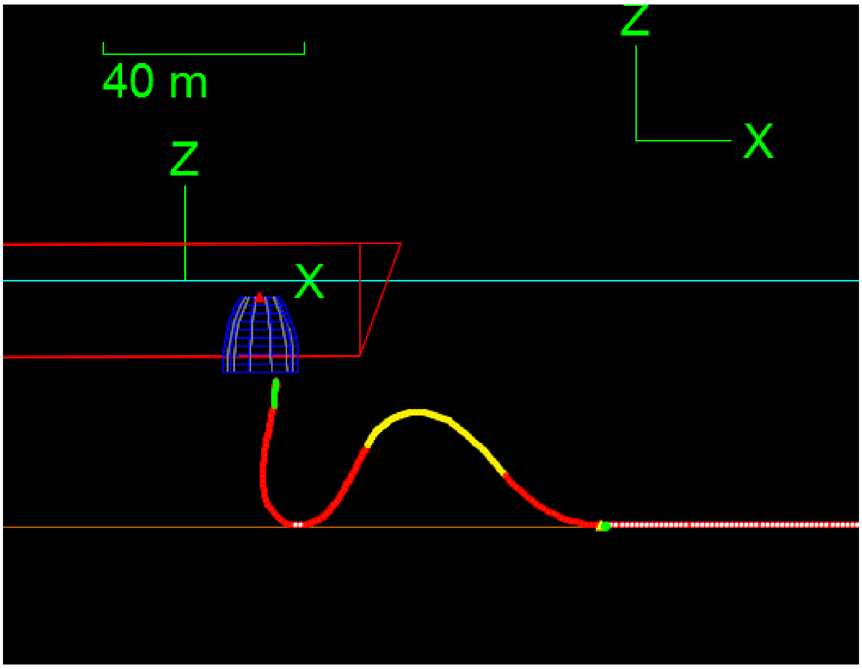


Figure 7-6 Case 23-Riser Touch Seabed in Temporary (water filled condition)

7.3 Touchdown Chain Added Wave Configuration

The Touchdown Chain Added Wave configuration has a distributed buoyancy section (buoyancy modules) and is connected to a heavy chain near the touchdown point. It has similar characteristics as the Steep Wave solution, although no fixed vertical anchor point. It allows for some more movement near the touchdown point compared to the Pliant Wave, but it avoids the use of a fixed gravity anchor. This could make the installation procedure less complex. The Touchdown Chain Added Wave solution is, however, not known to have been installed anywhere before.

The method chosen for finding a system configuration for the Tether Anchored Wave was to regard the chain as ideal having the same effect on the system as the anchor in the Pliant Wave configuration. So parameters were adjusted to achieve a mean configuration that resembled the mean Pliant Wave configuration as closely as possible.

The following parameters are studied:

- Horizontal distance from turret connection to anchor.
- Length of floating section of riser line.
- Length of buoyant section.
- Buoyancy factor.
- Chain connection point.

The mean configuration described in Figure 7-7 and Table 7-4 is found for the Touchdown Chain Added Wave configuration, and will be used in the further steps of the analysis.

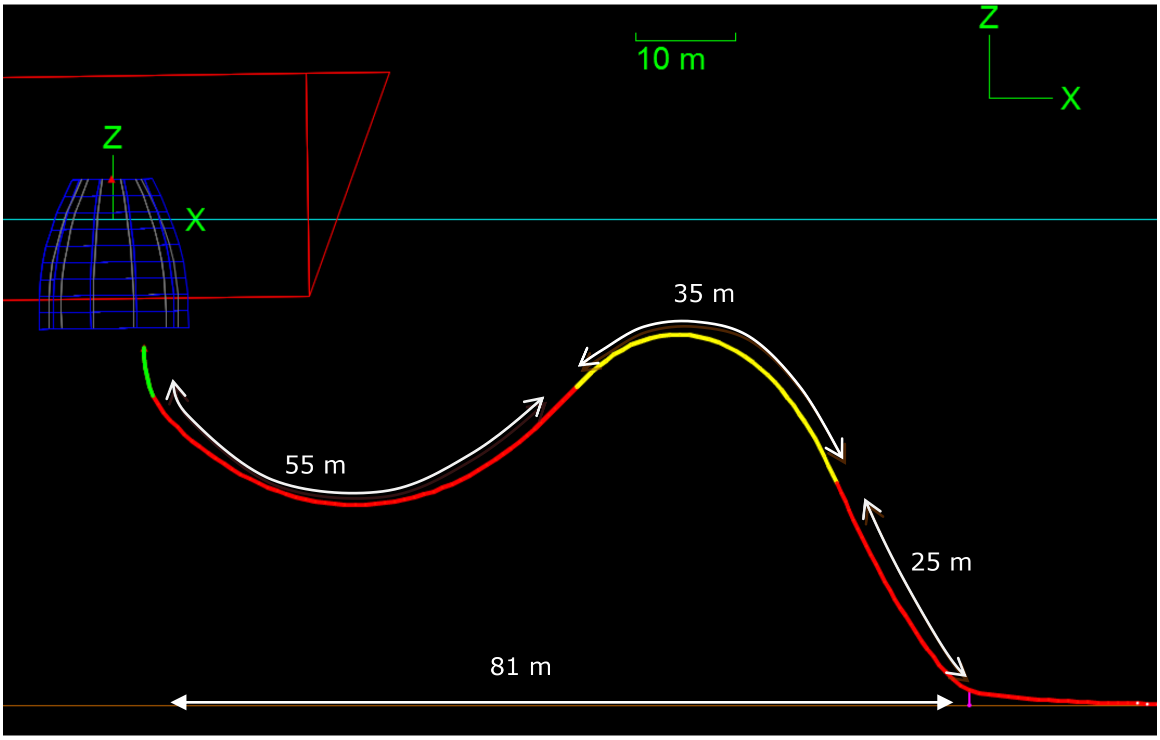


Figure 7-7 Mean Configuration of the 10" Riser Chain Added Wave Solution-Empty

Table 7-4 System Configuration Details for Touchdown chain Added Wave

Dimension	Value
Chain initial touchdown point on sea bed, horiz. distance from turret	81 m
Riser arc length from turret connection to chain connection	115 m
Arc length from turret connection to start of buoyant section	55 m
Arc length of buoyant section	35 m
Net buoyancy of buoyant section	276 kg/m
Chain length	50 m
Chain weight	800 kg/m

Figure 7-8 shows the riser configuration during far offset of the vessel including far current for 100 years return period.

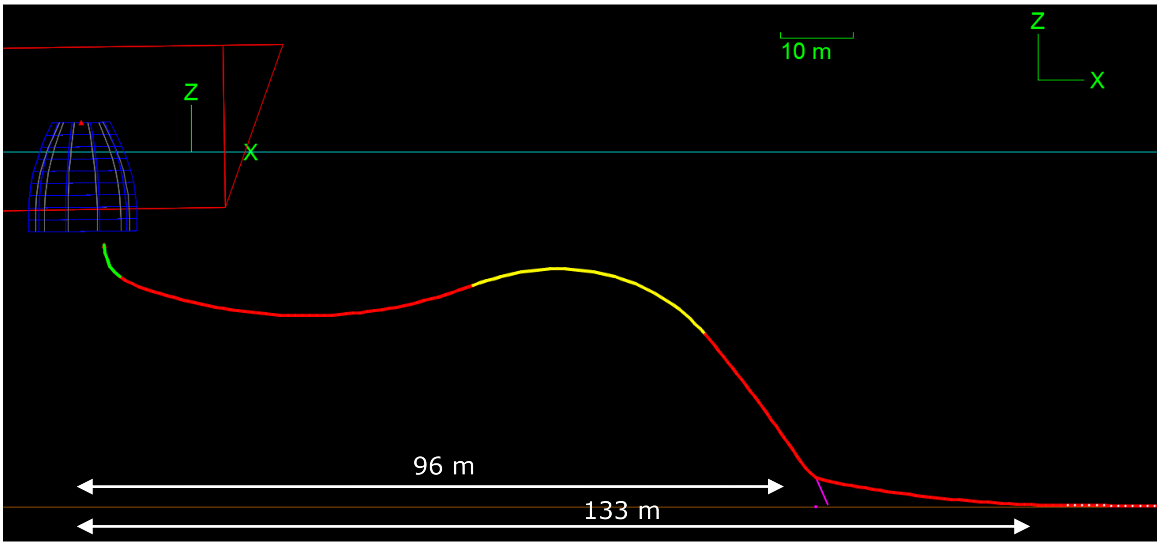


Figure 7-8 Far Configuration of the 10” Riser Chain Added Wave Solution-Empty-Far Current

Figure 7-9 shows the riser configuration during near offset of vessel including near current for 100 years return period.

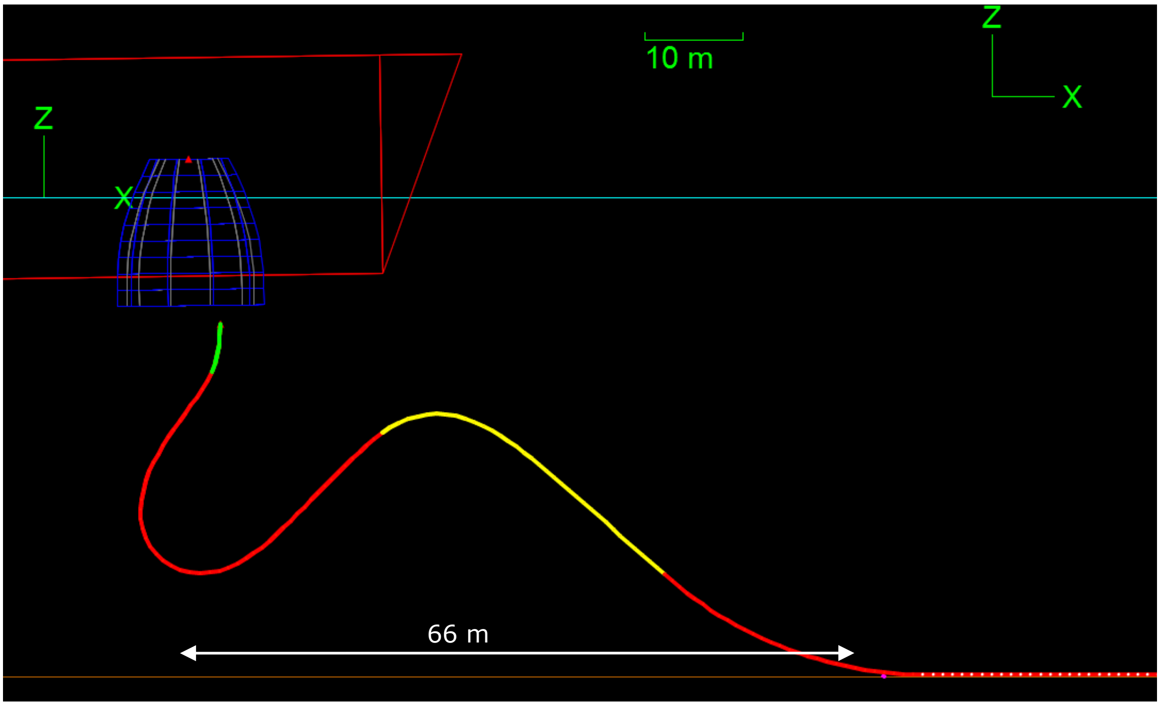


Figure 7-9 Near Configuration of the 10” Riser Chain Added Wave Solution-Empty-Near Current

Figure 7-10 shows the riser configuration during cross offset of vessel including cross current of 100 years return period.

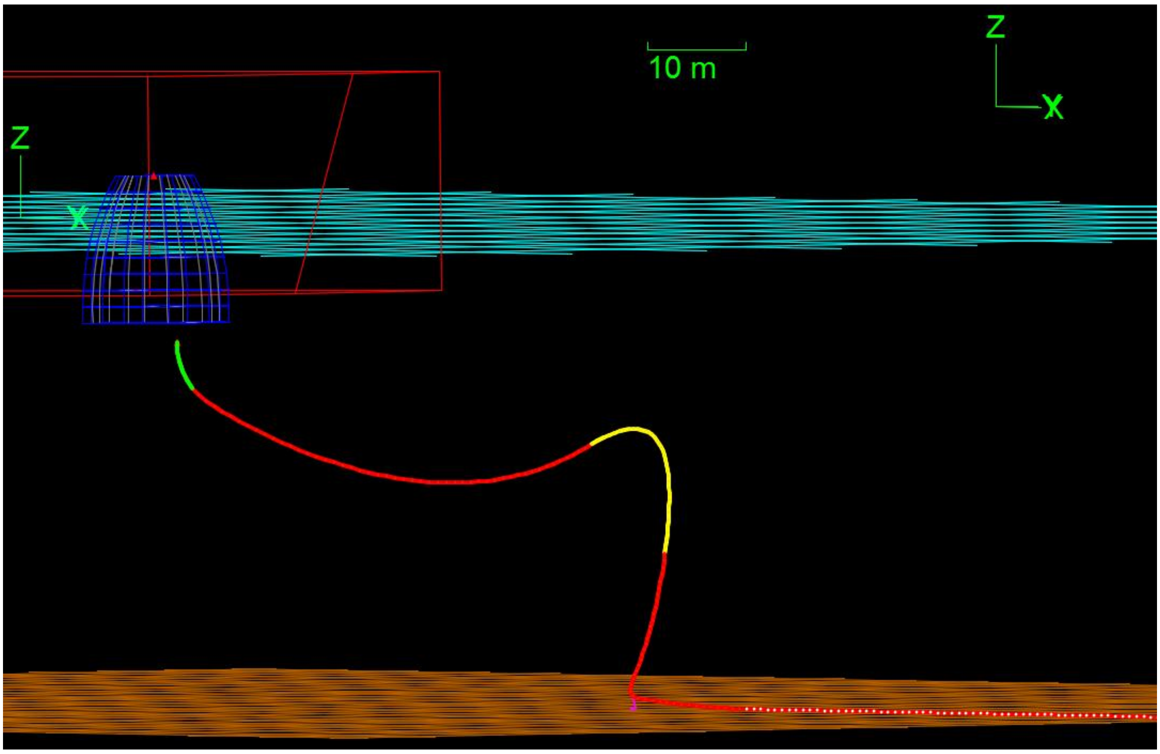


Figure 7-10 Cross Configuration of the 10” Riser Chain Added Wave Solution-Empty-Cross Current

The following results were extracted for the static configuration in each case:

- Minimum bending radius along the riser line.
- Minimum bending radius in chain location.

- Riser line tension at turret connection point.
- Riser line tension at Chain connection point.
- Riser line tension at riser base (PLET) connection point.
- Riser line Moment at turret connection point.
- Riser line clearance from surface.
- Riser line clearance from seabed.

Summary of above results are listed in Table 7-5.

Table 7-5 Static Analyses Results-Chain Added Wave Configuration

Load Case	Minimum Bending Radius (m)	Riser tension at Turret (kN)	Riser Line Tension at Chain connection(kN)	Moment at turret connection (kN.m)	Riser line Tension at PLET (kN)	Surface Clearance (m)	Sea Bed Clearance (m)
1	4.7	40.5	180.1	8.9	166.5	11.7	21.4
2	4.1	71	223	24.4	209.8	15.7	26.2
3	5.8	33.7	66.2	9.8	65.2	22.7	10.6
4	3.1	55.8	175.2	16.2	170.6	20.7	22.7
5	4.7	40.5	179.6	8.7	166.5	12.5	20.7
6	5.1	63.8	238.7	20.3	222.6	18.2	24.2
7	6.9	36.1	126.5	3.4	119.9	14.1	11.8
8	3.1	57.5	165.1	16.1	157.5	21.2	21.5
9	11.3	62.4	49.8	6.5	38.9	20.7	11.3
10	6.9	75.9	106.1	16.1	95.4	24.6	18.3
11	6.5	60.1	51.8	4.1	40.8	23.9	4.7
12	3.5	79.1	83.7	14.4	79.5	30.1	14.1
13	4.8	35.5	176.1	9.3	162.6	13.3	15.7
14	4.8	55.6	236.6	20.4	219.4	18.8	19.9
15	6.1	30.4	131.5	3.2	124.9	15.6	7.1
16	3.2	51.3	157.4	16.3	150.8	23.8	16.4
17	5.1	36.9	163.5	9.1	151.3	14.1	15.6
18	4.9	56.9	226.5	19.3	208.2	19.9	19.5
19	6.8	33.1	262.9	2.8	253.1	16.6	7.1
20	3.2	52.7	148.7	16.4	139.1	23.5	16.4
21	10.9	59.1	46.4	6.5	29.2	23.1	6.7
22	6.9	69.8	66.1	15.5	62.2	26.6	11.3
23	6.1	54.1	50.9	4.1	40.6	26.2	**0**
24	3.4	73.7	81.1	14.9	77.5	32.8	9.8

Summary of results are:

- Bending radius in the chain connection location for cases 4, 8, 12, 16, 20, 24 are less than the MBR limit.

- The tension reported in the turret is at a reasonable limit. Tension data can be used to check with dynamic conditions and report dynamic amplification factor (DAF).

- The tension reported in the PLET location where the riser is connected to the pipeline is high. This should be checked with allowable forces in the PLET.

- The biggest challenge for very shallow water is the surface and seabed clearances. Different cases show that there is a limited clearance with the surface and the bottom and it may cause problems during dynamic motions. One case shows that in temporary condition (water filled) riser will touch the seabed. This condition will happen during near position of vessel and near current (100 years return period). This condition can be studied in more real conditions for the current.

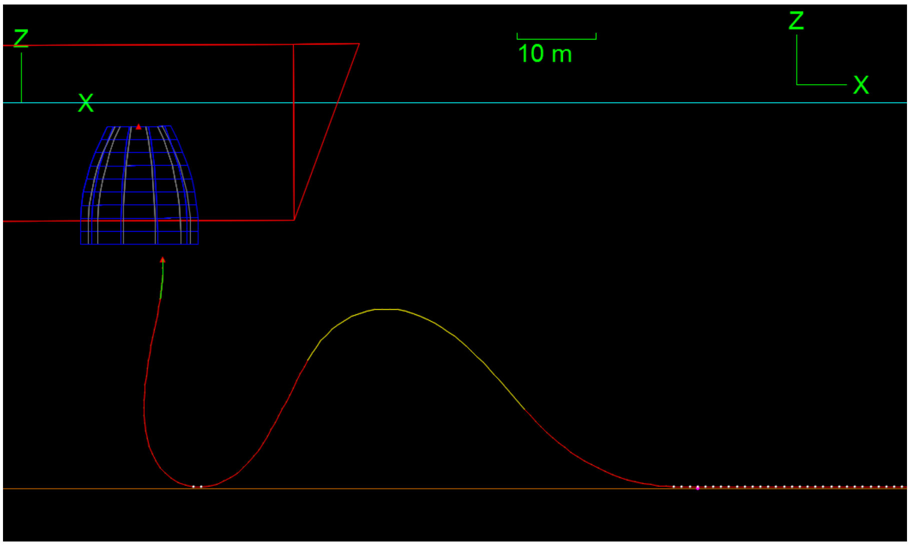


Figure 7-11 Case 23-Riser Touch Seabed in Temporary (water filled condition)

7.4 Risk Assessment (Static Analysis)

A risk assessment is necessary to be done to assess probability of occurrence of each case when combine abnormal condition and extreme loads in each case.

Criteria for probability of occurrence can be set to avoid overdesign. Based on ISO 13628-2 section 5 when the yearly combined probability of different cases are less than 1E-4 they can be neglected.

Below the assumptions for the yearly probability of each event considered for this study are listed(Table 7-6):

Table 7-6 Probability of Each Event

Item	Condition	Yearly Probability
Normal operation		100%
FSO Loading	Ballasted	33%
	Loaded	33%
Internal Fluid	Empty	5%
	Operation	90%
	Flooded	5%
FSO Offset	Mean	40%
	Far	25%
	Near	25%
	Cross	10%
Current Probability	None	80%
	Far 100 yr	1%
	Near 100 yr	1%
	Cross 100 yr	1%

Based on the yearly probability for each event listed in Table 7-6 , the yearly probability for each case is calculated.

The Calculated combined probability is listed in Table 7-7.

