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ASSESSMENT OF THERMO-MECHANICAL BEHAVIOR OF OFFSHORE PIPELINE IN OPERATIONAL CONDITIONS

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Abstract. *Recently Petrobras has been developing a production module of Roncador field through the P-52 platform in the Campos Basin, offshore Brazil. This platform is a floating production facility located in deep water and was tied back to the PRA-1 platform in shallow water by an 18-inch pipeline in order to export the oil production. This pipeline operates under high pressure and high temperature conditions and was laid on the seabed. As a result of the extreme operating conditions, this pipeline is highly susceptible to lateral buckling. A buckle initiation strategy based on triggers to control the buckling behavior was adopted where sleepers and distributed buoyancies were designed and installed along the pipeline route. In addition to the buckles at the triggers, some additional, on-bottom, buckles were assessed in order not to compromise the design strategy. In recent side scan sonar surveys carried out along the route length with the pipeline in operation, both engineered and on-bottom buckles were identified. This paper aims to present a comparison between the results obtained in design and observed during operation. Thus this paper intends to evaluate the pipeline as-built plus the operational pipeline configurations, and to assess the robustness of the design strategy applied regarding lateral buckling behavior. Therefore, a feedback from operating conditions of lines designed on the basis of controlled lateral buckling was obtained in this paper.*

Keywords*: Offshore Pipeline, Lateral Buckling, Thermo-Mechanical Analysis*

1. INTRODUCTION

In high pressure and high temperature (HP/HT) subsea pipeline design, extreme conditions can be developed within a lateral buckle; on first load the stresses can exceed yield and may involve significant plasticity; in addition, shutdowns will lead to very high stress cyclic fatigue. Lateral buckling if left uncontrolled can compromise the integrity of the pipeline. If the buckling response of the pipeline is not understood and controlled, rogue buckling could occur and hence lead to integrity issues with the pipeline. The end expansion of the pipeline will also be influenced significantly by the buckling behavior of the pipeline. In order to control such phenomenon man-made triggers such as sleepers and distributed buoyancies can be installed along pipeline length, as described by Brunner et al. (2003) and Bruton et al. (2005). Figure 1 illustrates these techniques of control of thermo-mechanical buckling.

Figure 1 – Single Sleeper and Distributed Buoyancy - Brunner et al. (2003)

The thermo-mechanical behavior of subsea pipeline has been extensively analyzed during design phases. Lateral and upheaval buckling, end expansion, pipeline walking as well as lateral ratcheting are behaviors that have been analyzed with detail in HP/HT pipeline designs. However, uncertainties that influence buckle formation, e.g. pipe-soil interaction, as-laid out-of-straightness (OOS), seabed undulations and initial heat-up, have been known as real challenges due to the influence of its effects. The situation has also been exacerbated as the lack of feedback from operating conditions of lines designed on the basis of controlled lateral buckling. One such opportunity has recently presented itself and this paper presents an analysis based on the all important feedback information.

At the pioneer work, Kaye (1996) performed a comparison between lateral buckling design predictions and the observed movement of an operational pipeline, where the buckle assessment was based on side scan surveys. However, the side scan specification and system accuracy were not presented, and the survey data exhibited some scatter in spite of the overall shape of each feature can be identified. In spite of this, Kaye described that the discrepancies between the predicted and observed behavior were due to the unknown pipeline out-of-straightness and also because of variability in the axial and lateral soil forces. In fact these parameters are important sources of uncertainties that lead to adoption of conservative assumptions during the design stage. Data from surveys can be used not only to confirm such assumptions demonstrating the robustness of the thermo-mechanical design but also to provide information that can be included in FE models.

Some years after, Harrison et al. (2003) presented the use of sleepers in a HP/HT pipeline as an original development in order to control the lateral buckle initiation. The start-up of the pipeline was described in the paper, besides the side scan sonar (SSS) survey carried out by AUV (Autonomous Underwater Vehicle), mentioned as being the first AUV survey of an operating pipeline. This survey revealed thermal buckling along the pipeline, however the lateral deflection amplitude and peak bending levels of the buckles at full operating temperature were not assessed, although the verification of such data was recommended in order to insure that they are reasonably representative of the predicted values.

