Abstract

Steel catenary risers (SCRs) have been successfully deployed on the Shell Auger TLP in the Gulf of Mexico and will also be deployed on the Shell Mars TLP. There is considerable interest in using SCRs for other applications, in particular for semi-sub based FPS systems.

Petrobras is developing an SCR for installation on the P-XVIII platform, located in the Marlim Field, Campos Basin, in a water depth of 910 meters. The riser will be a dead-ended prototype which will be monitored for a period of up to one year. Subsequently, it will be connected via flexible piping to the P-XXVI platform, located approximately 5 kilometres from P-XVIII.

This paper describes the design, materials, components, specification and installation of the Petrobras P-XVIII SCR. The static/dynamic design, VIV analysis and fatigue analysis methodologies are discussed in detail and results are presented. Important aspects of the flex joint design and specification are discussed. This project represents the first application of SCRs to semi-sub based FPS systems. In addition, it is the first use of SCRs outside of the Gulf of Mexico.

Introduction

Petrobras uses flexible risers extensively in all of their FPS installations. However, there are technical and economic limitations for large diameter flexible risers in deep waters (normally used for oil and gas export by Petrobras). In the case of Petrobras XVIII (P-XVIII), it was necessary to use two 12 inch oil export flexible risers instead of a single 16 inch flexible line, due to technical limitations in manufacturing the bigger line. Steel Catenary Risers (SCRs) can provide a technically feasible alternative.

In addition to the manufacturing limitations mentioned above, significant potential savings may be achieved by deploying SCRs instead of flexible risers. This is due to the high procurement costs for flexible lines, which cannot compensate for their lower installation costs. A recent cost estimate for the next five FPS platforms to be installed in the Marlim and Albacora Fields (which will require 17 export/import risers ranging from 8 inch to 16 inch ID) indicates a difference of around US$70 million in favour of the SCR solution.

Project Background

Currently there are only two installed SCRs, both on Shell's Auger TLP [1] (the SCRs for the Mars TLP will be installed in the first six months of 1996). The behaviour of a semi-submersible in terms of movements and displacements is significantly different from a TLP and implies a different operational environment for the riser. Because the static displacements are larger and the dynamic motions more severe, it is necessary to employ higher tension in the SCR, in order to reduce bending in the sag bend.

Therefore, for the case of the P-XVIII, a detailed evaluation was mandatory. Five different deep water scenarios in the Campos Basin were analysed by the University of São Paulo [2]. These studies concluded that an SCR installation was feasible.
and it was therefore decided to initiate detailed design of an SCR for the P-XVIII FPS.

The SCR will be part of a 10 inch import gas line (16.2 MPa working pressure), connecting FPS P-XVIII to P-XXVI. Although the P-XXVI will not be installed until mid 1997, the plan is to install the SCR at P-XVIII in mid 1996 and monitor it for a period of up to one year. The monitoring will increase knowledge of SCR behaviour for FPS applications, allowing for possible optimisation of the design process and giving increased confidence in future SCR projects.

A flex joint will be used at the top of the riser, as this is a field proven solution (Shell's Auger TLP). Oil States Industries (OSI) was contracted to supply the flex joint. It was also their responsibility to perform the detailed design of the SCR, prior to starting the design and fabrication of the flex joint. OSI subcontracted MCS International to perform the detailed design of the SCR. The following sections describe the key aspects of the riser specification and SCR system analysis (including the flex joint).

**Riser Specification**
A schematic of the SCR design is given in Fig. 1. The riser is connected above the MWL at the deck level of the FPS. Note that this configuration is required due to substantial difficulties in connecting the SCR to a pontoon of the already installed FPS. The riser length to the mean seabed touchdown point is 1319 metres. The SCR is connected to the FPS at a mean top angle of 20° to the vertical. No VIV suppression devices are used.

The riser is to be constructed of welded pipe, in accordance with API Spec 5L, grade X60 steel. The outside diameter is 273mm (10.75 inch) with a wall thickness of 20.6 mm (0.812 inch). The entire pipe will be coated with a fusion bonded epoxy, with an additional anti-abrasion coating at the seabed touchdown area. Anti-fouling cladding will be used in the upper 100m of the riser to prevent marine growth.

The cathodic protection system for the SCR will be based on impressed current provided from the FPS. Zinc sacrificial anodes will be used for the portion of the riser on the seabed. The cathodic protection system is designed in accordance with DnV RP B401 [3].