Combined Probability (P_c) = P_1xP_2xP_3XP_4xP_5

Table 7-7 Combined Probability for Each Case

Load Case	Service Conditions Probability (P_1)	FSO Loading Condition Probability (P_2)	Internal Fluid Probability (P_3)	FSO Offset Probability (P_4)	Current Probability (P_5)	Combined Probability (P_c)
1	Normal Operation P=1	Ballasted P=0.33	Empty P=0.1	Mean, P=0.4	None P=0.8	1.06E-02
2				Far, P=0.25	Far 100yr P=0.01	8.25E-05
3				Near, P=0.25	Near 100yr P=0.01	8.25E-05
4				Cross, P=0.1	Cross 100yr, P=0.01	3.30E-05
5	Normal Operation P=1	Ballasted P=0.33	Operating P=0.8	Mean, P=0.4	None P=0.8	8.45E-02
6				Far, P=0.25	Far 100yr P=0.01	6.60E-04

Load Case	Service Conditions Probability (P_1)	FSO Loading Condition Probability (P_2)	Internal Fluid Probability (P_3)	FSO Offset Probability (P_4)	Current Probability (P_5)	Combined Probability (P_c)
7				Near, P=0.25	Near 100yr P=0.01	6.60E-04
8				Cross, P=0.1	Cross 100yr P=0.01	2.64E-04
9	Normal Operation P=1	Ballasted P=0.33	Flooded P=0.1	Mean, P=0.4	None P=0.8	1.06E-02
10				Far, P=0.25	Far 100yr P=0.01	8.25E-05
11				Near, P=0.25	Near 100yr P=0.01	8.25E-05
12				Cross, P=0.1	Cross 100yr P=0.01	3.30E-05
13	Normal Operation P=1	Loaded P=0.33	Empty P=0.1	Mean, P=0.4	None P=0.8	1.06E-02
14				Far, P=0.25	Far 100yr P=0.01	8.25E-05
15				Near, P=0.25	Near 100yr P=0.01	8.25E-05
16				Cross, P=0.1	Cross 100yr P=0.01	3.30E-05
17	Normal Operation P=1	Loaded P=0.33	Operating P=0.8	Mean, P=0.4	None P=0.8	8.45E-02
18				Far, P=0.25	Far 100yr P=0.01	6.60E-04
19				Near, P=0.25	Near 100yr P=0.01	6.60E-04
20				Cross, P=0.1	Cross 100yr P=0.01	2.64E-04
21	Normal Operation P=1	Loaded P=0.33	Flooded P=0.1	Mean, P=0.4	None P=0.8	1.06E-02
22				Far, P=0.25	Far 100yr P=0.01	8.25E-05
23				Near, P=0.25	Near 100yr P=0.01	8.25E-05
24				Cross, P=0.1	Cross 100yr P=0.01	3.30E-05

The results of the combination of probabilities are illustrated in Figure 7-12. Red bars show the cases with probabilities less than 1E-04.

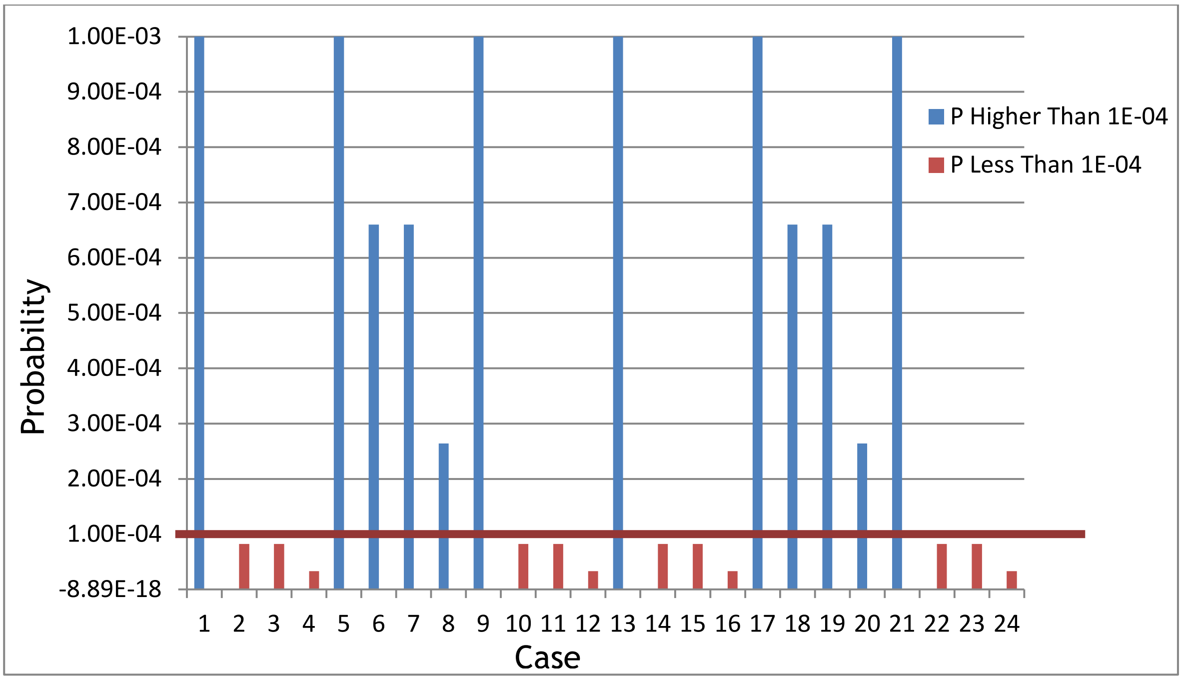


Figure 7-12 Combined Probability Graph for all cases

7.5 Conclusion (Static Analysis)

From static analyses done on two selected configurations, the main challenges with flexible risers in shallow waters are:

- Large vessel offset compared to water depth
- Strong currents.
- Very little clearance between flexible riser and seabed.
- Very little clearance between flexible riser and sea surface.
- Minimum Bending Radius limitation.
- High difference in density range between water filled and empty condition.

Below points are concluded based on results from static analysis on two type of configuration and results from risk assessment:

- Pliant Wave configuration is selected for further step of analysis (Dynamic analysis) as it gives better results based on MBR.
- Based on risk assessment some cases have probability of occurrence less than 1E-04. Those cases can be ignored from further step of project. But as long as they are not checked for lower probability of Current (1 year and 10 year) we will consider them for further step of study.
- Static result on case 23 (water filled condition) show that there will be some limitation regarding the size of riser and fluid density condition. This can be studied separately when the configuration selected. So this case will not be considered in further step (dynamic analysis) when riser touches the seabed.

8. Dynamic Analysis

After static analysis the next stage in the design procedure is to perform dynamic analyses of the system to assess the global dynamic response. The objective of performing this analysis is to predict the lifetime maximum that is the extreme response of the flexible riser system. These load cases combine different wave and current conditions, vessel positions and motions, riser content conditions to provide an overall assessment of riser suitability in operation and extreme environmental condition, [4].

Based on above in Table 8-1 different cases have been defined for dynamic analyses.

The currents in same direction of vessel heading are defined as far currents. The currents in opposite directions of vessel heading are defined as near currents. The currents 90 degree with vessel heading is defined as cross currents.

The Waves in same direction of vessel heading are defined as far waves. The waves in opposite directions of vessel heading are defined as near waves. The waves 90 degree with riser is defined as cross waves.

The worst condition for riser position is in such direction that current and wave make worst loading. This loading occurs in the transverse direction and this direction is therefore avoided by the vessel as it turns in the wave direction.

For all cases wave is in opposite or same direction as vessel.

In this section one type of configuration will be studied: Pliant wave Configuration.

Double wave configuration will also be studied to check the effect of double wave on design.

Table 8-1 Dynamic Analyses Matrix

Load Case	Service Conditions	FSO Loading Condition	Internal Fluid	FSO Offset	Current	Wave
1	Normal Operation	Ballasted	empty	Far	Far 100yr	Far 10yr
2				Near	Near 100yr	Near 10yr
3				Cross	Cross 100yr	Cross 10yr
4	Normal Operation	Ballasted	Operating	Far	Far 100yr	Far 10yr
5				Near	Near 100yr	Near 10yr
6				Cross	Cross 100yr	Cross 10yr
7	Normal Operation	Ballasted	Flooded	Far	Far 100yr	Far 10yr
8				Near	Near 100yr	Near 10yr
9				Cross	Cross 100yr	Cross 10yr
10	Normal Operation	Loaded	empty	Far	Far 100yr	Far 10yr
11				Near	Near 100yr	Near 10yr
12				Cross	Cross 100yr	Cross 10yr
13	Normal Operation	Loaded	Operating	Far	Far 100yr	Far 10yr
14				Near	Near 100yr	Near 10yr
15				Cross	Cross 100yr	Cross 10yr
16	Normal Operation	Loaded	Flooded	Far	Far 100yr	Far 10yr
17				Cross	Cross 100yr	Cross 10yr

The following results were extracted for the Dynamic analysis in each case:

- Minimum bending radius along the riser line.
- Minimum and Maximum Riser line tension at turret connection point.
- Maximum Riser line tension at riser base connection point.
- Minimum and Maximum Tether Tension.

8.1 Pliant Wave Configuration

8.1.1 General

Dynamic results for pliant wave are extracted based on the OrcaFlex dynamic analysis. Below Figure 8-1 to Figure 8-3 show the configuration of risers with application of dynamic loads. For dynamic analysis wave forces and vessel RAO's are applied to the system.

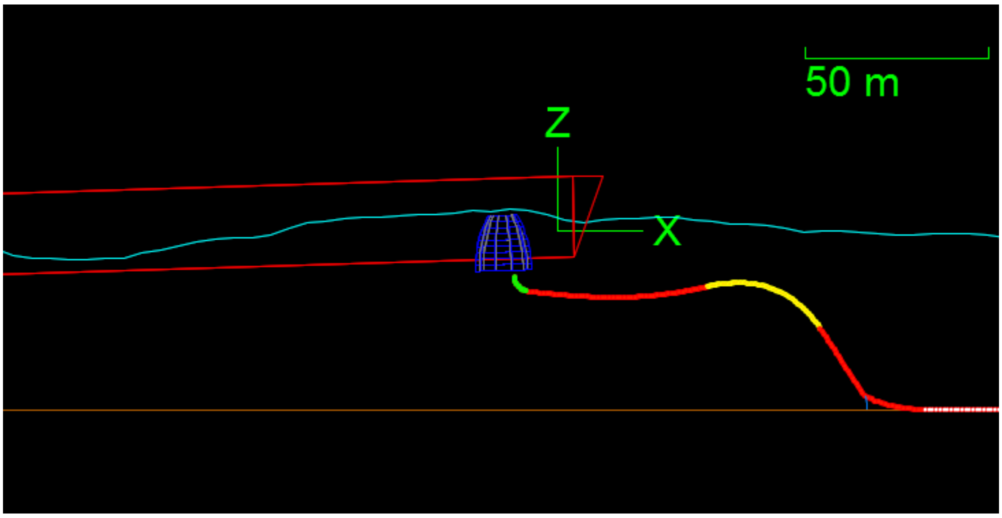


Figure 8-1 Far Configuration of the 10" Riser Pliant Wave Solution-Case 4

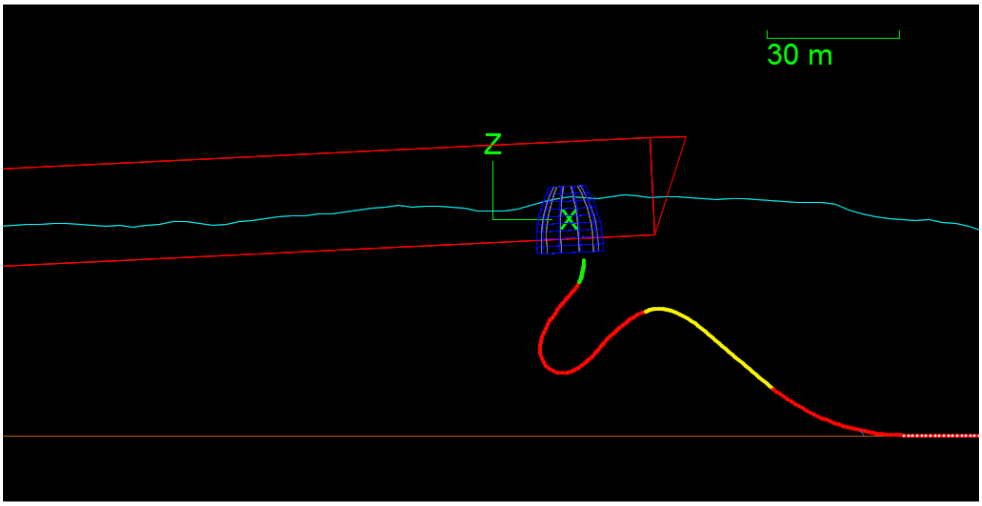


Figure 8-2 Near Configuration of the 10" Riser Pliant Wave Solution-Case 5

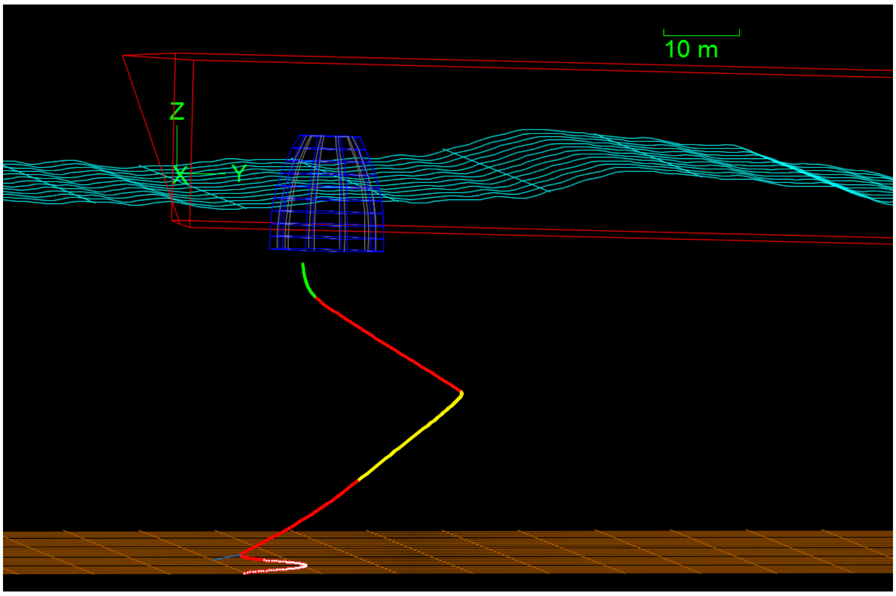


Figure 8-3 Cross Configuration of the 10” Riser Pliant Wave Solution-Case 6

8.1.2 Minimum Bending Radius

The main design criterion given by the cross-section configuration design is the minimum bending radius requirement. The risers should everywhere have a bending radius larger than the specified minimum allowable bending radius (4 m).

See Table 8-2 for a summary of MBR.

Results show that the MBR is critical in the tether connection location. At the turret connection location the MBR is just in the limit and it is acceptable. For tether connection location some solution therefore needs to be presented.

Table 8-2 Minimum Bending Radius

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Minimum bending Radius (m)	Location	utilization
1	Ballasted	empty	Far	3.8	Turret Connection	1.2
2			Near	4.8	Along the riser	0.8
3			Cross	1.9	Tether Connection	2.1
4	Ballasted	Operating	Far	3.5	Turret Connection	1.1
5			Near	4.8	Along the riser	0.8
6			Cross	1.9	Tether Connection	2.1
7	Ballasted	Flooded	Far	4.4	Turret Connection	0.9
8			Near	5.5	Along the riser	0.7
9			Cross	2.0	Tether Connection	2.0
10	Loaded	empty	Far	3.8	Turret Connection	1.1
11			Near	3.8	Along the riser	1.1
12			Cross	1.9	Tether Connection	2.1
13	Loaded	Operating	Far	3.8	Turret Connection	1.1
14			Near	3.9	Along the riser	1.0

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Minimum bending Radius (m)	Location	utilization
15			Cross	1.9	Tether Connection	2.1
16	Loaded	Flooded	Far	4.58	Turret Connection	0.9
17			Cross	2.0	Tether Connection	2.0

8.1.3 Minimum and Maximum Tension at Turret Connection location

Tension is important at the turret location which have interface with FSO. There shall be no compression on the whole length of any of the flexible risers. This requirement is fulfilled by the riser system.Also maximum tension needs to be reported to find the Dynamic Amplification Factor.

Table 8-3 shows the extreme tension in turret connection location.

The result shows that in cross wave and current condition, the DAF seems to be high. This is because of the high cross wave loads impacts on riser.

Table 8-3 Extreme Axial Tension at Turret Connection Location

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Min Tension at turret (kN)	Max Tension at turret (kN)	Static Tension (kN)	DAF
1	Ballasted	empty	Far	50.1	138.5	79	1.75
2			Near	25.7	46.2	33.7	1.4
3			Cross	41.3	285.0	96.0	3.0
4	Ballasted	Operating	Far	55.8	138.5	63.5	2.2
5			Near	25.7	46.2	35.2	1.3
6			Cross	42.2	287.1	96.7	2.95
7	Ballasted	Flooded	Far	63.8	109.6	75.1	1.45
8			Near	49.5	72.4	60.1	1.2
9			Cross	60.5	313.0	114.8	2.7
10	Loaded	empty	Far	49.3	110.3	55.6	2.0
11			Near	20.05	37.5	30.4	1.2
12			Cross	39.6	229.6	87.2	2.6
13	Loaded	Operating	Far	49.7	107.9	56.2	1.9
14			Near	21.6	39.1	31.5	1.2
15			Cross	41.2	231.5	88.75	2.6
16	Loaded	Flooded	Far	58.7	88.0	69.8	1.2
17			Cross	56.6	256.6	105.6	2.4

8.1.4 Minimum and Maximum Tether Tension

Tension in tether connecting riser to seabed is important. Table 8-4 shows the maximum and minimum tension and the static tension in the tether for different cases.

In some cases the tension is reported to be zero which shows that the tether is not acting in the riser system. The maximum and minimum tension in the tether is important for tether design.

Table 8-4 Extreme Axial Tension in Tether Connection Point

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Tether Min Tension (kN)	Tether Max Tension at (kN)	Static Tension (kN)	DAF
1	Ballasted	empty	Far	7.5	130.5	49.1	2.7
2			Near	0	0	0	
3			Cross	95.0	314.5	131.3	2.4
4	Ballasted	Operating	Far	7.7	138.5	49.5	2.8
5			Near	0	0	0	
6			Cross	95.0	311.4	129.5	2.4
7	Ballasted	Flooded	Far	0	20.7	10.8	2.0
8			Near	0	0	0	
9			Cross	81.5	301.2	106.3	2.8
10	Loaded	empty	Far	3.6	107.8	41.4	2.6
11			Near	0	0	0	
12			Cross	105.0	289.0	125.8	2.3
13	Loaded	Operating	Far	1.0	109.2	38.4	2.8
14			Near	0	0	0	
15			Cross	105.2	287.0	123.8	2.3
16	Loaded	Flooded	Far	0	0	0	
17			Cross	88.4	262.5	101.3	2.6

8.1.5 Minimum and Maximum Tension at PLET location

Tension is also important at PLET location. This should be reported to design the dynamic connection to the PLET.

Table 8-5 presents minimum, maximum and static tension of riser at PLET connection.

These interface loads need to be reported to design the connector to the PLET.

Table 8-5 Extreme effective Tension at PLET Connection

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Min Tension at turret (kN)	Max Tension at turret (kN)	Static Tension (kN)
1	Ballasted	empty	Far	13.0	60.55	41.6
2			Near	41.0	75.2	58.9
3			Cross	67.3	243.0	79.0
4	Ballasted	Operating	Far	13.0	60.6	41.65
5			Near	40.9	75.5	58.9
6			Cross	66.5	241.8	77.8
7	Ballasted	Flooded	Far	-9	84.2	35.5
8			Near	35.4	62.1	49.2
9			Cross	49.4	237.7	55.9
10	Loaded	empty	Far	11.8	57.4	37.7
11			Near	41.4	90.1	60.2
12			Cross	76.3	234.2	77.0
13	Loaded	Operating	Far	11.1	57.1	37.1
14			Near	41.2	75.1	59.1
15			Cross	74.0	233.8	75.5
16	Loaded	Flooded	Far	-23.0	82.3	30.3
17			Cross	54.7	225.2	54.0

8.2 Double Wave Configuration

As seen from dynamic results for pliant wave configuration there is some limitations with regard to the MBR in the tether connection and high loads in the turret connection.

One solution to accommodate high vessel offset and high dynamic loads can be using double wave configuration for riser.

As we had limitation in MBR and turret connection loads, double wave configuration will be checked with regard to these two issues.

With regard to different content density and near and far vessel offset the best double wave configuration is shown in Figure 8-4.