Recently, Sinclair et al. (2009) described the main design challenges and experience with controlled lateral buckle initiation methods, affirming the importance of rigorous visual inspection and survey to monitor the performance of flowlines during the first months and years after start-up. In addition to this, Sinclair proposed a new phase of the Safebuck JIP in order to collate and interpret information on operating pipelines, so that the knowledge of lessons learned from recent projects can be shared, without the need to share potentially sensitive project specific data. Therefore, clearly there are still some challenges facing designers of new pipeline systems given the trend towards deeper water and higher pressures and temperatures. A greater level of detail and interaction may be required between flow assurance assessment and pipeline thermo-mechanical analysis, to ensure that the likely flow conditions in the flowline are fully understood by the designer.

Concerning Petrobras works focused in HP/HT pipelines, some developments have been started to assess lateral buckles of pipeline recently designed with controlled lateral buckle initiation methods. Hansen et al. (2011) and Sriskandarajah et al. (2011) present a complete re-analysis of a these pipelines, performing an assessment of lateral buckles using SSS data and evaluating the operational behavior of a deepwater oil export pipeline designed on the basis of controlled lateral buckling. Before, Solano et al. (2010) presented some details regarding post-installation assessment, where SSS surveys allowed to perform a brief evaluation of lateral buckles initiated by sleeper and distributed buoyancy triggers as well as of lateral buckles on-bottom. However, there were SSS surveys only a pipeline section and was not possible to evaluate all lateral buckles along the pipeline. This paper aims to present updated results of this last paper mentioned in order to show the buckle shapes (length and amplitude of buckles) along of entire pipeline, in addition to carry out a initial comparison with thermo-mechanical design results. Thus the evaluation the pipeline as-built plus the operational pipeline configurations as well as the robustness of the design strategy applied regarding lateral buckling behavior are presented in this work.

2. PDET PIPELINE

The Oil Flow Master Plan (PDET) project consists of the oil export system, including the P-52 semi-submersible Floating Production Unit (FPU), an 18-inch oil export pipeline and a Free Standing Hybrid Riser (FSHR) connecting the P-52 platform at 1800m water depth to the PRA-1 jacket at approximately 100m water depth. The high expected production rates of the P-52 platform required an 18-inch oil export pipeline with 52mm thickness of thermal insulation coating for both pipeline and the vertical portion of the riser in order to fulfill requirements of flow assurance. The instrumented pigging requirements dictated the export riser to have also 18-inch diameter. This large bore specification combined with the deep water site put this application outside the present feasibility range of solutions such as flexible pipes and steel catenary risers (SCRs), once these solutions present high top tension loads in installation and operational conditions. Therefore, the FSHR system was selected because it has a reduced dynamic response, as a result of significant motion decoupling between the FPU and the vertical portion of the FSHR system, and its vessel interface loads are small when compared with SCR or flexible pipe solutions. The P-52 oil export system was described in detail by Roveri et al. (2008).

The 18-inch PDET pipeline is approximately 57 km long, going from 1800m water depth up to 100m water depth. The detailed design was performed in accordance with DNV-OS-F101 (2000). The PDET line terminates with a PLEM on the shallow water PRA-1 side and with a PLET on the P52 side. The first approach was to have equipments along the pipeline (PLEM Y and PLEM T) interconnected by rigid jumpers to the pipeline, in order to deal with thermal expansion effects. However, during developing of the thermo-mechanical design, In Line Sled (ILS) structures concept was adopted. The ILS structure base is composed by piping, two mandrels and a guiding system for the valve module connection, which was installed after deployment of the ILS structure base on the seabed. Figure 2 illustrates the PDET schematic with the pipeline route and subsea equipments.