**Flex Joint**

**Description.** Schematics of the flex joint configuration and design are given in Figs. 2 and 3 respectively. The flex joint incorporates alternating laminations of spherically shaped rubber and steel components, within a steel support structure, which includes an extension for welding to the main riser. The flex joint reacts, at any angle within the performance envelope, to the tension forces and angular deflections imposed at the termination of the riser. The design and analysis sequence is described in the following sections. Note that the steel and rubber laminations are described in the following sections as the flex element.

**Preliminary Analysis of Flex Element.** The initial flex element design and material properties were selected based on prior configurations with similar performance requirements. Then, using SPHERE, an in-house closed form solution design program, the flex element configuration was refined iteratively to minimise the strains and meet the stiffness requirements. This was followed by an initial 2D ABAQUS finite element (FE) analysis to assess stress levels in the reinforcements and strains in the elastomer. Using results of the 2D FE analysis, a preliminary S-N based fatigue analysis was performed on the elastomer pads.

**Detailed Analysis of Flex Element.** The elastomer compound selected was used to develop a material model for the FE analysis. A two coefficient model was derived and employed in the 2D and 3D analyses of the flex element. This was followed by development of optimised 2D and 3D flex element models. FE grid bias ratios were established and the boundary and load conditions were added. The completed 2D and 3D models were subjected to an axial load. The resulting stress and strain data permitted comparison with each other and with the initial SPHERE output. Using the 2D and 3D FE models, a large deformation, nonlinear FE analysis was performed with full pressure, tension and conical rotation. This provided rubber stress/strain data and reinforcement/nipple extension stresses due to the applied loading conditions. The design was then further optimised to minimise the Von Mises stresses.

Using the optimised elastomer stress/strain data obtained from the above analyses and the fatigue spectrum for the riser developed by MCS, a detailed S-N fatigue analysis was performed on the elastomer pads. Additionally, the fatigue life of the reinforcements and the flex joint nipple extension was evaluated using the cumulative damage method (Miner's Rule), based on each component's peak principle stresses obtained from the FE analyses.

**Detailed Analysis of the Flex Joint.** Upon completion of the flex element analyses, the complete flex joint assembly was modelled and analysed. Both FE and classical stress analyses were employed to verify the structural integrity of the flex joint's components. Three separate models were developed, representing various combinations of the flex joint components. These models were 2D axisymmetric with specially formulated elements to simulate 3D loading conditions.

The working pressure, axial tension and bending moment loads corresponding to the extreme loading condition were imposed on all three models. These analyses provided the Von Mises stress data required for a classical stress analysis evaluation. Since all elastomers have some inherent damping, material testing was performed to determine static to dynamic
ratios at different angular amplitude. While this effect does not increase maximum stresses, it was incorporated into the fatigue analysis since it does increase alternating stress ranges. The potential for lift-off from the receptacle was also assessed. The flex joint was further analysed for flex element stability and accidental load case criteria.

This completed the design and analysis of the flex joint and was followed by the development of detailed drawing and material specifications for the manufacture of the flex joint.

**SCR Design and Analysis**

**General.** The overall design methodology used for the SCR is shown schematically in Fig. 4, and involves the following main phases:

(i) Sizing
(ii) Static Design
(iii) Dynamic Design
(iv) VIV Analysis
(v) Fatigue Analysis
(vi) Flex Joint Analysis
(vii) Installation Analysis

This section addresses Phases I to V of the design process, while Phases VI and VII are dealt with elsewhere in this paper.

**Configuration Design.** The main parameters defining the SCR configuration design are wall thickness, top connection angle and riser length to touchdown point (TDP). These were selected initially based on design Phases I to III (sizing, static design and dynamic design). The wall thickness was selected to provide sufficient strength to resist internal pressure, external pressure, hydrostatic collapse under bending and tension, propagation buckling, corrosion and on-bottom stability. A corrosion allowance of 3.0 mm was used.

In the wall thickness sizing the critical parameter was found to be buckle propagation requirements. Note that the SCR is designed to prevent buckle propagation without the use of buckle arrestors.

The static/dynamic design of the SCR was based on a comprehensive set of design load cases, as listed in Table 1. Design criteria were developed for each of the loading conditions and were based on allowable Von Mises stresses in both tension and compression. Initially an SCR design based on a top connection angle of 15˚ was selected. This configuration satisfied all static/dynamic design criteria, but was subsequently changed to a 20˚ top angle design as a result of VIV considerations (see following section).