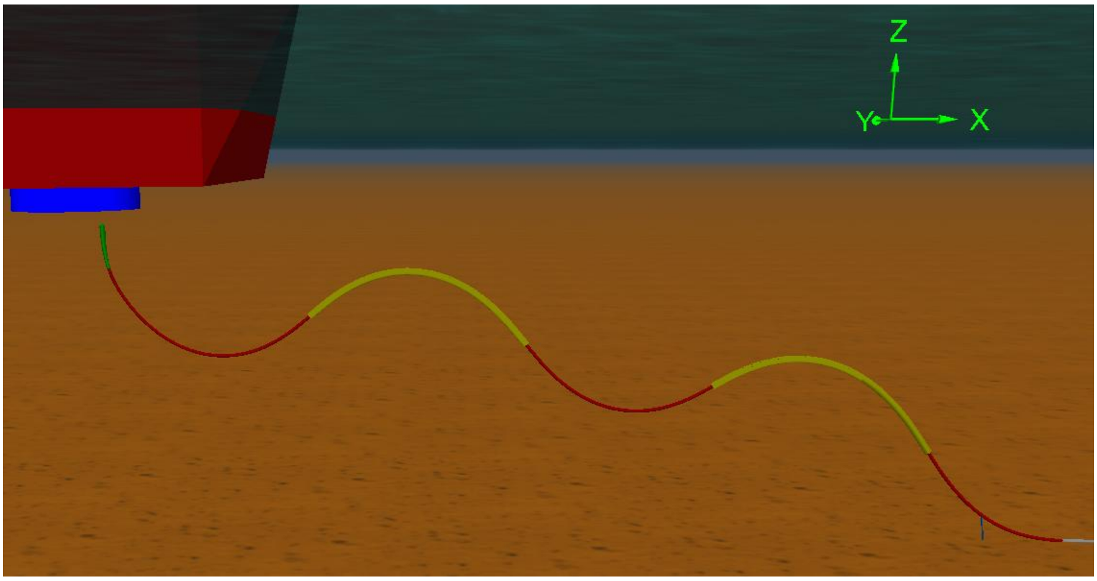


Figure 8-4 Double Wave Configuration of the 10" Riser

8.2.1 Minimum Bending Radius

The main challenge for the pliant wave configuration is the MBR in tether connection in cases with cross current and waves. So those cases will be checked with double wave configuration.

See Table 8-6 for a summary of MBR in cases 3,6,9,12,15 and 17.

Results show that MBR in tether connection and turret connection still below the limit. Double wave configuration is not a good solution with regard to MBR. As we have more suspended area more current force and wave force affect on the riser and MBR in connection points will be worse.

Table 8-6 Minimum Bending Radius

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Minimum bending Radius (m)	Location
3	Ballasted	empty	Cross	1.95	Tether Connection, Turret Connection
6	Ballasted	Operating	Cross	1.97	Tether Connection, Turret Connection
9	Ballasted	Flooded	Cross	2.10	Tether Connection, Turret Connection
12	Loaded	empty	Cross	1.95	Tether Connection, Turret Connection

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Minimum bending Radius (m)	Location
15	Loaded	Operating	Cross	1.93	Tether Connection, Turret Connection
17	Loaded	Flooded	Cross	1.97	Tether Connection, Turret Connection

8.2.2 Minimum and Maximum Tension at Turret location

The maximum tension at the turret is high for the pliant wave configuration. The double wave configuration can accommodate vessel offset and may decrease the maximum tension in the turret connection.

The cross current and wave cases have extreme tensions and need to be checked for the new double wave configuration.

Table 8-7 shows extreme tension and DAF in turret connection.

Results show that the DAF in the turret connection is higher than the results from the pliant wave configuration. Double wave configuration is not a good solution with regard to tension in turret. As we have more suspended area more current force and wave force affect on the riser and the extreme tension in connection points will be much higher.

Table 8-7 Extreme Axial Tension at Turret

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Min Tension at turret (kN)	Max Tension at turret (kN)	Static Tension (kN)	DAF
3	Ballasted	empty	Cross	30	514	133.0	3.9
6	Ballasted	Operating	Cross	30	515	134.2	3.85
9	Ballasted	Flooded	Cross	44.2	591	153.7	3.85
12	Loaded	empty	Cross	29.4	417.5	120	3.50
15	Loaded	Operating	Cross	29.4	418.1	120.6	3.50
17	Loaded	Flooded	Cross	42	499.5	141	3.53

8.2.3 Double wave configuration with change of content density

Double wave configuration seems to be sensitive with regard to density change of the content in the flexible riser.

Some configuration for 10” flexible riser when it is water filled shown in Figure 8-5 and Figure 8-6.

Based on the results from different cases analyzed, the double wave configuration is not suitable when we have high change in content density in very shallow water.

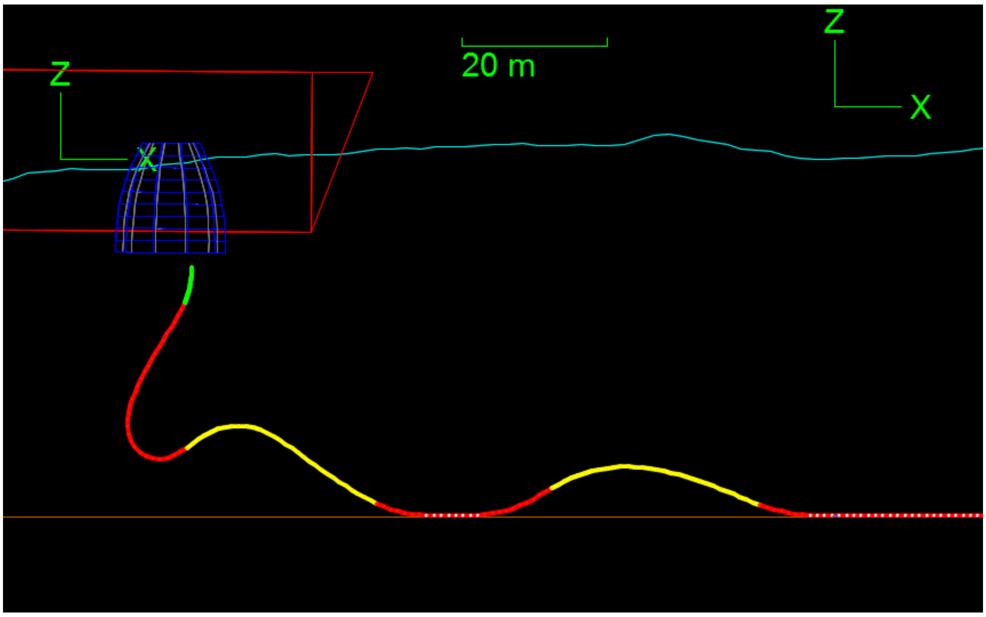


Figure 8-5 Double Wave Configuration, 10” Riser, Waterfilled, Near Offset, Vessel Ballasted

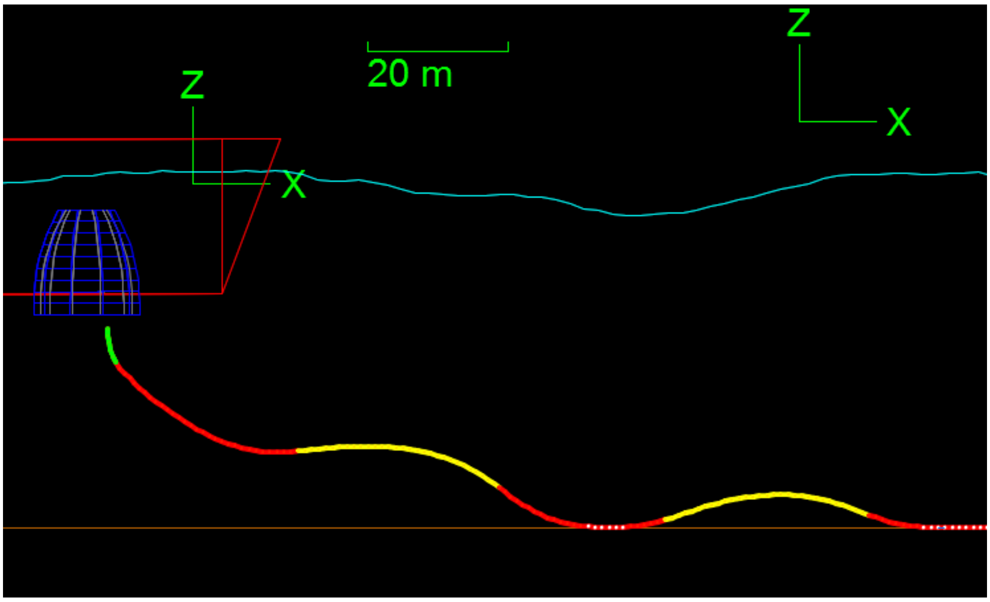


Figure 8-6 Double Wave Configuration, 10” Riser, Waterfilled, Far Offset, Vessel Loaded

8.3 Dynamic Analysis with Bend Restrictor in the Tether Connection (Pliant Wave)

The minimum bending radius results presented in section 8.1.2 shows that bending radius is below the MBR.

The critical location is the point where the tether is connected to the riser. Also the critical cases are the cases with cross current and wave.

A solution which can be proposed is to use bend stiffener in the location where the tether is connected to the riser. So below, critical cases were studied with adding a bend stiffener tether connection to the riser.

Table 8-8 Minimum Bending Radius (without stiffener)

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Minimum bending Radius (m)	Location
3	Ballasted	empty	Cross	1.9	Tether Connection
6	Ballasted	Operating	Cross	1.9	Tether Connection
9	Ballasted	Flooded	Cross	2.0	Tether Connection
12	Loaded	empty	Cross	1.9	Tether Connection
15	Loaded	Operating	Cross	1.9	Tether Connection
17	Loaded	Flooded	Cross	2.0	Tether Connection

The property of the bend stiffener is the same as the one used at turret connection. The length of the bend stiffener is 8 m. Figure 8-7 shows the bend stiffener schematic at the tether connection.

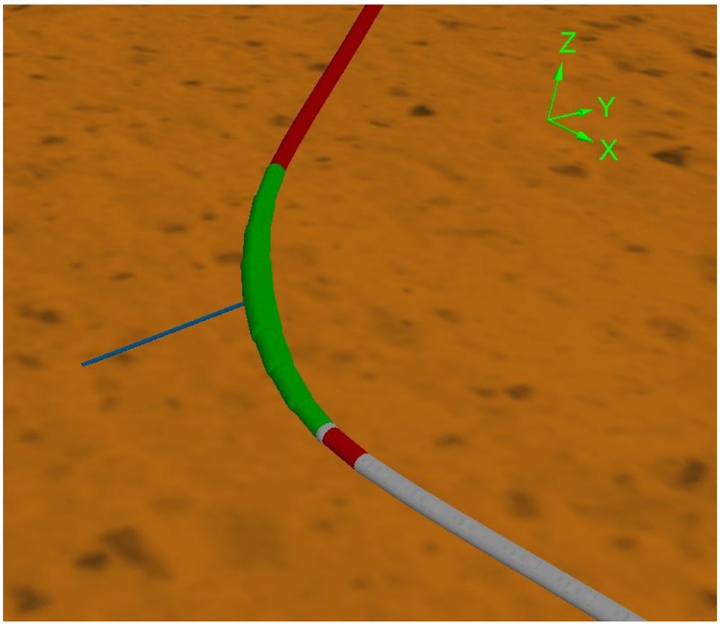


Figure 8-7 Bend Stiffener at tether connection

Figure 8-8 shows general riser configuration with dynamic loads.

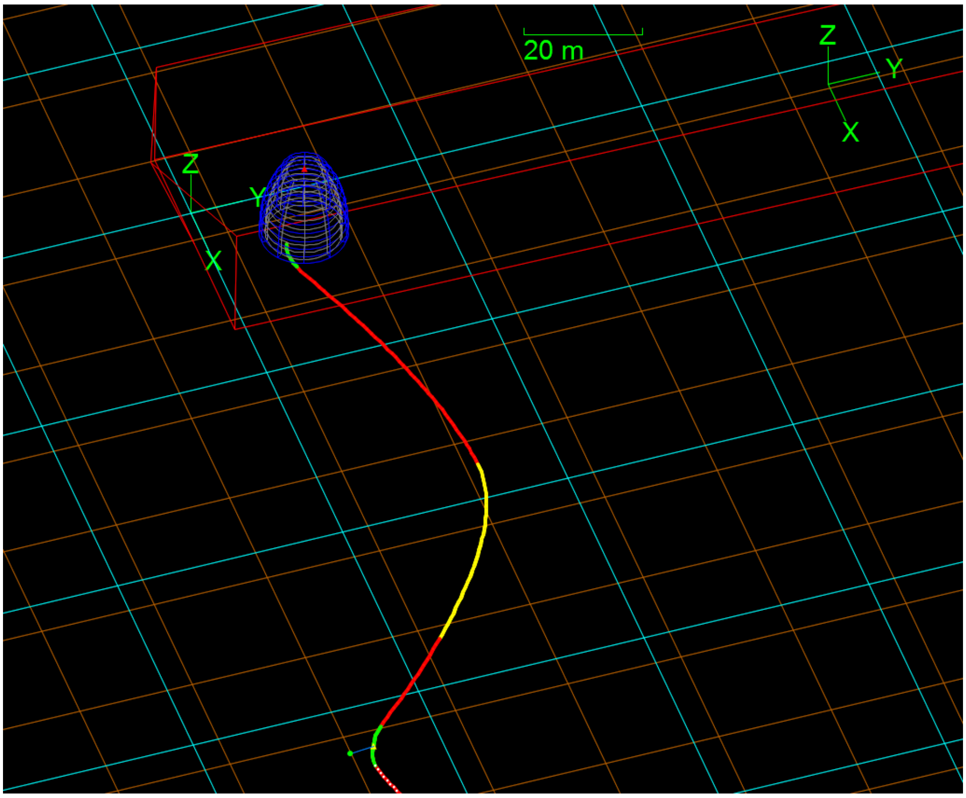


Figure 8-8 Riser Configuration with bend stiffener in tether connection

Results for the bending radius from the dynamic analysis are listed in Table 8-9.The results shows that the bending radius in the tether connection is higher than the MBR with bend stiffener, Compare with Table 8-8 the results using bend stiffener are acceptable.

Table 8-9 Minimum Bending Radius (with bend stiffener)

Case	FSO Loading Condition	Internal Fluid	FSO Offset, 100 yr Wave and 10 yr Current	Minimum bending Radius (m)	Location
3	Ballasted	empty	Cross	5.4	Tether Connection
6	Ballasted	Operating	Cross	5.5	Tether Connection
9	Ballasted	Flooded	Cross	5.7	Tether Connection
12	Loaded	empty	Cross	5.7	Tether Connection
15	Loaded	Operating	Cross	5.6	Tether Connection
17	Loaded	Flooded	Cross	5.8	Tether Connection

9. Conclusions

From static and dynamic analysis done in the thesis, the following are the main challenges for very shallow waters with harsh environments

- Large vessel offset in comparison to water depth
- Strong currents.
- Very little clearance between flexible riser and seabed.
- Very little clearance between flexible riser and sea surface.
- Minimum Bending Radius limitation.
- High difference in density range between water filled and empty riser condition.
- Marin growth.

Riser configuration design in very shallow water is a complex process. This thesis focuses on above main challenges. The Conclusions from Thesis are:

- The riser configuration must be restrained on the seabed at the touchdown point location. The use of pliant wave with clamp, tether and clump weight is a preferred option to avoid high lateral motions of the riser in the touchdown area under lateral current and wave loads. Recommended configuration including components is shown in Figure 9-1 and Figure 9-2.

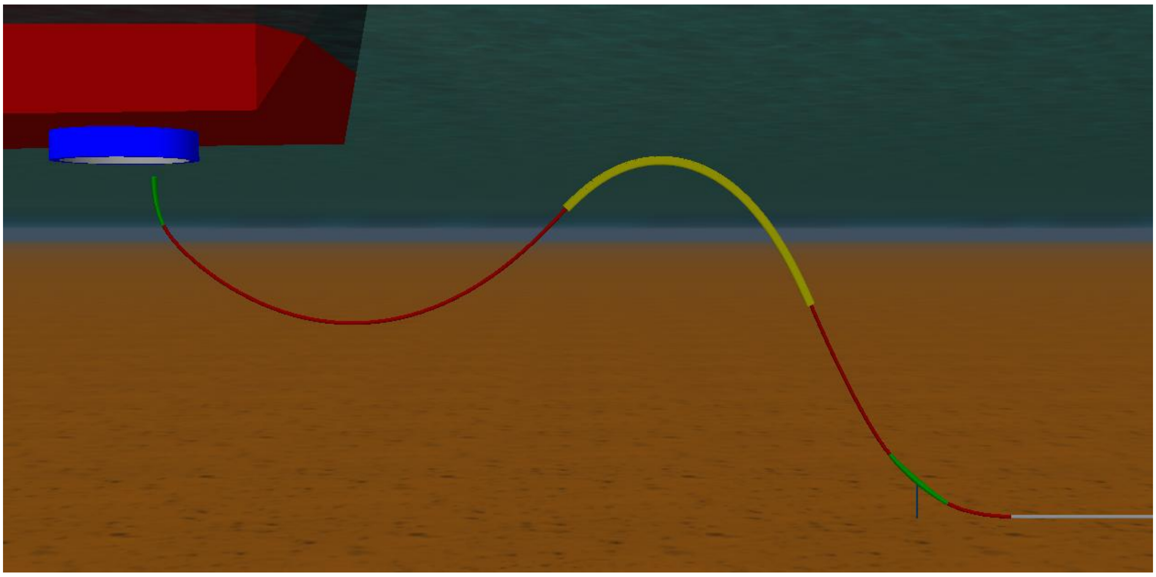


Figure 9-1 Pliant Wave Configuration

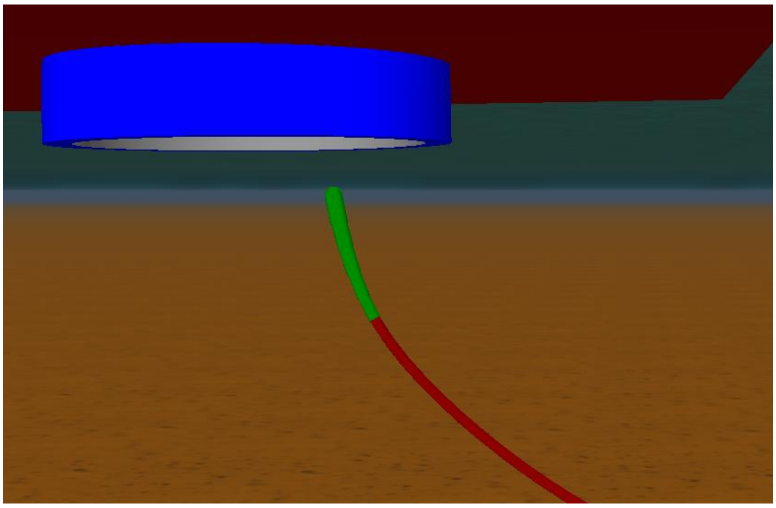


Figure 9-2 Bend Stiffener at Turret Connection

- In very shallow water specific attention should be given to the clamp design at the touch-down to avoid over bending. It is necessary to use bend stiffener at clamp location to avoid high curvature at the tether connection.

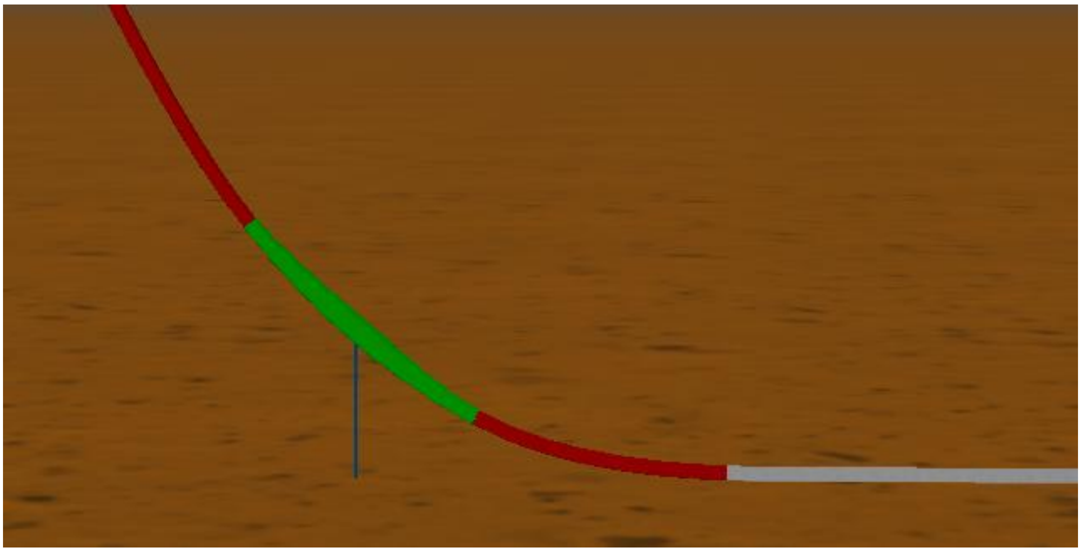


Figure 9-3 Bend Stiffener at tether connection

- The riser from the touchdown to the PLET needs some weight and protection from the effect of strong lateral current. This is to avoid transferring high lateral and axial forces to the PLET connection.