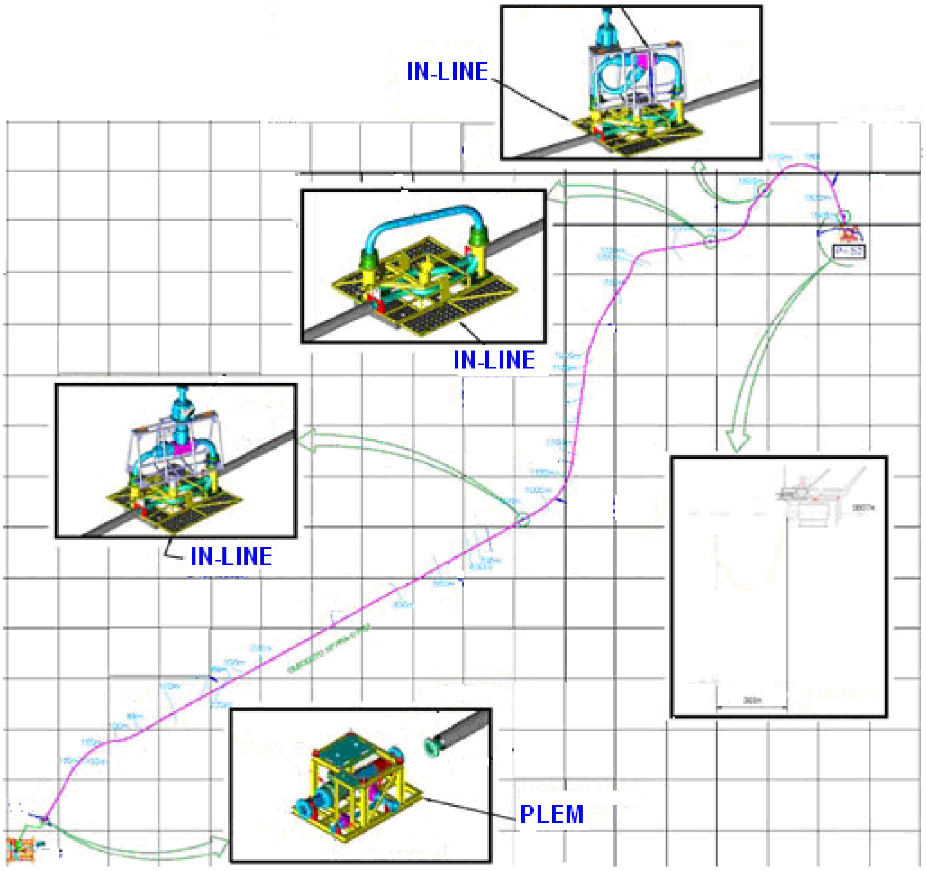

Figure 2 – PDET Project Schematic

Concerning the soil data for the PDET pipeline design, geophysical and geotechnical surveys were carried out along the corridor of the pipeline preliminary route. Thus, in order to have a better profile of the pipeline route, a detailed survey was performed prior to engineering design. Besides of this the pre-lay survey of the pipeline was assessed and route (Figure 2) was confirmed with respect to: slopes and rested undulations; seabed obstructions including debris, boulders, wrecks and construction dropped objects; seismic related hazards such as slope instability and liquefaction; and free span optimization.

Soil data were based on analysis carried out on soil samples located along pipeline route and in equipments (PLET, PLEM and ILS structures) sites. The axial and lateral friction factors between the pipe and the seabed were established based on these data, as well as the friction factors between equipments and seabed. Thus geotechnical data were used as design basis for PLET, PLEM and ILS foundations, in addition to furnish soil parameters for pipeline detailed design mainly in on-bottom stability, free span, on-bottom roughness and thermo-mechanical analysis.

In terms of operational data, Table 1 presents the main information considering in engineering detailed design.

Table 1 – Operational Data

Parameter	**Value**
Design Life	25 years
Service condition	Sweet service
Water depths	1800 to 100m
Maximum design pressure	11MPa
Minimum design pressure	0.1MPa
Maximum design temperature	70ºC
Minimum design temperature	0ºC

The temperature and pressure profiles along the pipeline route are presented in Figures 3.