The main results from the static/dynamic design of the 20˚ SCR configuration are as follows:

1. The mean and maximum tensions at the vessel connection are 1057 kN and 2113 kN respectively.
2. The maximum rotation of the flex joint from the mean position is 18.8˚. This occurs for the Accidental B load case (see Table 1) and is largely due to the initial 14.4˚ tilt of the FPS with one compartment flooded.
3. The maximum Von Mises stress in the pipe is 286 MPa or 69% of yield stress.
4. In all load cases the tension in the riser was always positive, i.e. no effective compression occurs in the riser.

Note that all analyses in the static/dynamic phase were performed with the MIT program SHEAR7, which was developed based on a comprehensive experimental program. The VIV analysis methodology was developed in consultation with MIT, since many of the inputs to the program are empirical based parameters [4]. Note that the capabilities of the current version of the program are limited to vertical risers and therefore the analysis methodology required the development of an equivalent vertical riser model for the SCR configuration.

In the analysis, a total of 13 current profiles were used, based on yearly fatigue current data for the Marlim Field. In this location the surface current is largely uni-directional with an 83% probability of occurrence for the South-East to the South-West sector. As the riser lies largely in the North-South plane, the fatigue currents induce vibrations in the out-of-plane direction. Consequently, VIV induced bending moments, stresses and fatigue damage are in the out-of-plane direction, which is at 90˚ to the plane where most of the wave induced damage occurs.

The calculated fatigue life, due to VIV effects only, for the 15˚ SCR design, was found to be sufficiently low so as to require the use of VIV suppression devices. Increasing the riser top connection angle to 20˚ gave a substantial increase in fatigue life. It was therefore decided to use the 20˚ SCR design without any VIV suppression devices, such as the strakes used on the Auger SCRs. The increase in fatigue life with top angle is mainly due to the increased riser tension, which amplifies the wavelength of the VIV response modes. This, in turn, reduces the modal curvature, thereby reducing stress amplitudes and increasing fatigue life.
Important results from the VIV analysis stage of the design process are as follows:

1. In general, the fatigue current profiles will not cause a dominant single mode response. For the critical profiles, the response will be partially single moded and partially multi-moded.

2. The maximum VIV damage occurs near the TDP region rather than in the wave zone. This is because the riser tension is lower at the TDP which gives shorter modal wavelengths and increased stress amplitudes.

**Fatigue Analysis.** The fatigue analysis methodology was based on a combined time and frequency domain approach. The time domain program (FLEXCOM-3D) was used to derive nonlinear static riser configurations, with the fatigue loading applied in the frequency domain (FREECOM-3D). The fatigue loading consisted of irregular seastates with combined first and second order vessel motions, and fatigue current profile. Note that the first and second order vessel motions were applied in a single analysis as it is unconservative to analyse the effects separately and simply add the respective damages.

The use of the frequency domain method was verified with time domain irregular sea analyses. Critical issues include seabed modelling, finite element discretisation and selected solution frequencies. The results of the time domain runs compared well with the frequency domain results, as shown in Figs. 5 and 6. These plots show comparisons for one critical seastate of bending moment standard deviations from both time and frequency domain for the TDP and splash zone regions. This verifies the use of the frequency domain method for this SCR fatigue analysis.

The second order vessel motions are critical in determining the fatigue life of the riser. To accurately determine the second order motions and periods for each seastate, time domain mooring analyses were performed with the Bureau Veritas program ARIANE. A total of 27 seastates were used, that is 9 seastates in 3 directions (two inline directions and one transverse direction).

The fatigue life calculations use the Palmgren-Miner methodology, based on both Rayleigh distribution of stress ranges and Dirlik’s bi-modal distribution [5]. The S-N data for the fatigue analysis is based on the API X curve, with a stress concentration factor of 1.45. A further scaling factor was used in the splash zone to account for the underprediction of stresses in this region by the frequency domain method. This scale factor was derived from the time domain analyses.

The maximum accumulated fatigue damage due to Miner’s Rule is limited to 10% of the 20 year service life. This gives a fatigue life requirement of 200 years from all sources. The calculated fatigue life (from VIV, and first and second order effects) in the TDP region exceeded the design requirement for both the uncorroded and corroded riser. In the splash zone, the fatigue life is substantially greater than the TDP region for both corrosion conditions.

Though the calculated fatigue life in the TDP region is only marginally greater than the specified design requirement of 200 years, this is acceptable as the fatigue life methodology used was significantly over conservative. Sensitivity studies were performed to demonstrate important conservatisms related to current profiles, vessel damping for second order motions, number of seastates and stress distribution assumptions.