- Double wave configuration is not a good solution for very shallow water with harsh environment (strong currents). The section of suspended area in connection with marine growth will make high drag force and makes high lateral force in touch down point.

- The internal diameter of the pipe has to be as small as possible. This means that in very shallow water the size of riser should not be higher than a certain size. If the fluid density varies during the service life it affects on the riser configuration. As 10 inch flexible riser has been checked in this thesis we may say that 10 inch is a good limit. Higher diameter riser could be feasible but only if the fluid density variation is limited (water injection or gas line).

- Risk of impact is high in such environment. It is therefore strongly recommended to protect the flexible riser by an additional protective sheath. This solution offers higher resistance to impact and protects the annulus from seawater ingress. Also impact tests should be performed to demonstrate that the riser can sustain impact loads without any induced damage or unacceptable deformation.

- Marine growth build up, may have a big impact on the riser. Marin growth will make the surface rough and increase the drag coefficient which increases the current and wave forces on the riser. It is recommended to clean the marine growth during the service life of the riser.

10. Recommendations and Further Work

The following recommendations can be made based on the work performed:

- The present analysis was performed with extreme wave and current. More detailed design, with directional wave and current shall be carried out which will improve the results.

- The present dynamic riser system is focused on a pliant wave configuration; a lazy s configuration with a MWA can be used for improvement and different riser conditions. Use of a fixed MWA such as a jacket MWA is recommended.

- Detailed fatigue analyses including local curvature analysis (bend stiffener section) and local stress analysis can be performed as future work.

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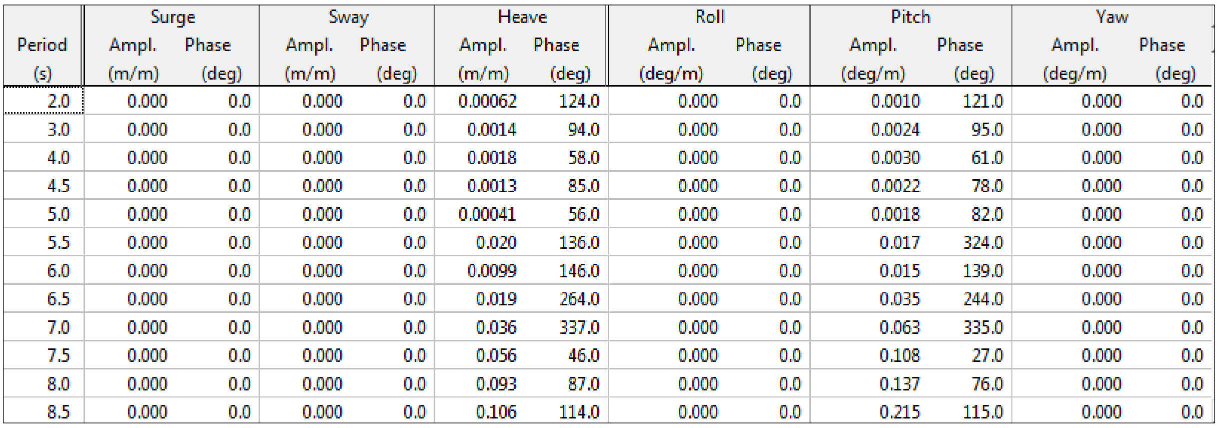
12. Appendix A: RAO Data

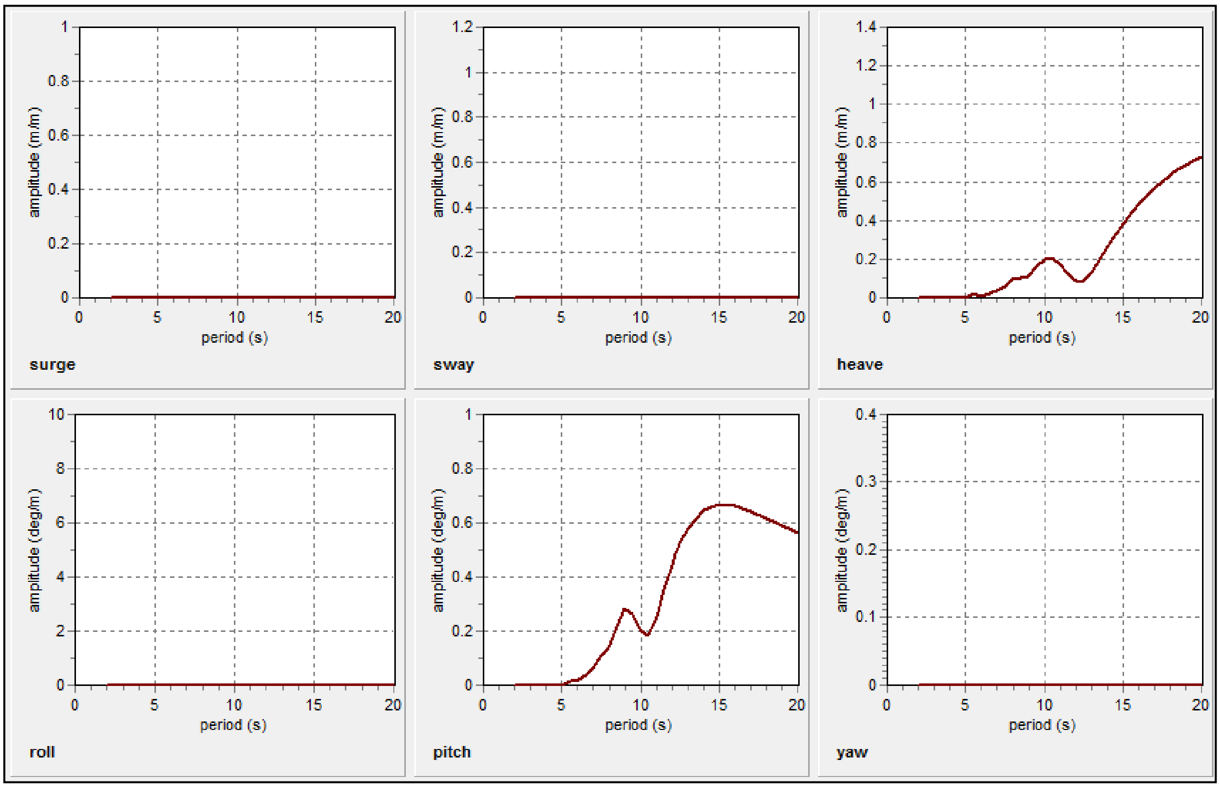
RAO data are available for 7 directions: 0, 30, 60, 90, 120, 150, 180 degree. These data are available from one typical FSO data for periods (T) 2 sec to 20 sec. All these direction are implemented in analyses. RAO data for some direction are presented for ballasted and loaded condition:

12.1 Ballasted Condition

0 Degree

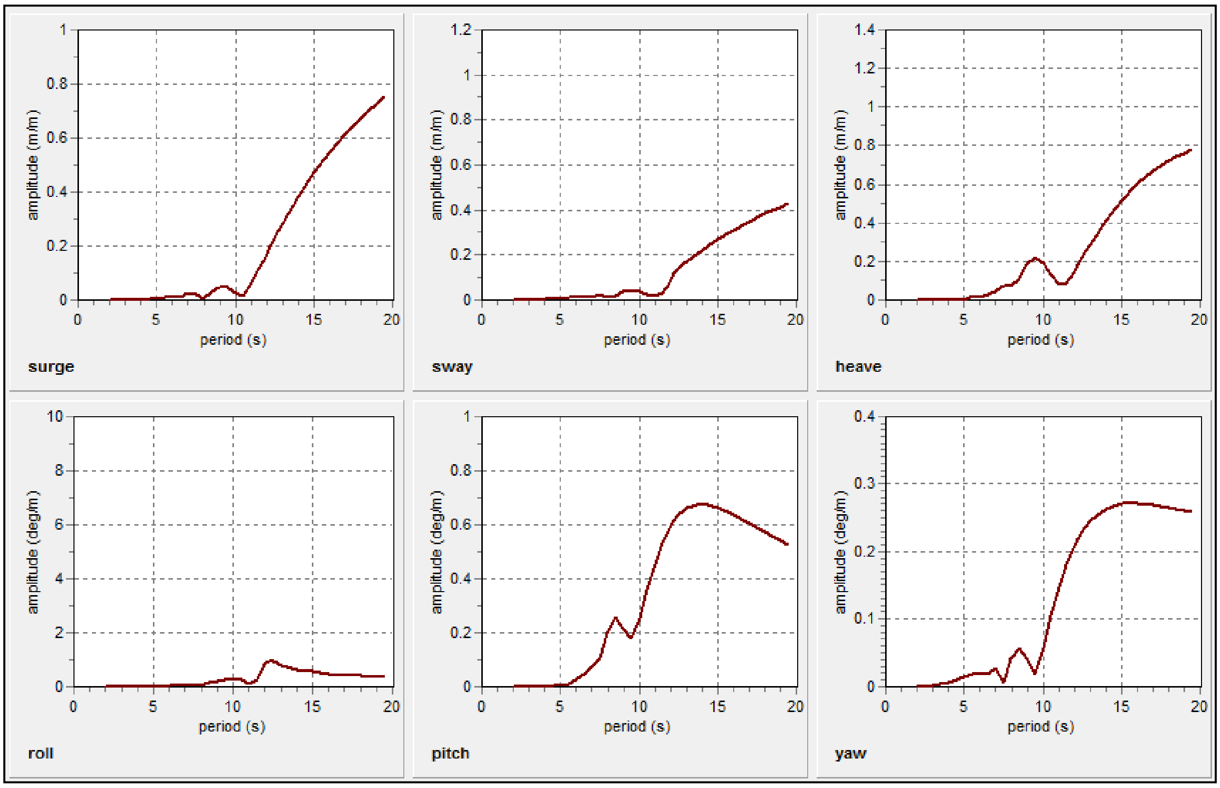


Period	Surge		Sway		Heave		Roll		Pitch		Yaw	
	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
(s)	(m/m)	(deg)	(m/m)	(deg)	(m/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)
2.0	0.000	0.0	0.000	0.0	0.00062	124.0	0.000	0.0	0.0010	121.0	0.000	0.0
3.0	0.000	0.0	0.000	0.0	0.0014	94.0	0.000	0.0	0.0024	95.0	0.000	0.0
4.0	0.000	0.0	0.000	0.0	0.0018	58.0	0.000	0.0	0.0030	61.0	0.000	0.0
4.5	0.000	0.0	0.000	0.0	0.0013	85.0	0.000	0.0	0.0022	78.0	0.000	0.0
5.0	0.000	0.0	0.000	0.0	0.00041	56.0	0.000	0.0	0.0018	82.0	0.000	0.0
5.5	0.000	0.0	0.000	0.0	0.020	136.0	0.000	0.0	0.017	324.0	0.000	0.0
6.0	0.000	0.0	0.000	0.0	0.0099	146.0	0.000	0.0	0.015	139.0	0.000	0.0
6.5	0.000	0.0	0.000	0.0	0.019	264.0	0.000	0.0	0.035	244.0	0.000	0.0
7.0	0.000	0.0	0.000	0.0	0.036	337.0	0.000	0.0	0.063	335.0	0.000	0.0
7.5	0.000	0.0	0.000	0.0	0.056	46.0	0.000	0.0	0.108	27.0	0.000	0.0
8.0	0.000	0.0	0.000	0.0	0.093	87.0	0.000	0.0	0.137	76.0	0.000	0.0
8.5	0.000	0.0	0.000	0.0	0.106	114.0	0.000	0.0	0.215	115.0	0.000	0.0

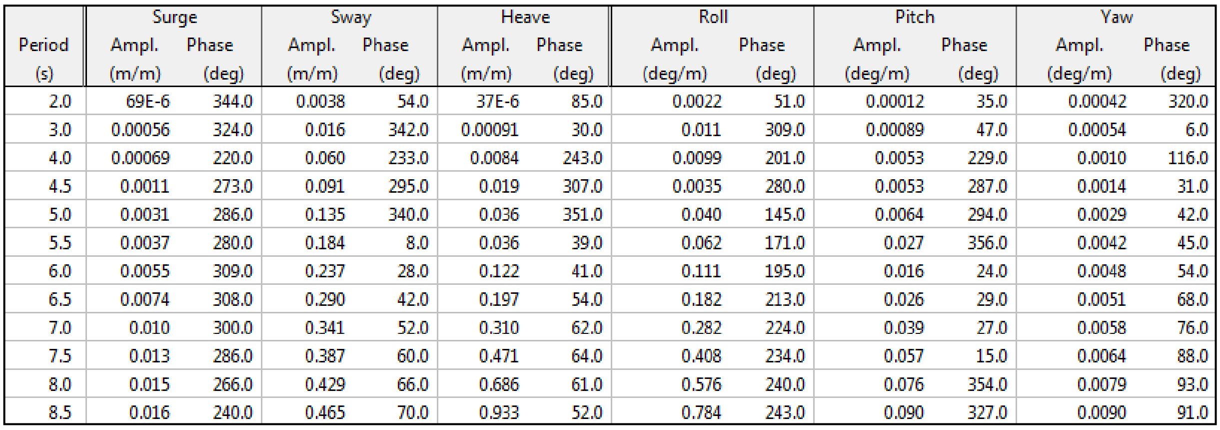


30 Degree

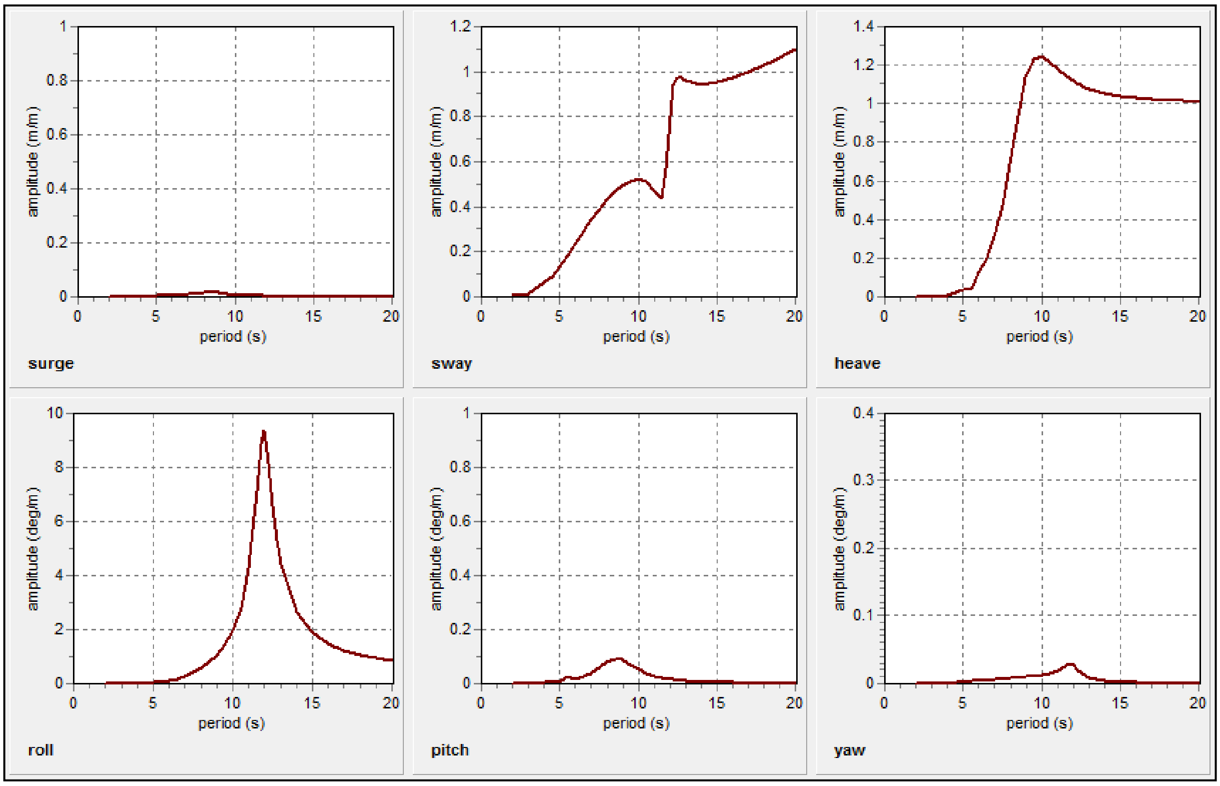
Period	Surge		Sway		Heave		Roll		Pitch		Yaw	
	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
(s)	(m/m)	(deg)	(m/m)	(deg)	(m/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)
2.0	0.00019	266.0	0.00037	18.0	0.00017	258.0	0.00030	141.0	0.00029	253.0	0.00063	205.0
3.0	0.00060	89.0	0.0013	281.0	0.00095	56.0	0.0014	258.0	0.0017	62.0	0.0022	88.0
4.0	0.0021	44.0	0.0035	54.0	0.00089	352.0	0.0058	7.0	0.0018	353.0	0.0069	226.0
4.5	0.0042	28.0	0.0056	0.0	0.0020	22.0	0.011	333.0	0.0044	14.0	0.0099	197.0
5.0	0.0060	254.0	0.0087	253.0	0.0034	278.0	0.012	183.0	0.0044	248.0	0.014	54.0
5.5	0.0084	81.0	0.011	59.0	0.024	138.0	0.022	334.0	0.011	34.0	0.019	223.0
6.0	0.013	204.0	0.014	170.0	0.014	235.0	0.043	100.0	0.028	214.0	0.021	358.0
6.5	0.011	315.0	0.016	264.0	0.026	320.0	0.043	183.0	0.047	324.0	0.019	100.0
7.0	0.025	25.0	0.014	6.0	0.043	46.0	0.076	253.0	0.076	23.0	0.028	159.0
7.5	0.020	50.0	0.025	44.0	0.072	90.0	0.082	287.0	0.105	93.0	0.0055	260.0
8.0	0.0028	226.0	0.015	31.0	0.076	131.0	0.069	348.0	0.202	129.0	0.041	336.0
8.5	0.031	252.0	0.016	277.0	0.110	182.0	0.134	40.0	0.258	141.0	0.057	337.0



90 Degree

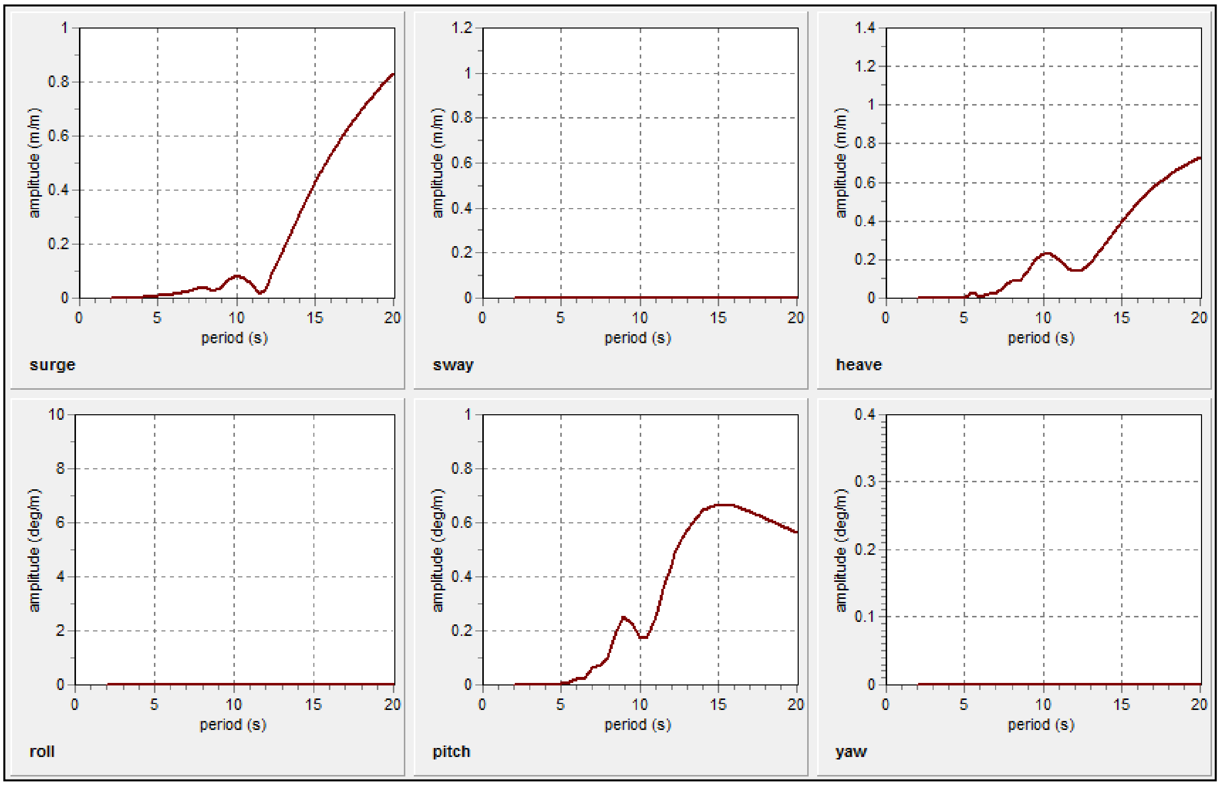


Period	Surge		Sway		Heave		Roll		Pitch		Yaw	
	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
(s)	(m/m)	(deg)	(m/m)	(deg)	(m/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)
2.0	69E-6	344.0	0.0038	54.0	37E-6	85.0	0.0022	51.0	0.00012	35.0	0.00042	320.0
3.0	0.00056	324.0	0.016	342.0	0.00091	30.0	0.011	309.0	0.00089	47.0	0.00054	6.0
4.0	0.00069	220.0	0.060	233.0	0.0084	243.0	0.0099	201.0	0.0053	229.0	0.0010	116.0
4.5	0.0011	273.0	0.091	295.0	0.019	307.0	0.0035	280.0	0.0053	287.0	0.0014	31.0
5.0	0.0031	286.0	0.135	340.0	0.036	351.0	0.040	145.0	0.0064	294.0	0.0029	42.0
5.5	0.0037	280.0	0.184	8.0	0.036	39.0	0.062	171.0	0.027	356.0	0.0042	45.0
6.0	0.0055	309.0	0.237	28.0	0.122	41.0	0.111	195.0	0.016	24.0	0.0048	54.0
6.5	0.0074	308.0	0.290	42.0	0.197	54.0	0.182	213.0	0.026	29.0	0.0051	68.0
7.0	0.010	300.0	0.341	52.0	0.310	62.0	0.282	224.0	0.039	27.0	0.0058	76.0
7.5	0.013	286.0	0.387	60.0	0.471	64.0	0.408	234.0	0.057	15.0	0.0064	88.0
8.0	0.015	266.0	0.429	66.0	0.686	61.0	0.576	240.0	0.076	354.0	0.0079	93.0
8.5	0.016	240.0	0.465	70.0	0.933	52.0	0.784	243.0	0.090	327.0	0.0090	91.0