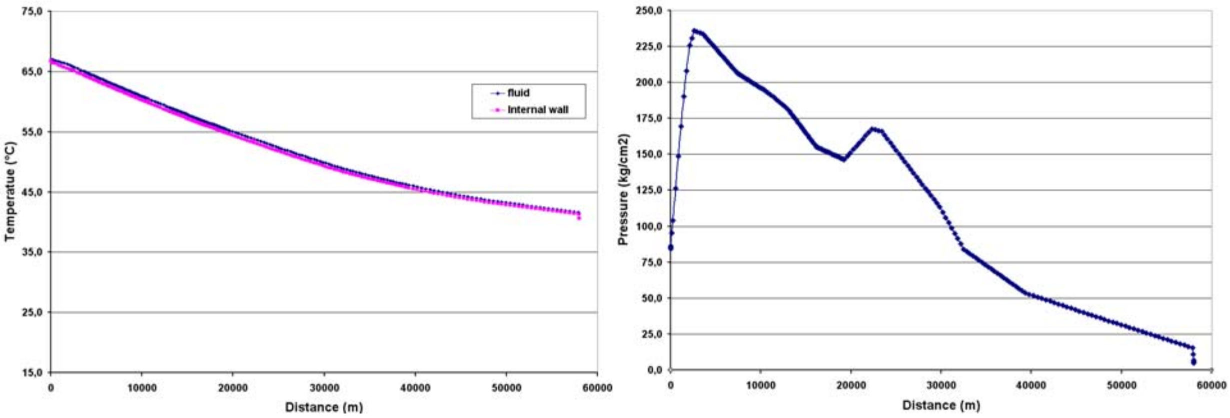

Figure 3 – Temperature and Pressure Profiles along the Pipeline Route

Considering the data and premises described above, the verification of the expansion in all pipeline sections was performed taken into account the pipeline route as well as the temperature and internal pressure profiles along the pipeline. The calculation of the axial expansion at the pipeline ends was performed for the hydro testing, operating and design conditions, including pressure effects and thermal expansion. The results of pipeline end expansions and effective axial forces were used to define the spool pieces devices in order to absorb the displacements.

Due to the operational conditions, the thermo-mechanical design evaluated the susceptibility of the pipeline to the phenomenon of lateral buckling and pipeline walking. These phenomenons were considered a great challenge for the design, once high stress and strains can be developed in the buckles and a conventional stress based approach was not suited to design this pipeline that buckles laterally. The conventional stress limits were therefore relaxed and replaced by a strain limit. For this the methodology and recommendations of the Safebuck JIP (Joint Industry Project) were adopted, vide Bruton et al. (2005). The PDET pipeline thermo-mechanical analysis selected a buckle initiation strategy based on distributed buoyancy and sleeper. The strategy combined six distributed buoyancy and ten dual sleeper triggers along the route together with the beneficial effect of the seabed bathymetry and OOS of the laying process. The analysis showed that the initiation strategy adopted is robust and highly reliable.

The PDET pipeline has been operating in Campos Basin, offshore Brazil, since the last months of 2007. And recently, Petrobras carried out geophysical data surveys (bathymetry, SSS and high resolution seismic) along the pipeline route. Therefore, it is possible to assess the buckle shapes of both engineered and on-bottom buckles identified along the route. Specifically regarding the SSS surveys, this provided images that allowed to analyze the lateral buckles. So, in all sites where buckle initiators were installed, as well as at the locations where on-bottom unplanned buckles occurred, images were captured. The length and maximum lateral offset of each buckle were measured, besides being observed the as-laid and post-buckling configurations of the pipeline in these sites. This information allowed comparing some design results with the pipeline configurations in operation.

To ensure a robust design, the pipeline system was designed to withstand all possible loading/severe operating conditions. A combination of design issues were considered in thermo-mechanical analysis, including pipeline end expansion, thermal cycle fatigue at lateral buckles, significant free spans under thermal expansion and contraction, lateral ratcheting (route curve pull-out), axial ratcheting (or walking), pipeline end fixity for pipeline walking, and finite element analysis (FEA) for planned pipeline buckle initiation and interaction.

3. THERMO-MECHANICAL DESIGN

The thermo-mechanical design including the buckle initiators was evaluated in the detailed analysis using global FEA models. Seabed terrain effects were included along with several operational heating and cooling cycles. Boundary conditions associated with buckle initiators, PLET, PLEM, ILS structures, jumpers, spool pieces, in-line sleds, pipeline crossings, lower and upper bound soil properties, and planned free span supports were also included.