**Installation**

A conceptual study of the installation was performed to identify the optimum installation method, to define the main guidelines for the riser construction (pipe manufacture, welding, coatings, anodes, instrumentation), general installation procedures (laying, pull-in, etc.), riser anchoring system, and connection method with the flexible line (which will hang from the P-XXVI FPS).

The main conclusions arising from this evaluation are as follows:

1. The most convenient installation method is J-lay using a converted drilling/completion rig.

2. Due to the relatively high top angle and the short static length resting on the seabed, it will be necessary to anchor the lower portion of the riser to avoid losing the design configuration. This will be done by pre-installing anchors on both sides of the pipe track and attaching them to the line after its installation.

3. The best way to link the SCR bottom extremity with the flexible pipe (to be installed at a later stage), is by means of a dry connection. This will be made up by the flexible pipe installation vessel which will recover the SCR extremity, connect rigid to flexible at the surface, and proceed to lay away. Again, to ensure that the SCR design configuration will not be modified, an anchoring system is necessary, but acting in the opposite direction of the one referred to in Point 2 above.

**Conclusions**

The main conclusions from this SCR project for the Marlim Field are as follows:

1. An SCR has been successfully designed for application as a 10 inch gas import riser for the Petrobras P-XVIII platform in the Marlim Field at 910m water depth. The SCR will be installed in mid 1996.
2. A single action flex joint with a rotational capacity of 18.8˚ has been successfully designed for this application and is currently being manufactured by Oil States Industries.

3. Detailed design methodologies have been developed and verified by MCS International for all phases of the project including sizing, static/dynamic design, VIV analysis and fatigue analysis. In particular, the fatigue analysis was based on the frequency domain method, which requires careful attention to the finite element discretisation, seabed and flex joint modelling, selection of load cases, and combination of first and second order effects.

4. VIV suppression devices, such as strakes, are not required for this installation. This is the major difference between this SCR and the Shell Auger SCRs.

5. The SCR will be installed by a converted drilling/completion rig using the J-lay method. This method has already been considered in other projects and proved to be feasible, although it is not known to have been used in practice before. The main advantage of this solution is that it avoids large mobilisation costs, for what is a relatively short installation period.

6. For a period of up to one year after installation the SCR will be monitored to further verify design and analysis procedures. Monitored parameters include environmental conditions, vessel motions, riser curvature at TDP, riser curvature and tensions in splash zone, and VIV response.

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Table 1 SCR Design Load Case Matrix.

<table>
<thead>
<tr>
<th>Loading Conditions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrotest</td>
<td>Functional loads, hydrotest pressure and one year environmental loads (wave, current and vessel offset).</td>
</tr>
<tr>
<td>Functional</td>
<td>Functional loads and vessel offsets (static analysis).</td>
</tr>
<tr>
<td>Operational</td>
<td>Functional and environmental loads (1 year return period).</td>
</tr>
<tr>
<td>Extreme</td>
<td>Functional and helical current loads (100 year return period).</td>
</tr>
<tr>
<td>Survival</td>
<td>Functional and environmental loads (100 year return period).</td>
</tr>
<tr>
<td>Accidental A</td>
<td>Functional and environmental loads (100 year return period), for case of one mooring line broken.</td>
</tr>
<tr>
<td>Accidental B</td>
<td>Functional loads with flooded compartment causing a static inclination (14.4 degrees) and environmental loads (1 year return period).</td>
</tr>
<tr>
<td>Installation</td>
<td>Relevant functional and environment loads (1 year return period).</td>
</tr>
</tbody>
</table>

References
Fig. 1 SCR Design Configuration.

Fig. 2 Flex Joint Configuration.
**Fig. 3** Flex Joint Design.

**Fig. 4** SCR Design Methodology.

- **Stage 1**: Static Case
- **Stage 2**: Full Set of Cases, Corrected
- **Stage 3**: Time Domain Static Analyses - Offsets & Currents [FLEXCOM-3D]
- **Stage 4**: Combined First and Second Order Analyses [FREECOM-3D/FLEXCOM-3D]
- **Stage 5**: Fatigue Current Analyses [SHEAR7]
- **Stage 6**: Perform Internal & External Pressure On-Bottom Stability [Sizing Spreadsheets]
Fig. 5 Comparison of Bending Moment Seastate 4, Far, Top

Fig. 6 Comparison of Bending Moment Seastate 4, Far