180 Degree

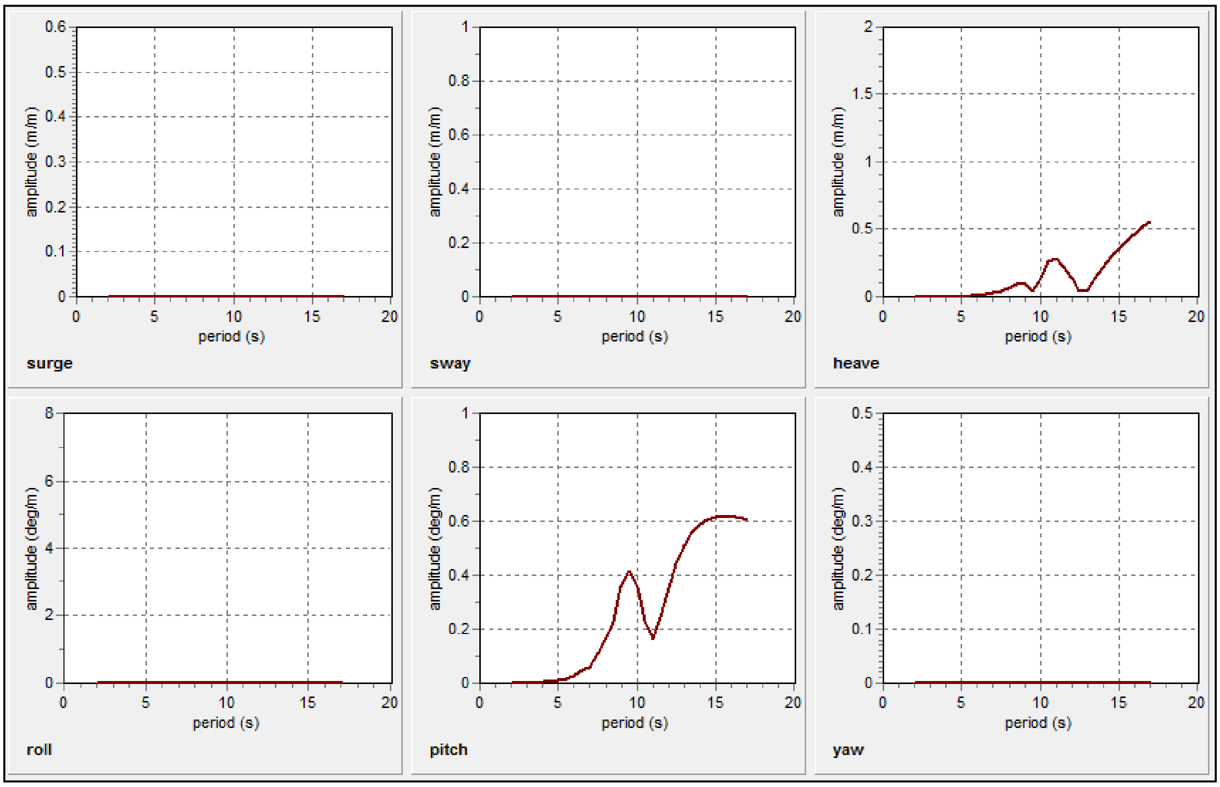
Period	Surge		Sway		Heave		Roll		Pitch		Yaw	
	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
(s)	(m/m)	(deg)	(m/m)	(deg)	(m/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)	(deg/m)	(deg)
2.0	0.00035	93.0	423E-12	165.0	0.00041	58.0	1.0E-9	53.0	0.00070	57.0	1.5E-9	289.0
3.0	0.00069	157.0	333E-12	99.0	0.00067	187.0	429E-12	140.0	0.0012	187.0	271E-12	146.0
4.0	0.0030	62.0	309E-12	10.0	0.00059	314.0	465E-12	315.0	0.0011	66.0	892E-12	60.0
4.5	0.0053	76.0	439E-12	273.0	0.0017	282.0	2.7E-9	51.0	0.0014	94.0	1.5E-9	44.0
5.0	0.0080	333.0	1.5E-9	318.0	0.0024	212.0	2.3E-9	241.0	0.0053	2.0	56E-12	156.0
5.5	0.013	167.0	2.2E-9	139.0	0.026	116.0	5.9E-9	71.0	0.013	248.0	676E-12	252.0
6.0	0.017	319.0	3.0E-9	328.0	0.0077	171.0	7.2E-9	309.0	0.023	340.0	1.4E-9	229.0
6.5	0.024	73.0	127E-12	330.0	0.024	271.0	14E-9	230.0	0.024	87.0	4.1E-9	55.0
7.0	0.028	159.0	3.6E-9	158.0	0.023	4.0	14E-9	144.0	0.062	169.0	2.0E-9	161.0
7.5	0.037	231.0	2.8E-9	205.0	0.060	76.0	22E-9	86.0	0.074	216.0	3.8E-9	212.0
8.0	0.041	275.0	2.3E-9	268.0	0.087	105.0	23E-9	51.0	0.097	288.0	3.2E-9	315.0
8.5	0.028	324.0	2.1E-9	7.0	0.088	146.0	20E-9	357.0	0.195	319.0	8.5E-9	348.0



12.2 Loaded Condition

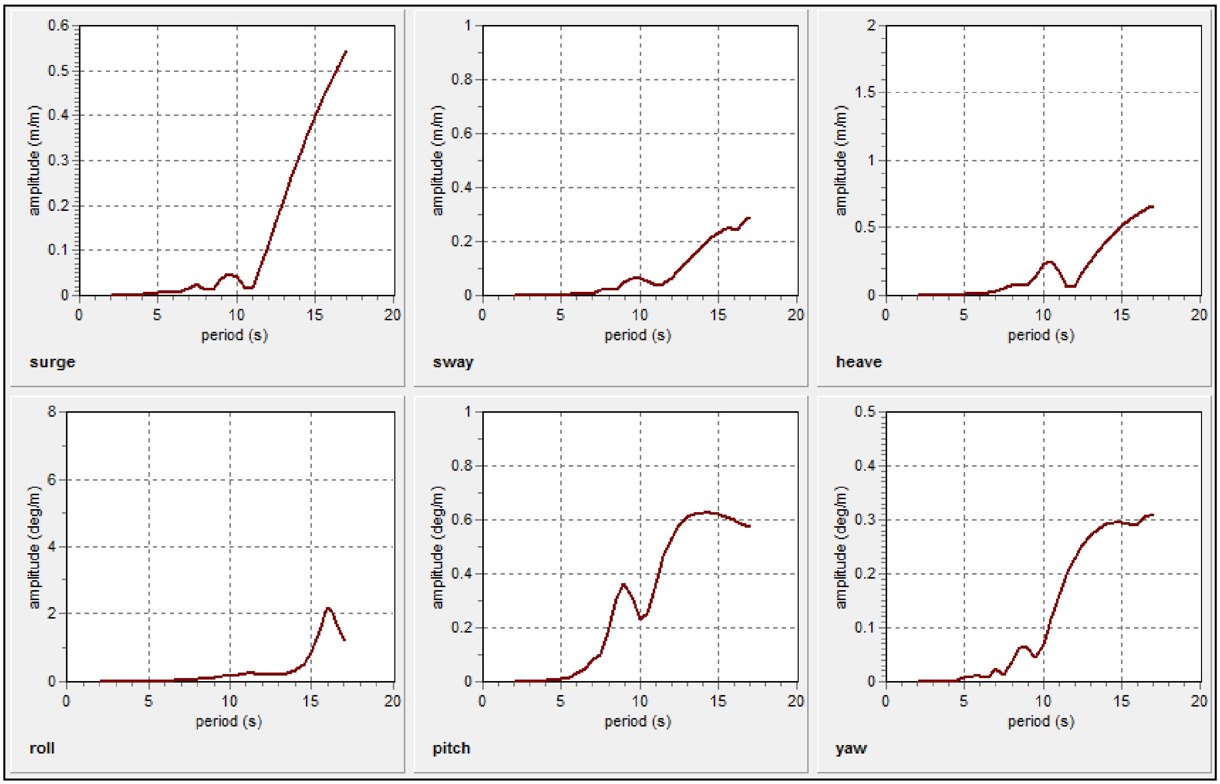
0 Degree

Period	Surge		Sway		Heave		Roll		Pitch		Yaw	
(s)	Ampl. (m/m)	Phase (deg)	Ampl. (m/m)	Phase (deg)	Ampl. (m/m)	Phase (deg)	Ampl. (deg/m)	Phase (deg)	Ampl. (deg/m)	Phase (deg)	Ampl. (deg/m)	Phase (deg)
2.0	0.000	0.0	0.000	0.0	0.00021	44.0	0.000	0.0	0.00035	40.0	0.000	0.0
3.0	0.000	0.0	0.000	0.0	0.00027	323.0	0.000	0.0	0.00056	323.0	0.000	0.0
4.0	0.000	0.0	0.000	0.0	0.0013	22.0	0.000	0.0	0.0029	21.0	0.000	0.0
4.5	0.000	0.0	0.000	0.0	0.0024	117.0	0.000	0.0	0.0049	119.0	0.000	0.0
5.0	0.000	0.0	0.000	0.0	0.0038	33.0	0.000	0.0	0.0088	29.0	0.000	0.0
5.5	0.000	0.0	0.000	0.0	0.0066	252.0	0.000	0.0	0.014	245.0	0.000	0.0
6.0	0.000	0.0	0.000	0.0	0.012	54.0	0.000	0.0	0.025	49.0	0.000	0.0
6.5	0.000	0.0	0.000	0.0	0.016	180.0	0.000	0.0	0.046	181.0	0.000	0.0
7.0	0.000	0.0	0.000	0.0	0.029	282.0	0.000	0.0	0.060	278.0	0.000	0.0
7.5	0.000	0.0	0.000	0.0	0.040	354.0	0.000	0.0	0.110	352.0	0.000	0.0
8.0	0.000	0.0	0.000	0.0	0.063	57.0	0.000	0.0	0.156	43.0	0.000	0.0
8.5	0.000	0.0	0.000	0.0	0.097	92.0	0.000	0.0	0.226	89.0	0.000	0.0



30 Degree

	Surge		Sway		Heave		Roll		Pitch		Yaw	
Period (s)	Ampl. (m/m)	Phase (deg)	Ampl. (m/m)	Phase (deg)	Ampl. (m/m)	Phase (deg)	Ampl. (deg/m)	Phase (deg)	Ampl. (deg/m)	Phase (deg)	Ampl. (deg/m)	Phase (deg)
2.0	0.00016	355.0	0.00012	274.0	0.00015	2.0	0.00025	72.0	0.00031	0.0	0.00011	77.0
3.0	0.00062	14.0	0.00027	48.0	0.00037	4.0	0.00055	193.0	0.00076	13.0	0.00013	193.0
4.0	0.0022	269.0	0.0015	237.0	0.0014	270.0	0.0020	44.0	0.0032	274.0	0.00086	342.0
4.5	0.0032	252.0	0.0014	328.0	0.0020	260.0	0.0019	129.0	0.0042	265.0	0.0022	116.0
5.0	0.0052	180.0	0.0019	181.0	0.0053	193.0	0.0071	21.0	0.012	186.0	0.0066	10.0
5.5	0.0066	5.0	0.0027	3.0	0.0079	23.0	0.012	215.0	0.017	13.0	0.010	190.0
6.0	0.0077	156.0	0.0067	133.0	0.011	141.0	0.015	12.0	0.030	155.0	0.0093	340.0
6.5	0.0099	237.0	0.0094	263.0	0.021	270.0	0.027	99.0	0.048	248.0	0.0083	42.0
7.0	0.016	8.0	0.0028	354.0	0.029	354.0	0.040	192.0	0.078	348.0	0.022	160.0
7.5	0.026	31.0	0.020	69.0	0.051	63.0	0.062	249.0	0.100	53.0	0.013	133.0
8.0	0.012	32.0	0.019	49.0	0.074	101.0	0.079	297.0	0.179	109.0	0.035	3.0
8.5	0.013	263.0	0.019	308.0	0.081	132.0	0.092	335.0	0.304	132.0	0.064	346.0

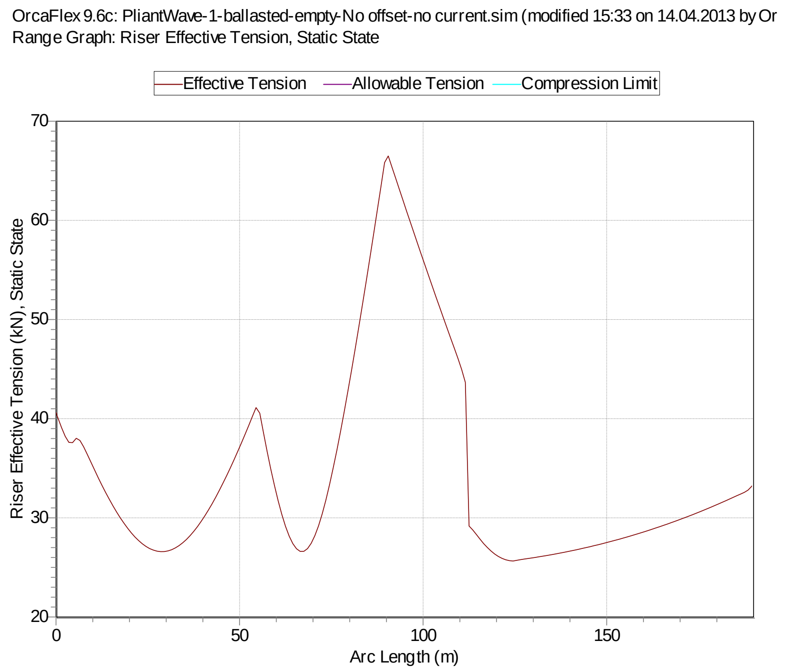


13. Appendix B: Static Analysis Result Graphs

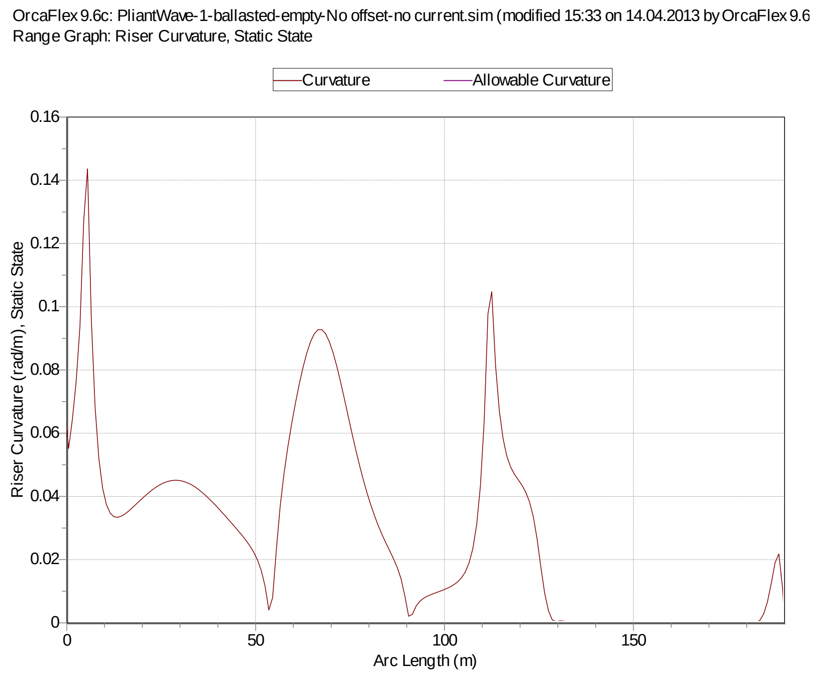
13.1 Pliant Wave configuration

Case 1:

Effective Tension Along the riser

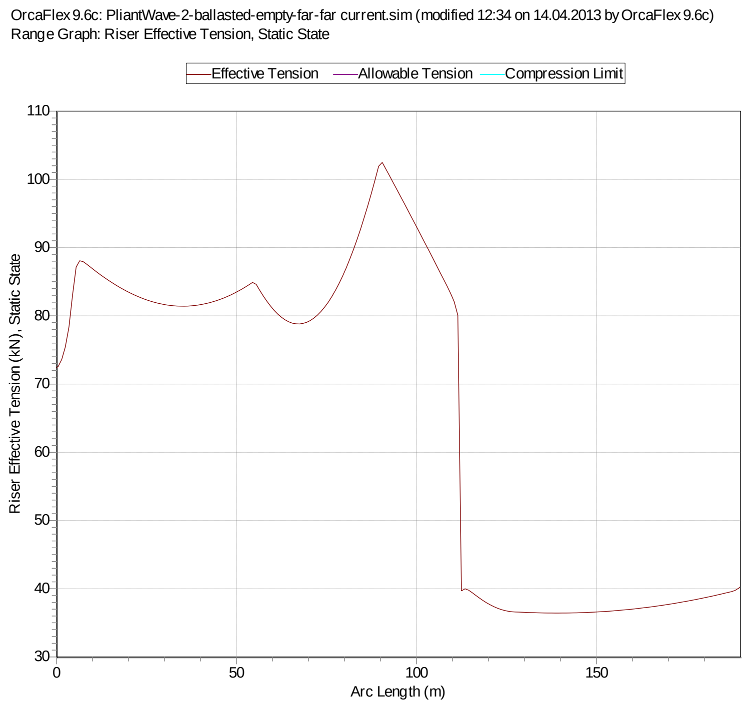


Curvature Along the riser

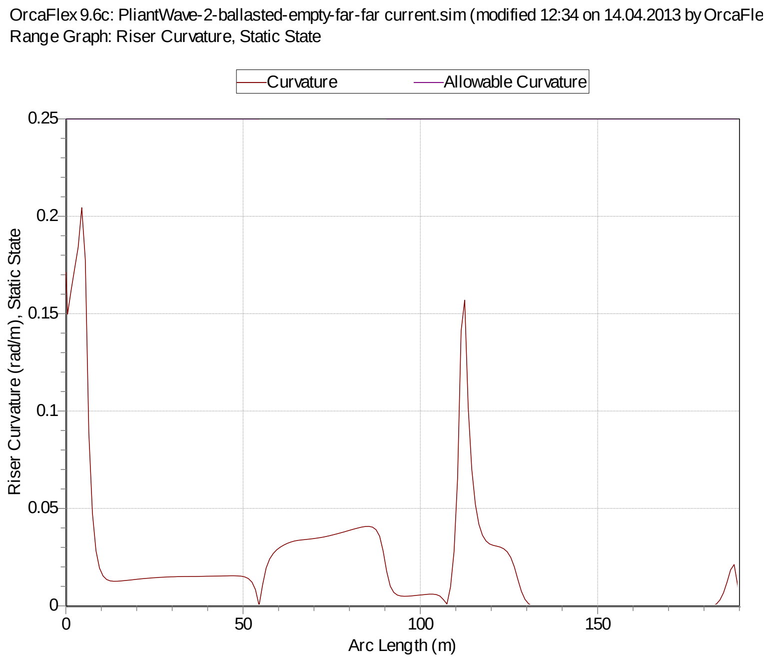


Case 2:

Effective Tension Along the riser

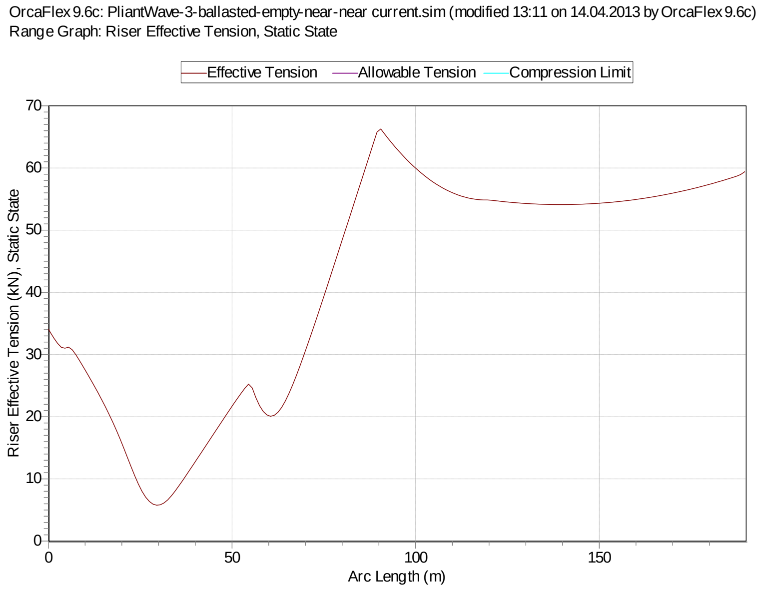


Curvature Along the riser

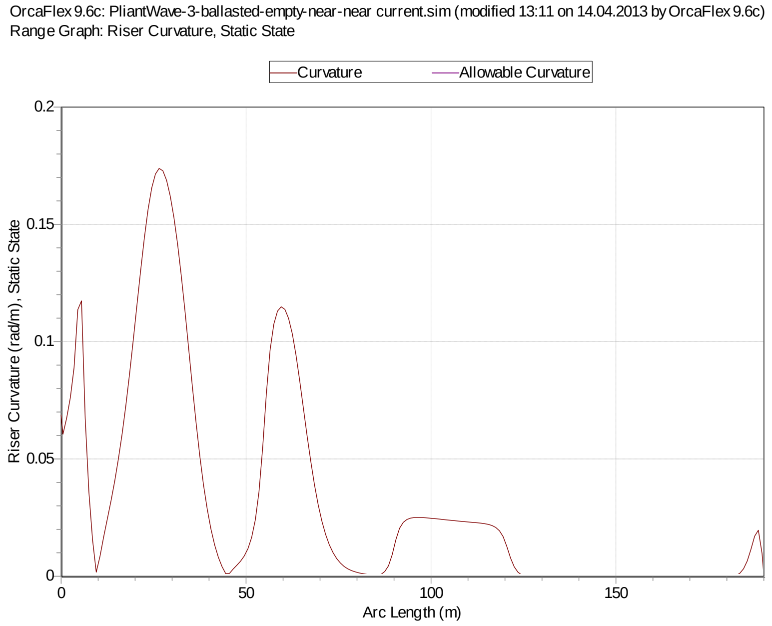


Case 3:

Effective Tension Along the riser

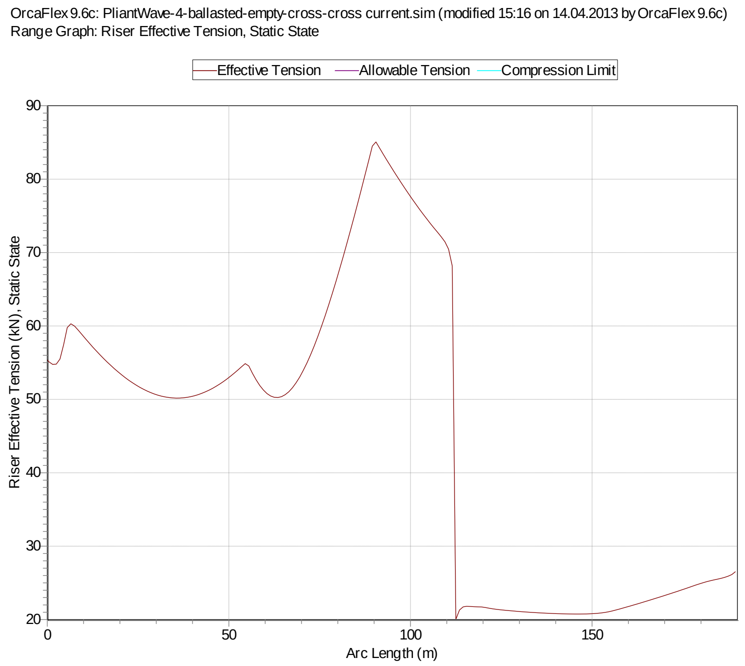


Curvature Along the riser

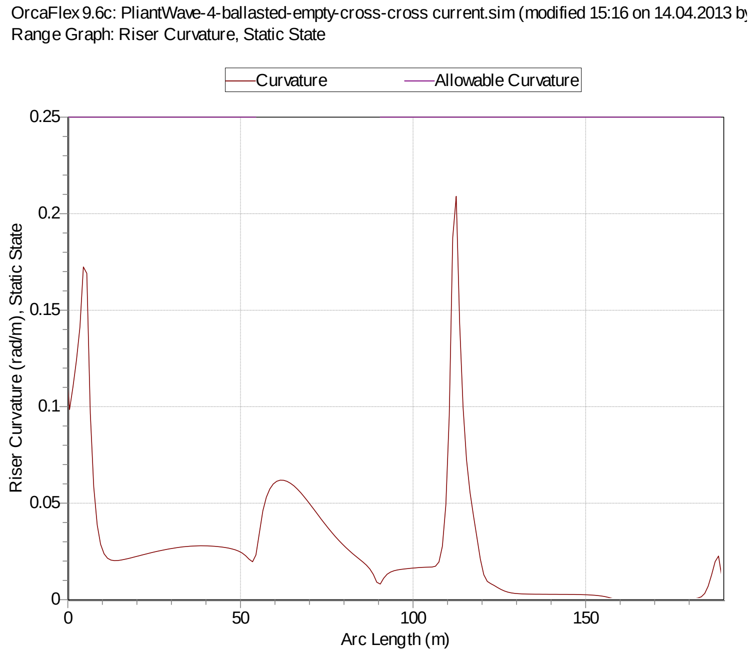


Case 4:

Effective Tension Along the riser



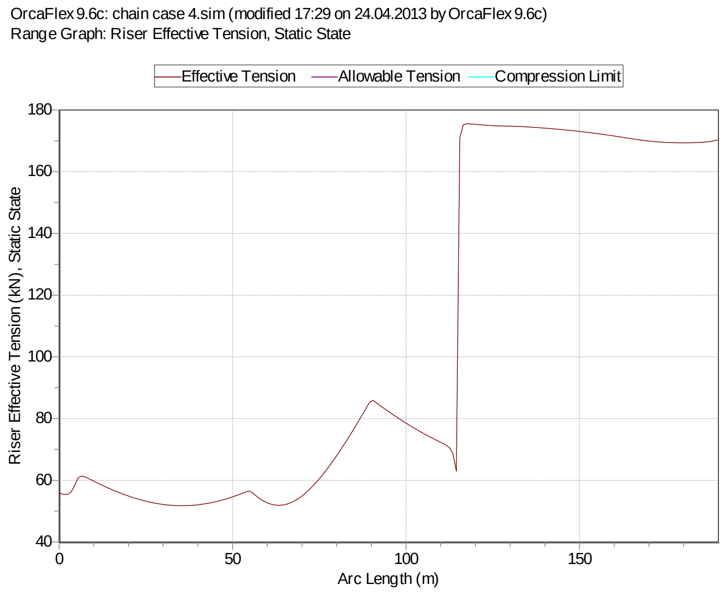
Curvature Along the riser



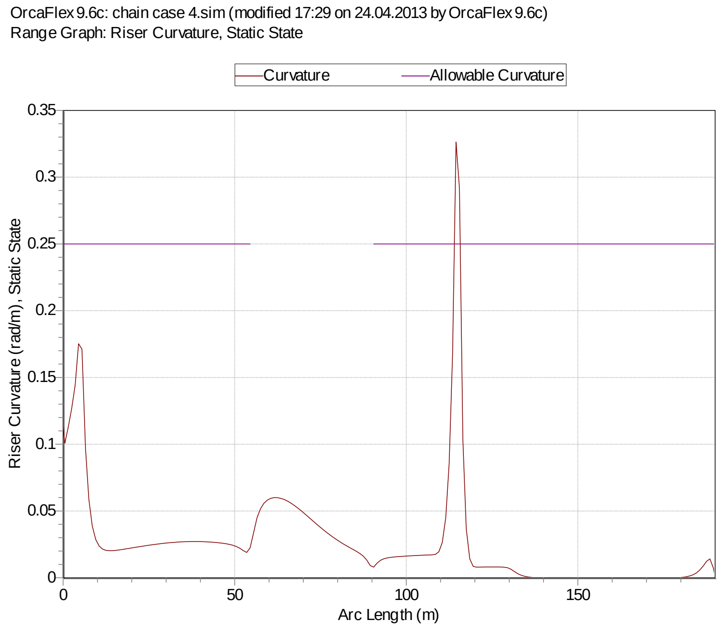
13.2 Touchdown Chain Added Wave Configuration

Case 4:

Effective Tension Along the riser

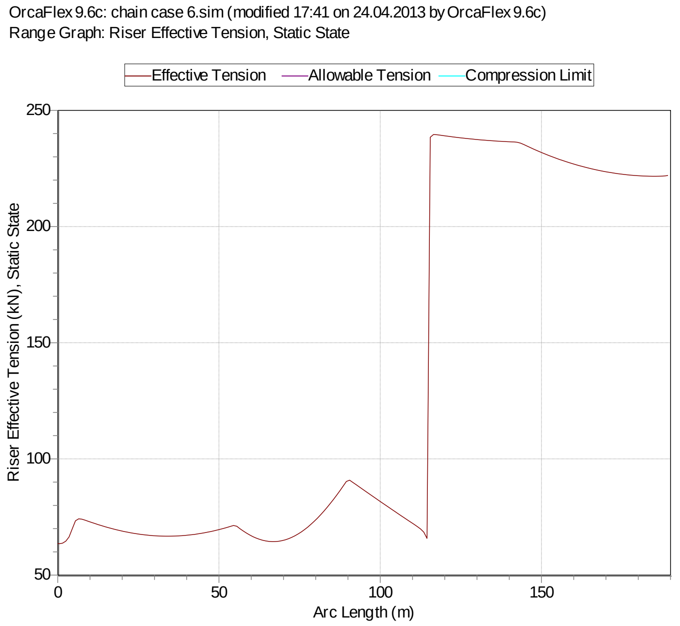


Curvature Along the riser

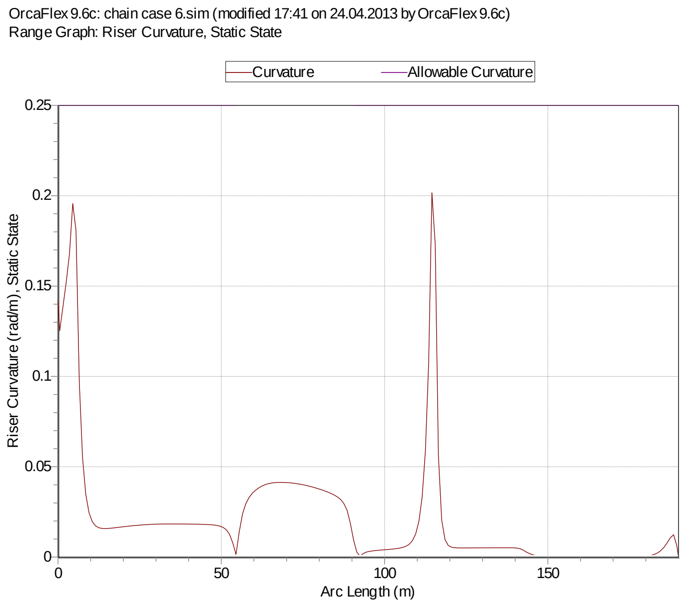


Case 6:

Effective Tension Along the riser

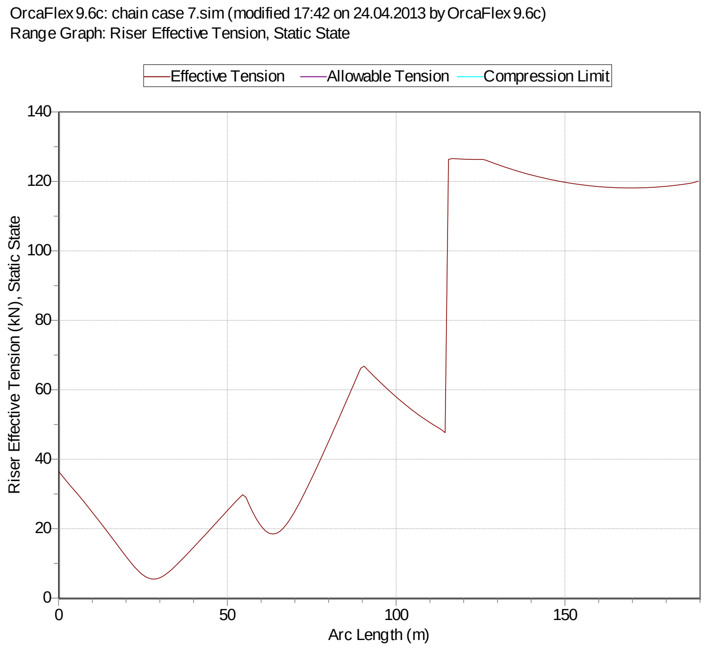


Curvature Along the riser

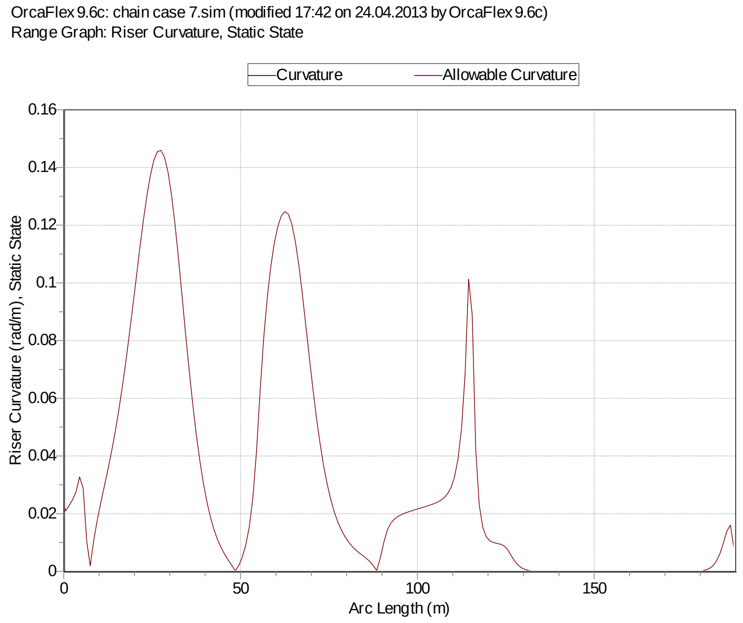


Case 7:

Effective Tension Along the riser



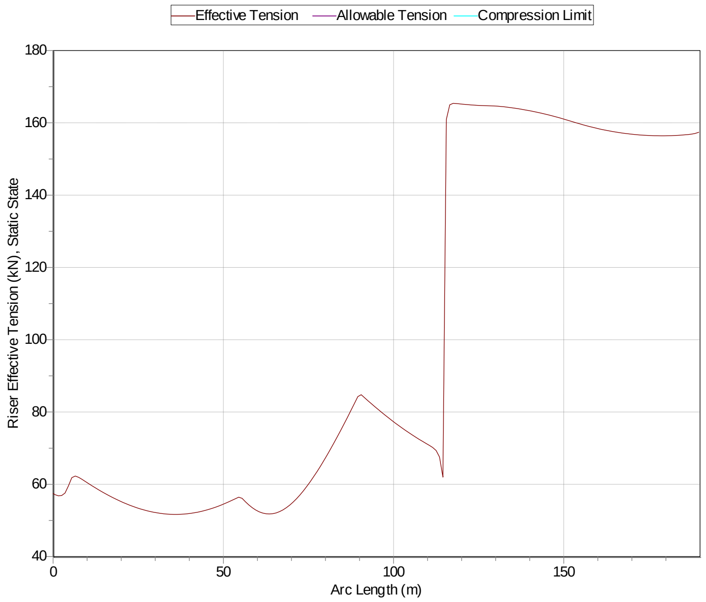
Curvature Along the riser



Case 8:

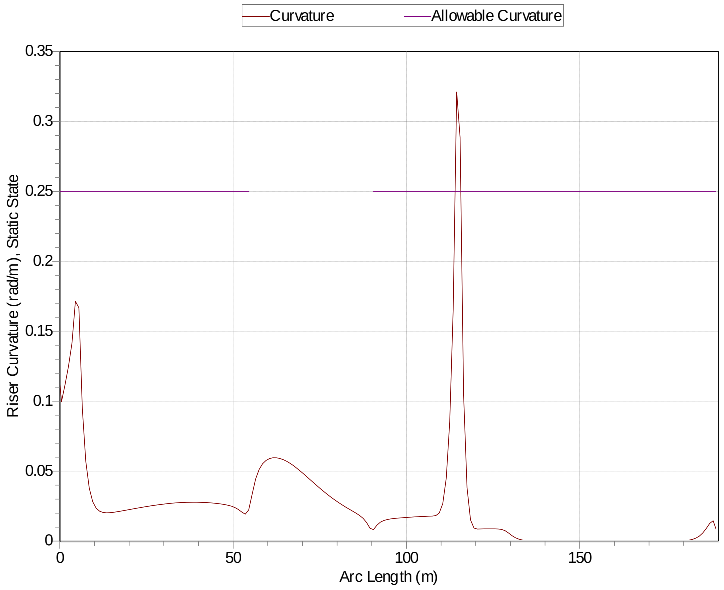
Effective Tension Along the riser

OrcaFlex 9.6c: chain case 8.sim (modified 17:43 on 24.04.2013 by OrcaFlex 9.6c)
Range Graph: Riser Effective Tension, Static State



Curvature Along the riser

OrcaFlex 9.6c: chain case 8.sim (modified 17:43 on 24.04.2013 by OrcaFlex 9.6c)
Range Graph: Riser Curvature, Static State



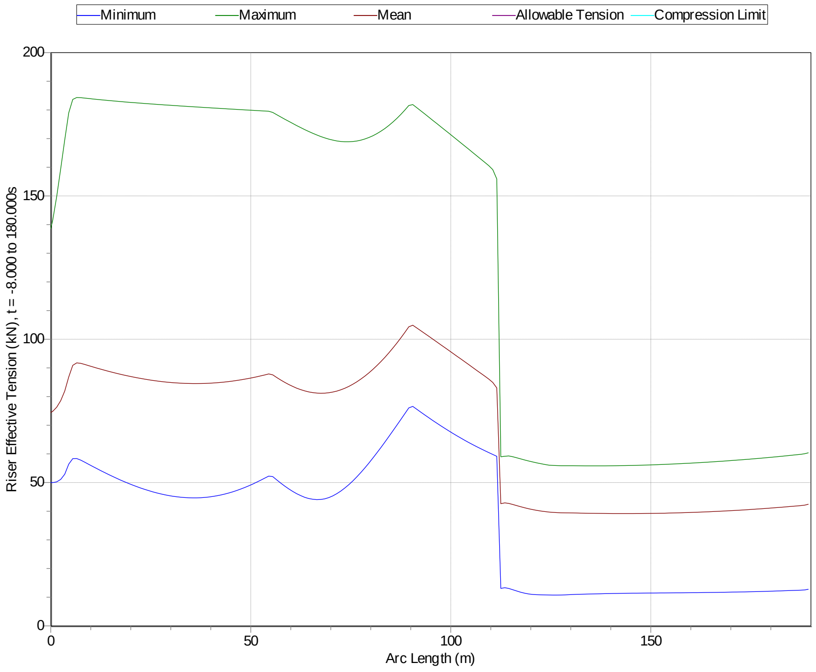
14. Appendix C: Dynamic Analysis Result Graphs