Due to the extreme length of the pipeline, along with the detail required to model the terrain, it was not possible to accurately model the entire pipeline at once for the detailed assessment of global lateral buckle strains. To assess the global behavior of the entire pipeline, longer element lengths had to be selected so as to keep the calculations to a manageable size. For this assessment, the loss of details at global lateral buckles and severe free spans was an unavoidable byproduct. The pipeline was therefore split up into four shorter and more manageable lengths for the assessment of global buckling. The breaks were taken at estimated virtual anchor locations (locations of little axial or lateral movement), so as to have the least impact on the global pipeline behavior.

A series of buckle initiation/mitigation devices were applied along the pipeline to absorb midline thermal expansion in a more controlled manner. Without these devices, the pipeline would be susceptible to excessive strains at unplanned global lateral buckle locations, and this could lead to localized buckling of the cross-section. Fracture of the girth welds associated with high strains at weld flaws was also a concern, as well as fatigue in certain regions.

The selected solution approach was to apply distributed buoyancy sections and dual sleeper upsets at discrete locations along the route. Dual sleeper triggers were specified in PDET pipeline design instead of single sleeper trigger mainly due to buckle initiation reliability, stress mitigation in global lateral buckles, and fatigue due to thermal cycling and vortex induced vibration (VIV). These devices work with the pipeline to initiate global buckles at planned locations and to control the maximum strains that will occur. The basic approach was to ensure that global lateral buckles occur at planned locations, however if all buckle do not occur as planned, and unplanned buckles form as well, it may still be possible to have an acceptable solution, so long as strains and other limit states were determined to be within the acceptable values.

Figures 4 to 7 present the selected solution to control the lateral buckling behavior in each section of PDET pipeline, including the sites of planned buckles with buckle initiators (dual sleepers and distributed buoyancy modules) and unplanned buckles (rogue buckles).

Figure 4 shows a von Mises stress contour of Section 1 under design temperature and pressure in the LB (Lower Bound) soil condition. The locations with significant lateral bending stresses indicate the global buckle initiation sites. Four planned buckles (three dual sleepers and one buoyancy sections) plus two unplanned buckles on route curves were indicated.

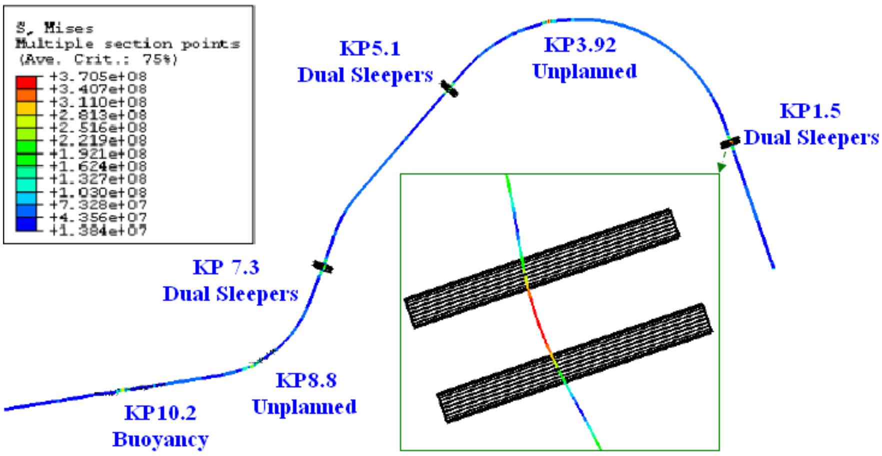

Figure 4 – Buckle Initiation Sites and von Mises Stresses of Section 1 at Initial Heatup [Pa]

Seemingly, Figure 5 illustrates the locations of buckle initiation sites, as well as the von Mises stress contour of Section 2. In this section, four global buckle locations were identified: three planned at buoyancy sections and one unplanned on a route curve (KP13.8). In the UB (Upper Bound) soil condition, the pipeline had an additional small unplanned lateral buckle at KP20.8. The unplanned buckles were less severe than the planned buckles, with lower stresses and strains. There were no lateral buckles at the pipeline crossings in either LB or UB soil condition.

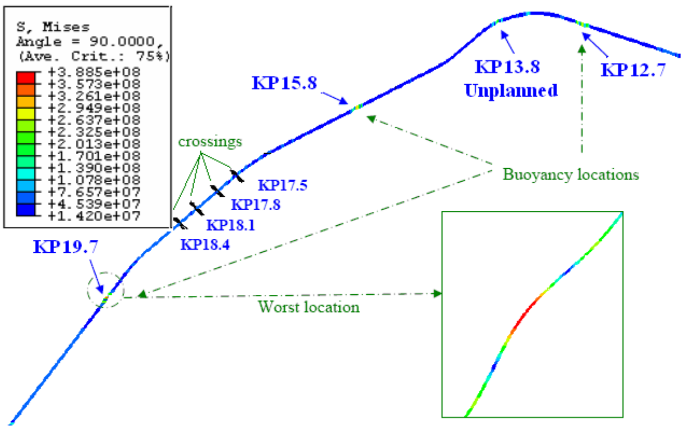

Figure 5 – Buckle Initiation Sites and von Mises Stresses of Section 2 at Initial Heatup [Pa]

Figure 6 shows the locations of buckle initiation sites, as well as the von Mises stress contour under design temperature and pressure in the LB soil condition. Seven global buckle locations were found: five at planned buckle locations and two at unplanned locations. The worst buckle was verified at KP23.7.

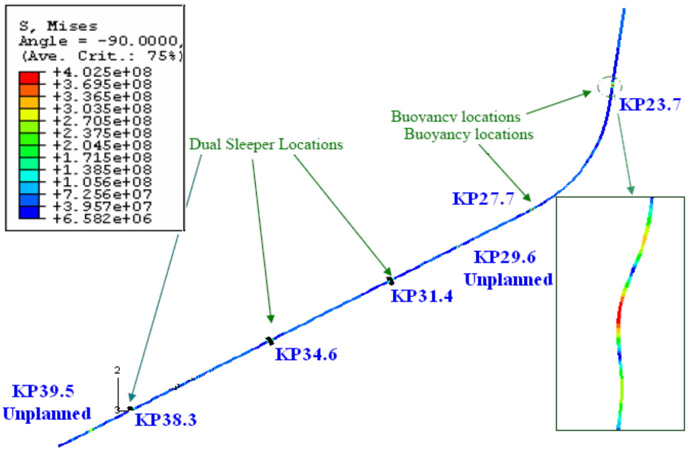

Figure 6 – Buckle Initiation Sites and von Mises Stresses of Section 3 at Initial Heatup [Pa]

The same pieces of information are presented in Figure 7 for the section 4, however for the UB condition. At this last section, six global buckle locations were identified, including one unplanned location (KP43.25) due to the seabed undulation.

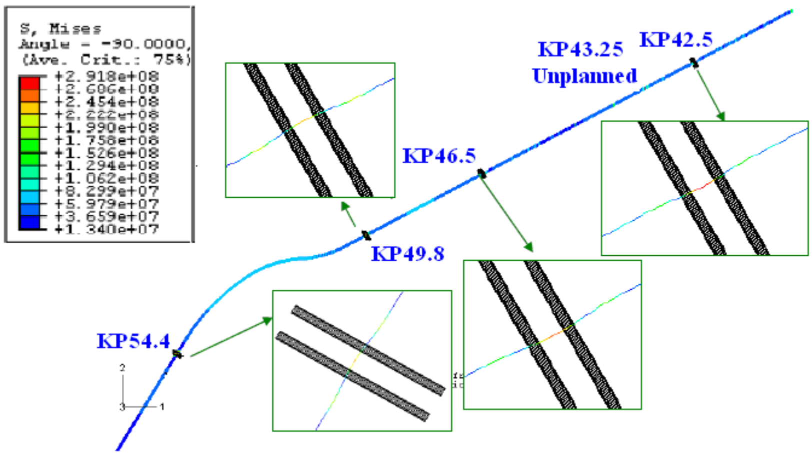

Figure 7 – Buckle Initiation Sites and von Mises Stresses of Section 4 at Initial Heatup [Pa]