14.1 Pliant Wave Configuration

Case 1:

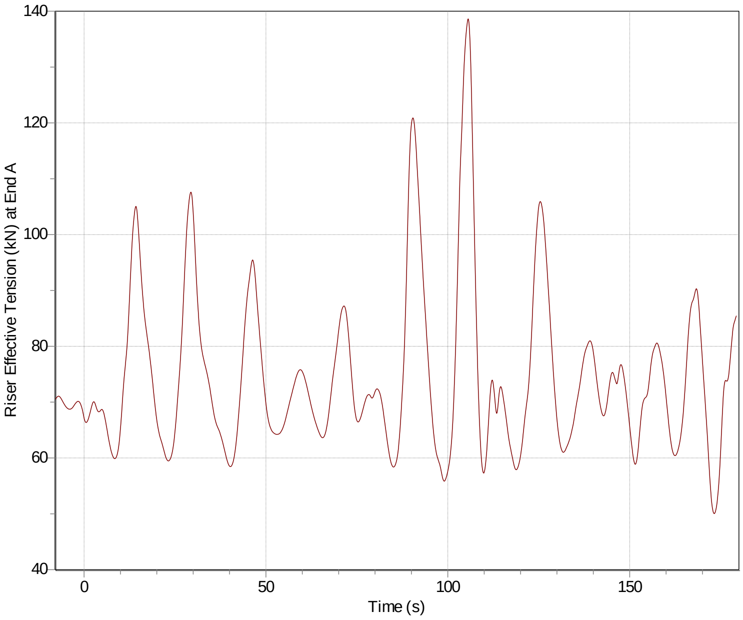
Effective Tension Along the riser

OrcaFlex 9.6c: PliantWave-1-ballasted-empty-far-far current.sim (modified 14:12 on 05.05.2013 by OrcaFlex 9.6c)
Range Graph: Riser Effective Tension, over Whole Simulation

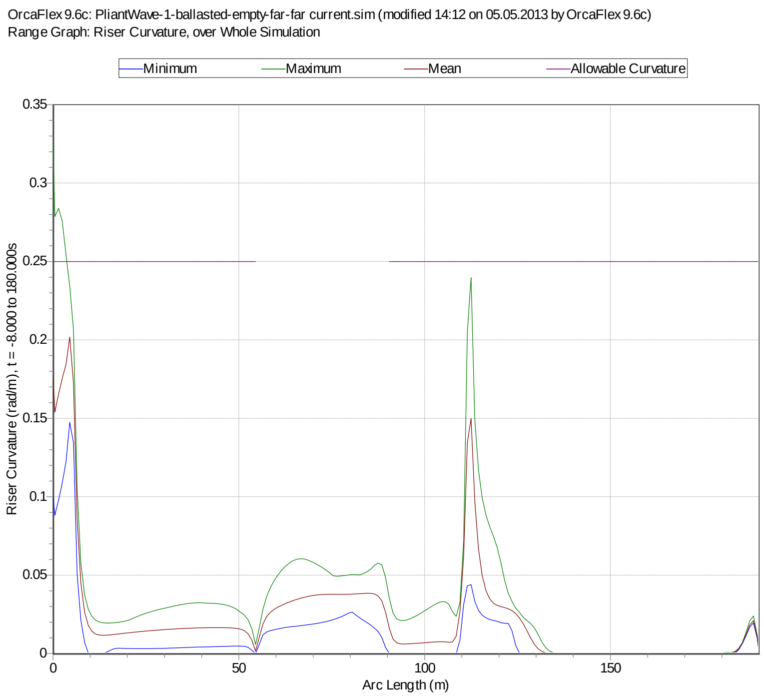


Effective tension in Turret connection during simulation time

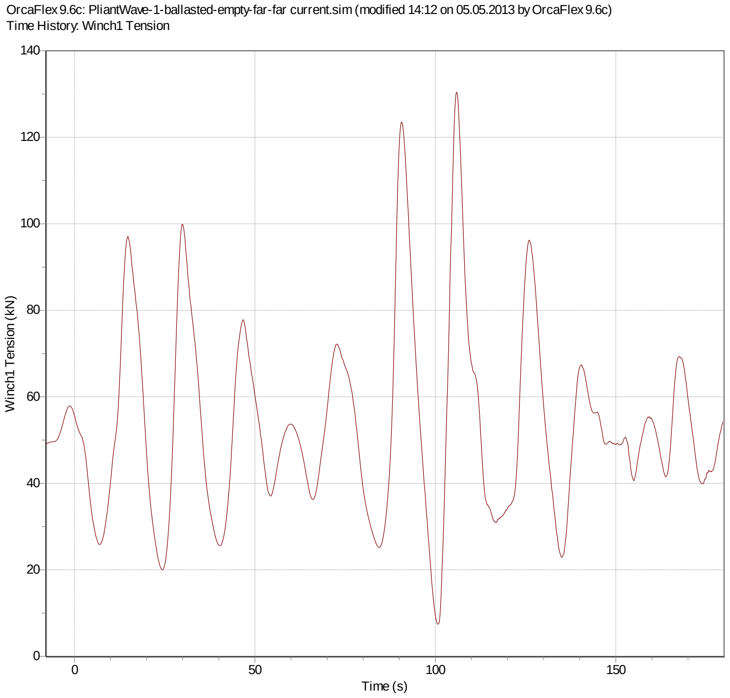
OrcaFlex 9.6c: PliantWave-1-ballasted-empty-far-far current.sim (modified 14:12 on 05.05.2013 by OrcaFlex 9.6c)
Time History: Riser Effective Tension at End A



Maximum and Minimum Curvature Along the riser

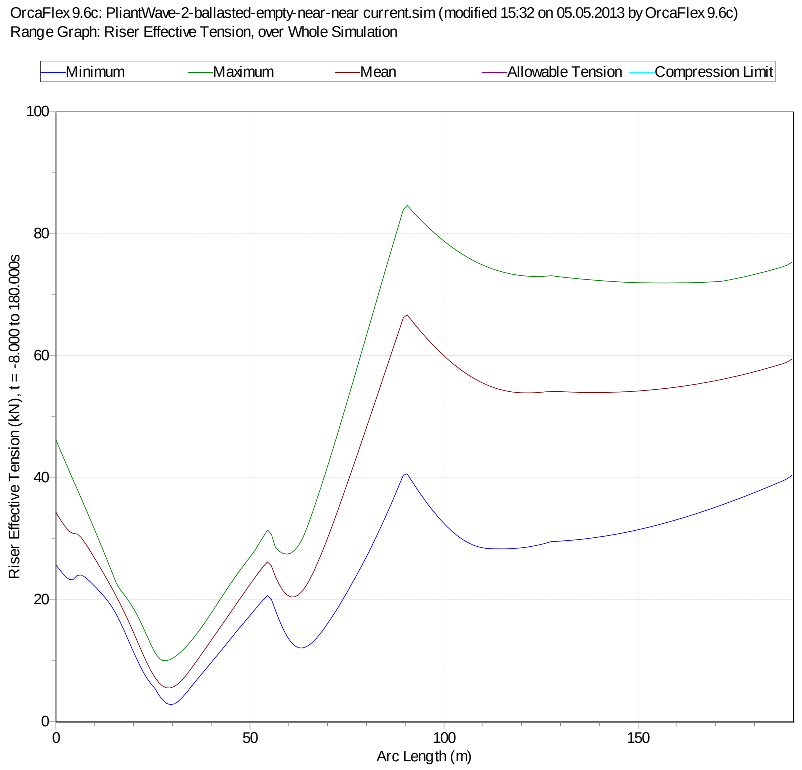


Tether tension during simulation time

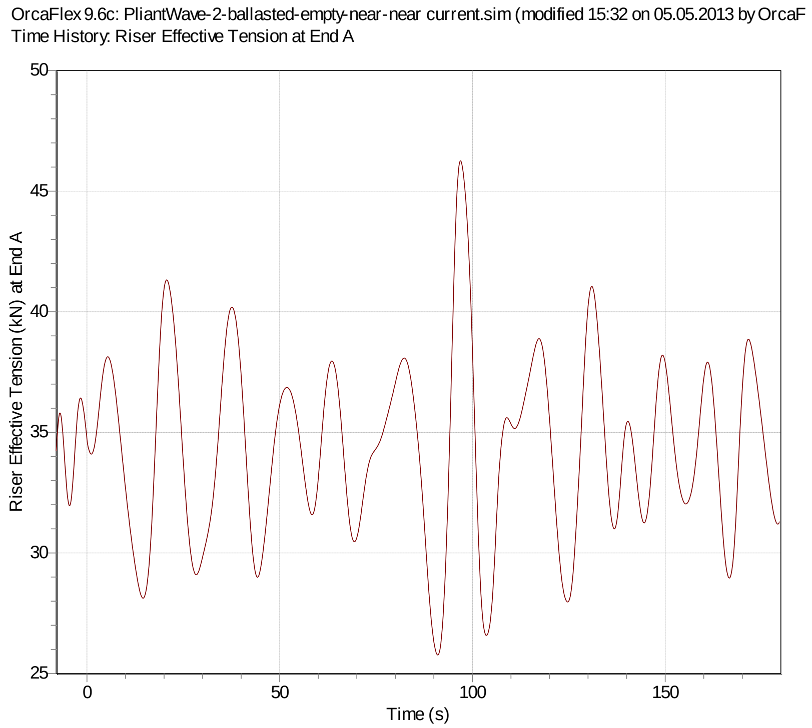


Case 2:

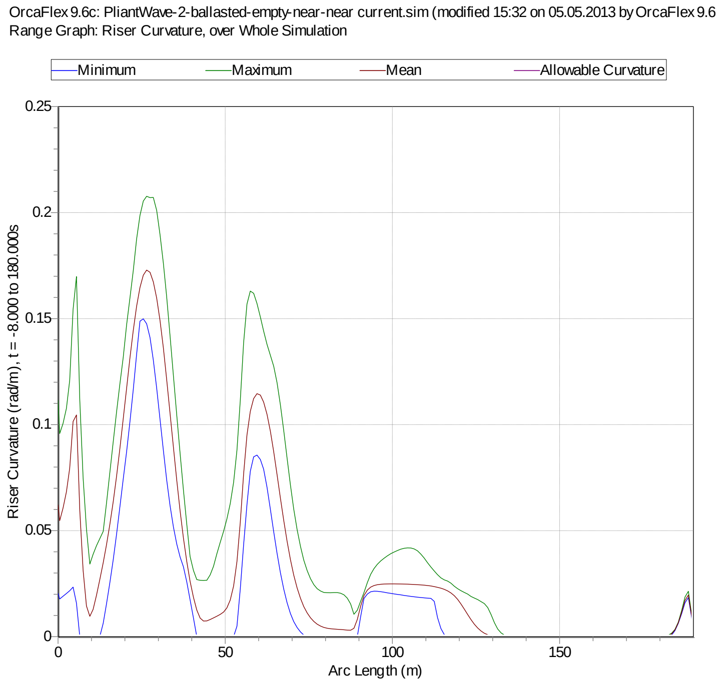
Effective Tension Along the riser



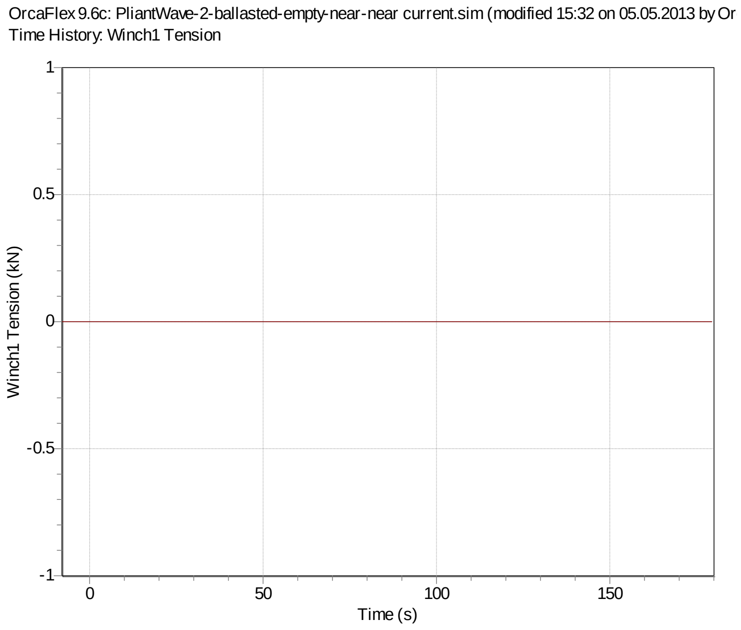
Effective tension in Turret connection during simulation time



Maximum and Minimum Curvature along the riser

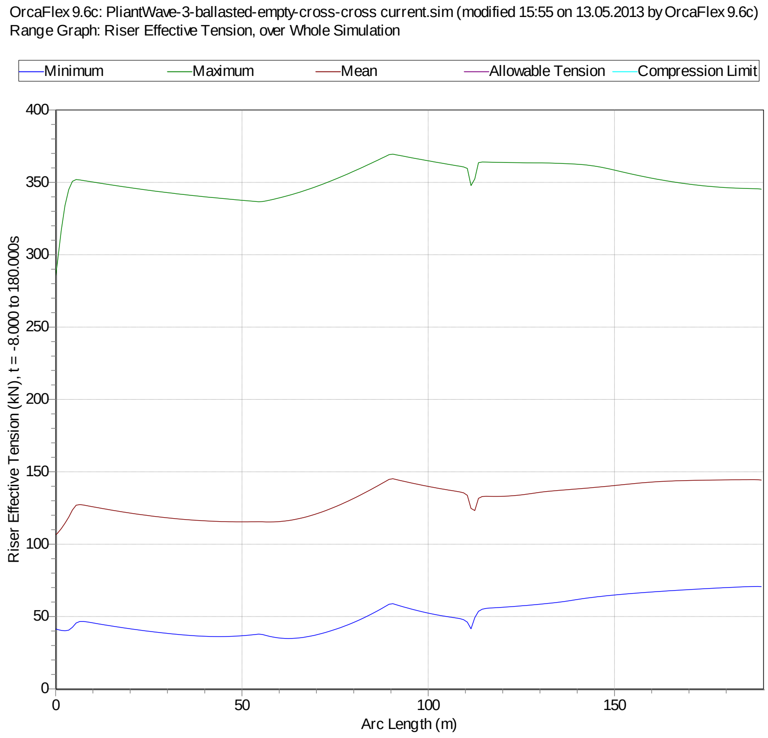


Tether tension during simulation time

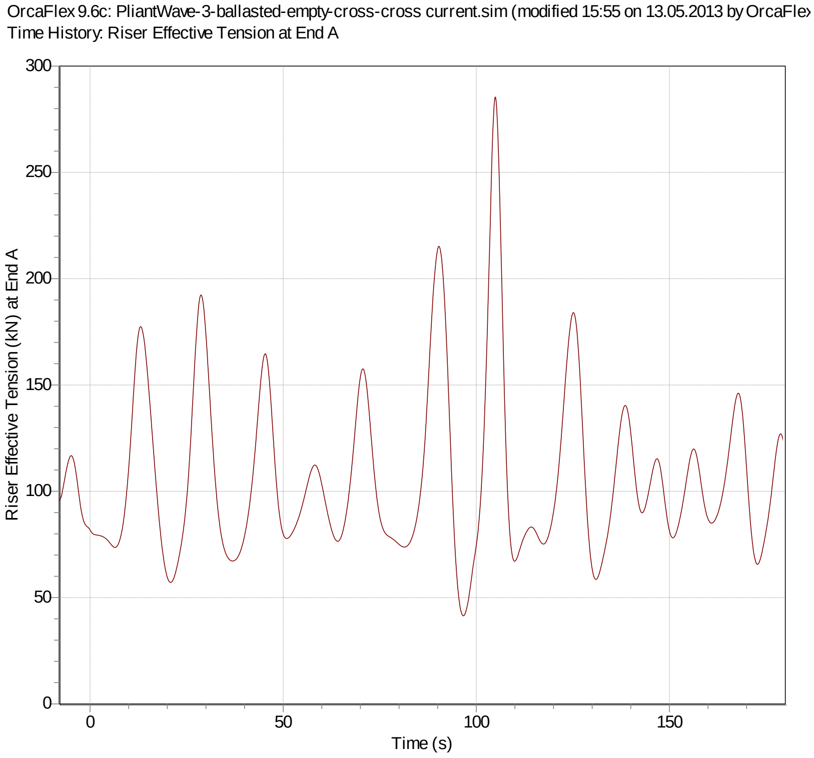


Case 3:

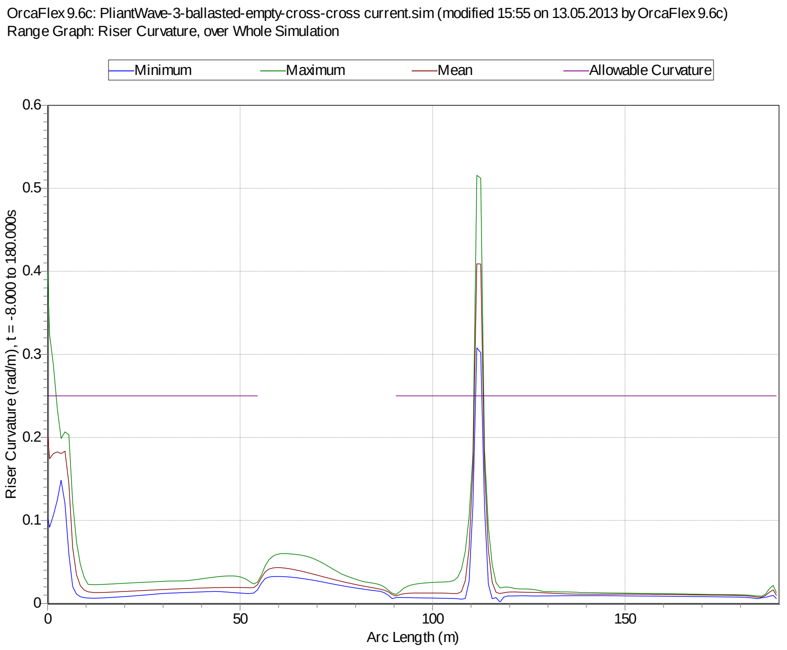
Effective Tension Along the riser



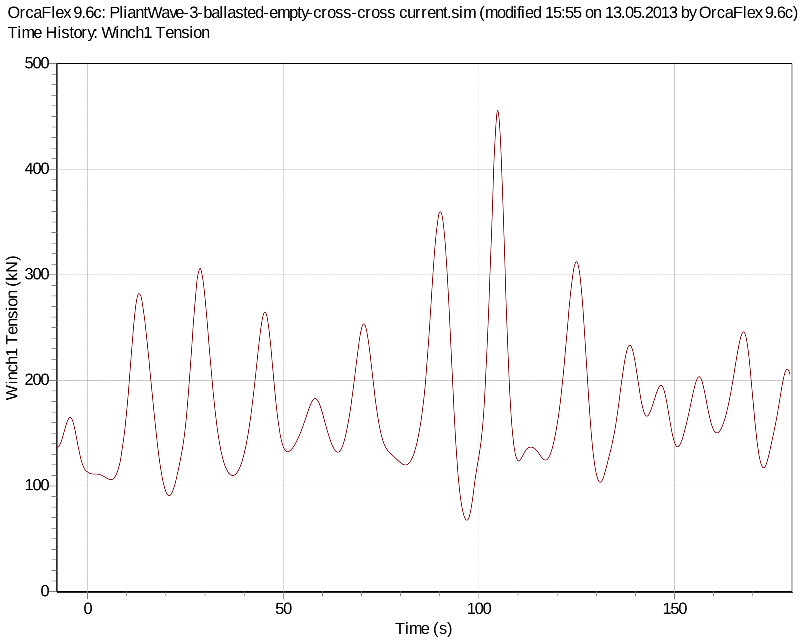
Effective tension in turret connection during simulation time