Table 2 – Main Global Lateral Buckle Initiation Sites

Location KP	Soil Condition	Type	Buckle Amplitude (m)
1.5	LB	Dual Sleepers	~7.3
1.5	UB	Dual Sleepers	~7.5
7.3	LB	Dual Sleepers	~8
7.3	UB	Dual Sleepers	~9.4
19.7	LB	Buoyancy	~9
19.7	UB	Buoyancy	~11
23.7	LB	Buoyancy	~12
23.7	UB	Buoyancy	~10
34.6	LB	Dual Sleepers	~7.5
34.6	UB	Dual Sleepers	~7
42.5	LB	Dual Sleepers	~7
42.5	UB	Dual Sleepers	~5
43.2	LB	Unplanned	~9
43.2	UB	Unplanned	~7
46.5	LB	Dual Sleepers	~7
46.5	UB	Dual Sleepers	~5
49.8	LB	Dual Sleepers	~7
49.8	UB	Dual Sleepers	~5
54.4	LB	Dual Sleepers	~7
54.4	UB	Dual Sleepers	~5

Table 2 summarizes the maximum lateral deflections of the most significant planned and unplanned initiation sites determined from the detailed FEA, for LB and UB soil conditions. Only the global buckle having the highest lateral deflections had their deflection amplitudes reported; it confirmed that the sleeper length (30m) provided for design was appropriate. The maximum lateral deflection on sleepers should be less than 10m. So, the 5m installation tolerance (+/-5m from the center of the sleepers) should be satisfied during the positioning of the pipeline on dual sleepers.

The pipeline deflects significantly during operation at the severe free spans, which absorbs thermal expansion and results in a compressive force reduction. Detailed free span analysis was performed. The unplanned buckles and severe seabed undulations were the reasons that the maximum stress and strain at global buckles were very small and much less than those calculated in the analytical analysis. The analytical analysis also had conservatively assumed a uniform temperature at the worst point for the entire section.

In terms of strains, the maximum longitudinal compressive strain and the maximum equivalent plastic strain at all global buckle locations were much less than the allowable values (DNV (2000)). The pipeline only had minor plastic deformation at a couple of the worst global buckle locations. The maximum longitudinal compressive strain and the maximum equivalent plastic strain at the free span of KP45.2, with the optimized pre-installed mattresses at each side of the span shoulder, was less than the allowable values for the as-laid, hydro test, and operating conditions.

4. PIPELINE AS-BUILT AND OPERATIONAL CONFIGURATIONS

The PDET pipeline installation was performed by Technip utilizing the J-Lay method of installation which involved onshore fabrication (quad fabrication), with offshore installation utilizing Technip's ship (CSO Deep Blue). Figure 8 shows distributed buoyancy sections being laid in deep water.

Figure 8 – Distributed Buoyancy Sections during Laying.

Sleepers were installed from a support vessel prior to commencement of the PDET pipeline installation by the Deep Blue. Pre-installation surveys of the proposed sleeper locations were completed prior to deployment, to ensure that the area was clear of debris, and to ensure that the gradient of the seabed permitted secure installation of the sleepers.

Regarding the sleeper foundation in very soft clay identified in deep water, concrete mattresses were specified in order to assure the vertical upset of the pipeline in the pre-determined locations, i. e., in each dual sleeper site. Figures 9 and 10 illustrate the detail of concrete mattresses under a sleeper and the PDET pipeline laid over a sleeper, respectively.

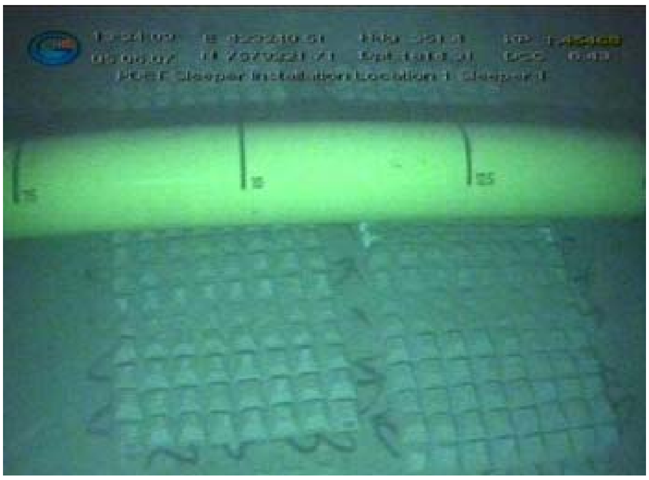

Figure 9 – Concrete Mattresses under a Sleeper.