Maximum and Minimum Curvature along the riser



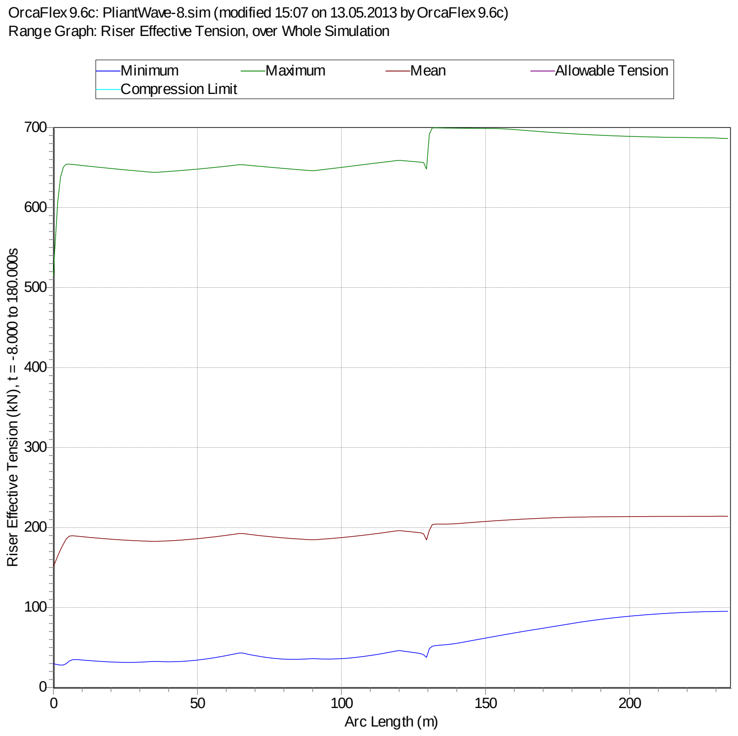
Tether tension during simulation time



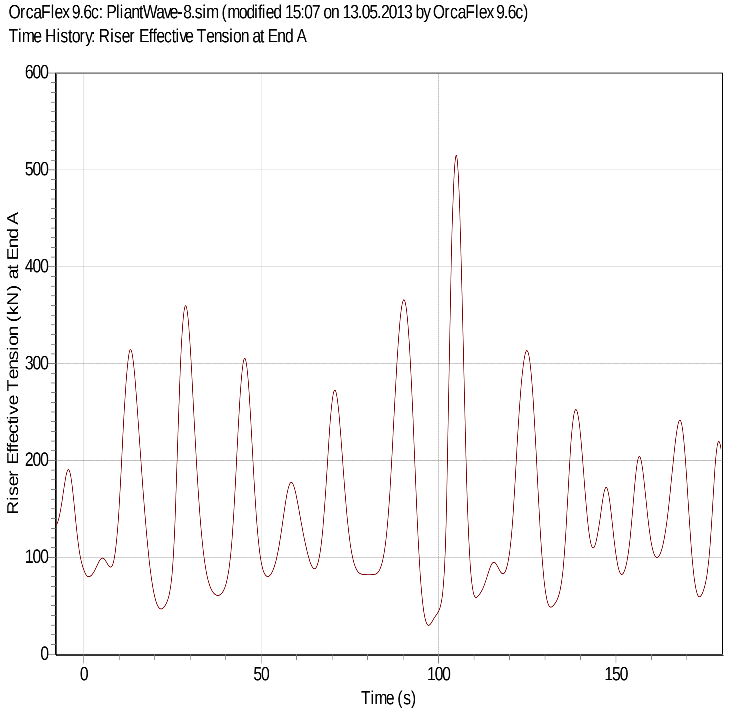
14.2 Double Wave Configuration

Case 6:

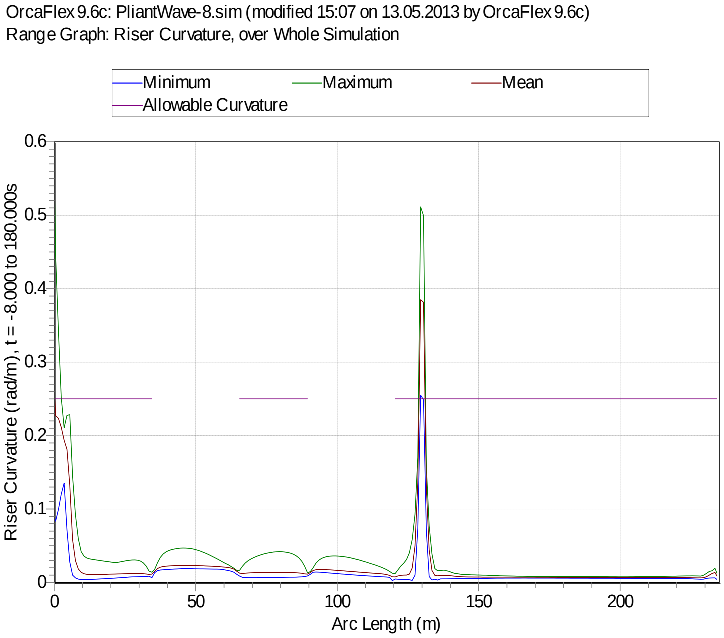
Effective Tension Along the riser



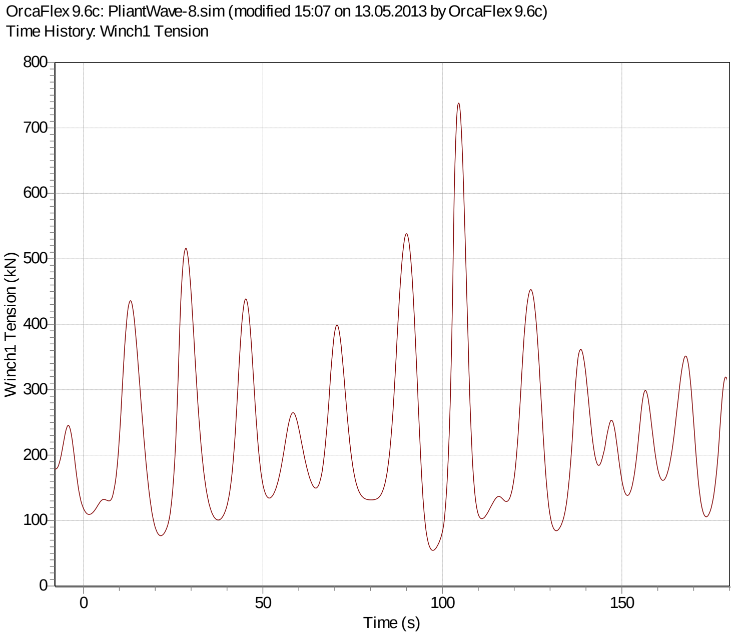
Effective tension in Turret connection during simulation time



Maximum and Minimum Curvature Along the riser

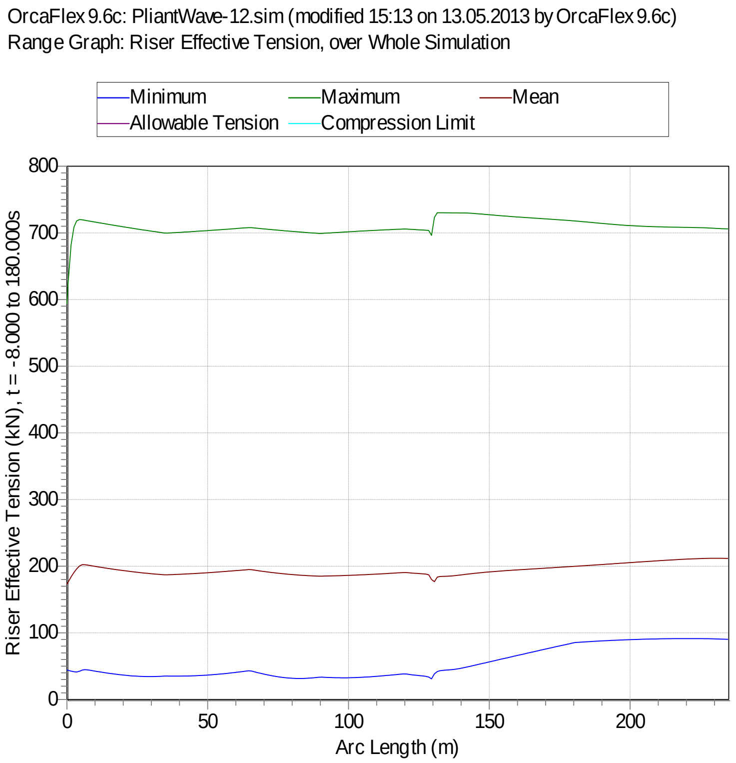


Tether tension during simulation time

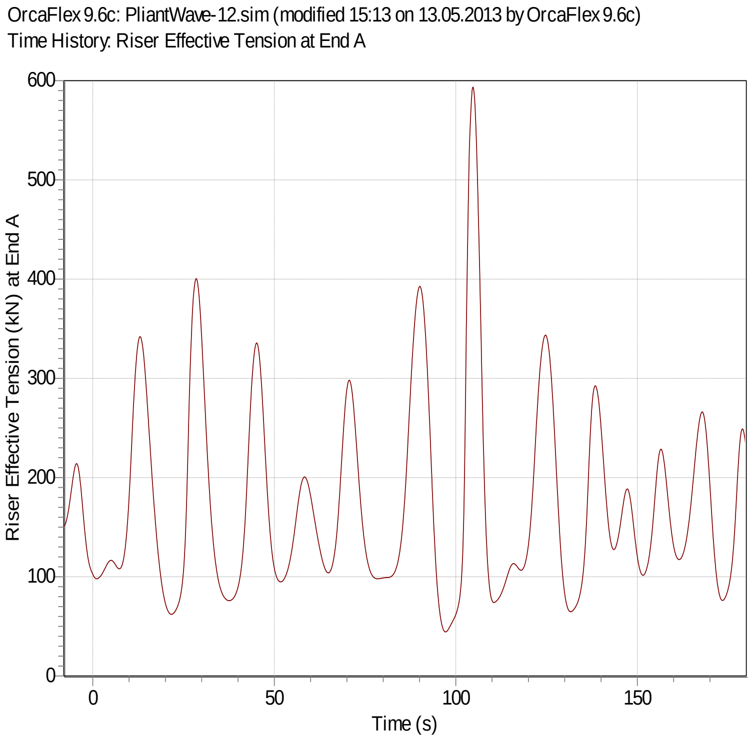


Case 9:

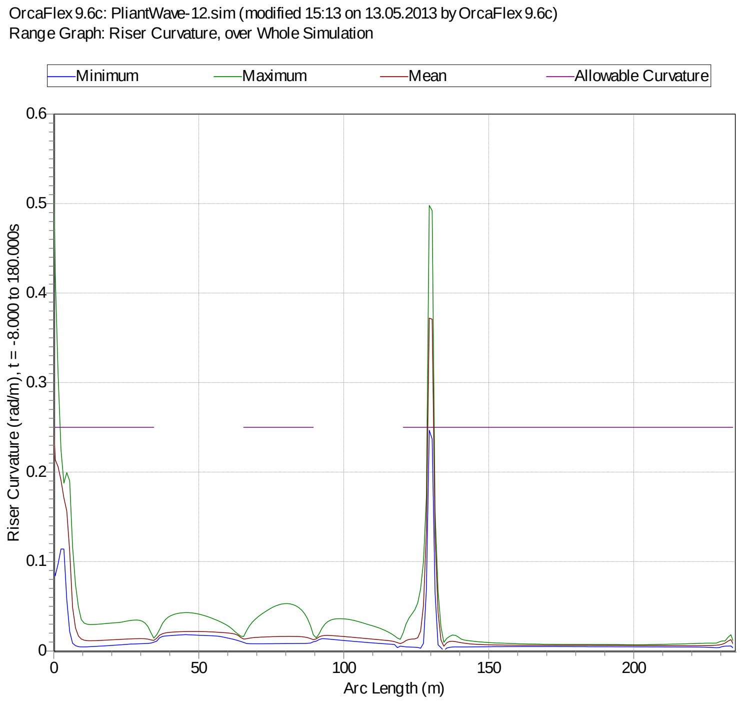
Effective Tension Along the riser



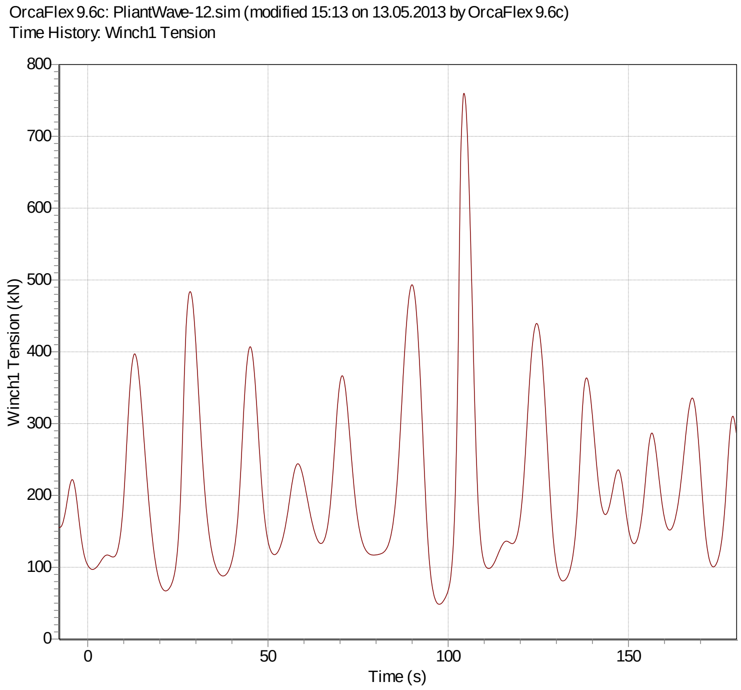
Effective tension in Turret connection during simulation time



Maximum and Minimum Curvature Along the riser



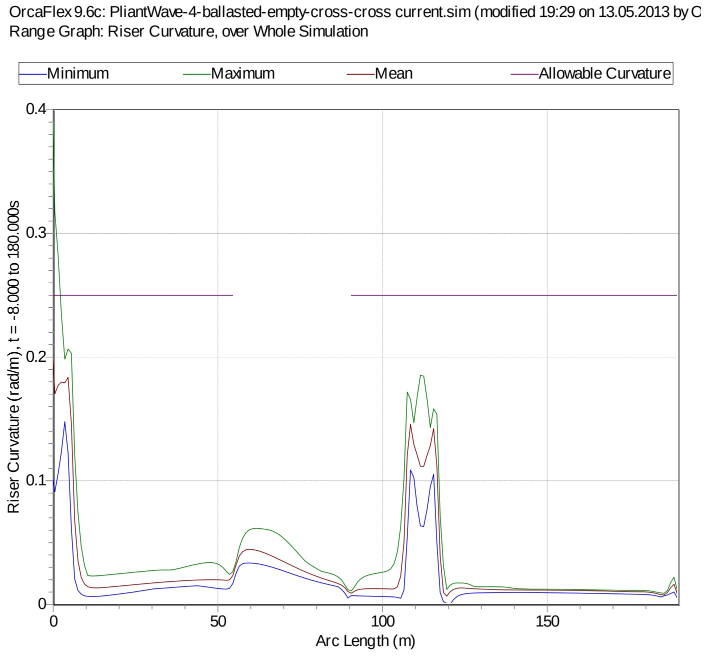
Tether tension during simulation time



14.3 Pliant Wave Configuration with Bend Stiffener at Tether Connection

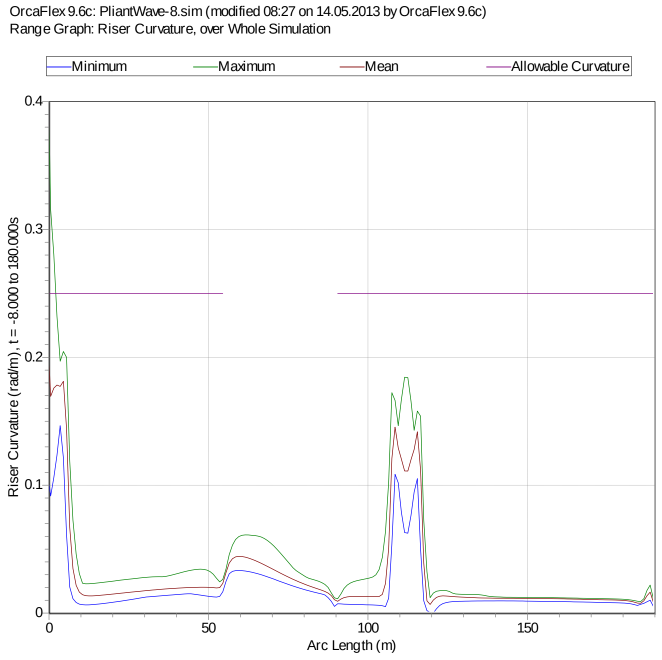
Case 3:

Maximum and Minimum Curvature Along the riser



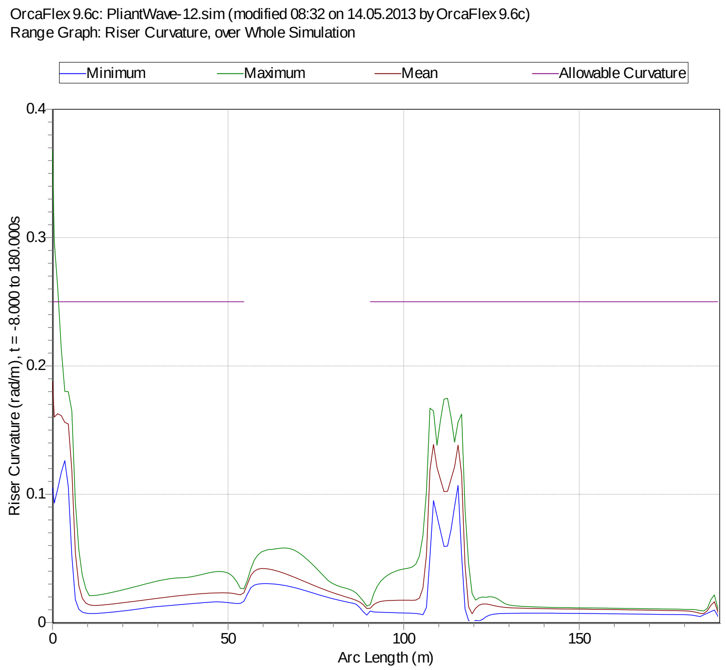
Case 6:

Maximum and Minimum Curvature Along the riser



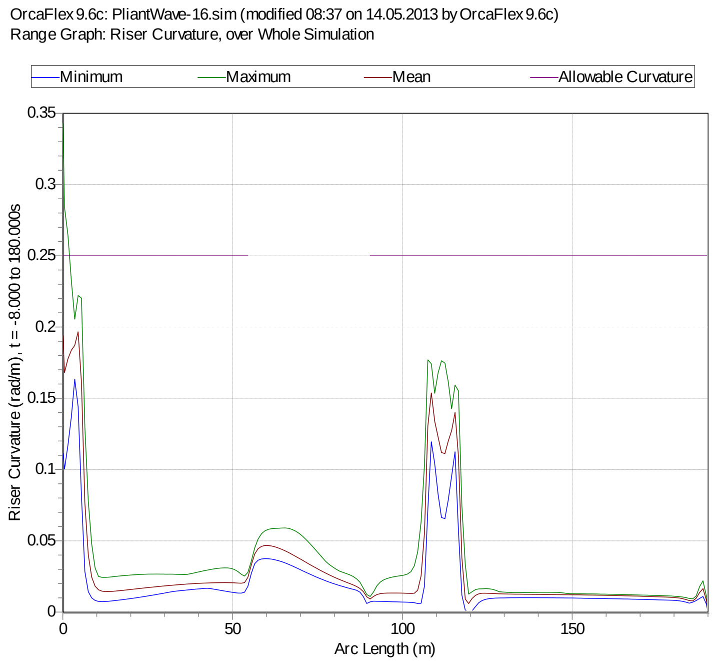
Case 9:

Maximum and Minimum Curvature Along the riser



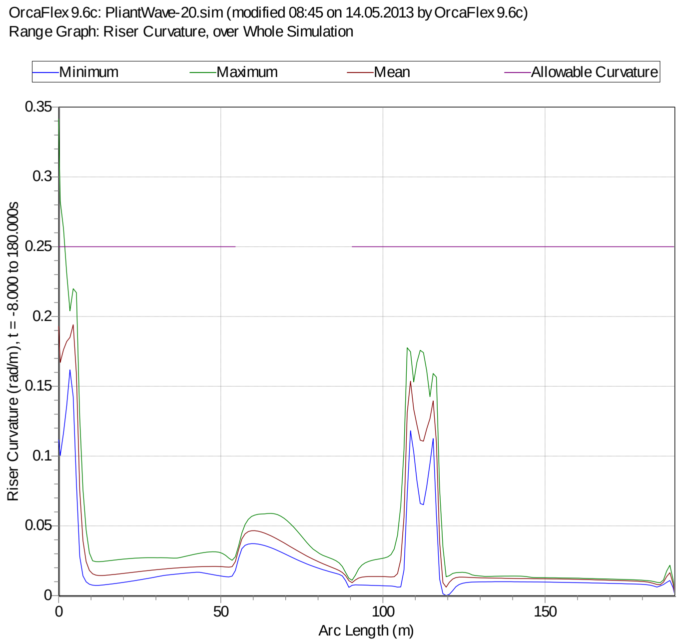
Case 12:

Maximum and Minimum Curvature Along the riser



Case 15:

Maximum and Minimum Curvature Along the riser



Case 17:

Maximum and Minimum Curvature Along the riser