Figure 10 – PDET Pipeline Laid over a Sleeper in KP1.5.

Recently, in order to continue the development the subsea production systems of Roncador field, Petrobras carried out geophysical data surveys (bathymetry, SSS and high resolution seismic) along the preliminary routes of pipelines that will be installed hereafter. Part of these surveys was performed in a corridor that only includes small sections of the PDET pipeline route. Therefore, it was possible to observe the PDET pipeline configuration in operation, in addition to verify some engineered buckles (planned buckles) and on-bottom buckles (unplanned buckles) along the route.

In order to perform a comparison between some results obtained in design and observed during operation, engineered and on-bottom buckles were mapped, SSS georeferenced images were captured and length and amplitude of each buckle were measured. Figures 11, 12 and 13 show images of two unplanned buckle sites, two planned buckle sites on dual sleepers and two planned buckle sites using distributed buoyancy modules, respectively.

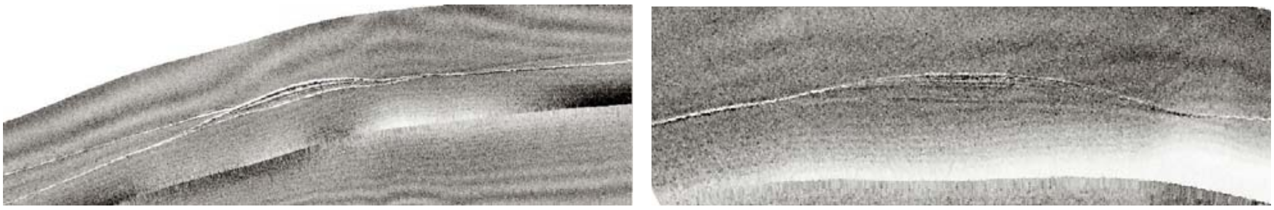

Figure 11 – On-Bottom Buckle (Unplanned Buckle) at KP3.9 and KP13.8.

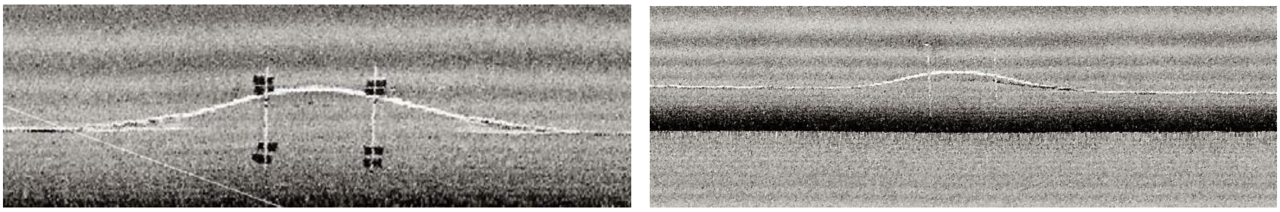

Figure 12 – Planned Buckle on Dual Sleepers at KP1.5 and KP34.6.

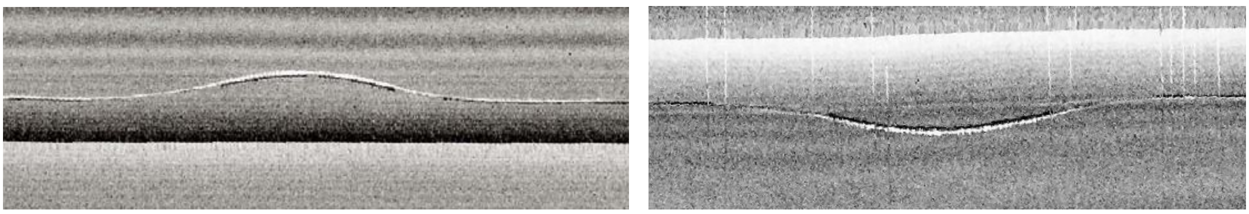

Figure 13 – Planned Buckle using Distributed Buoyancy Modules at KP12.7 and KP19.7.

Some characteristics of an on-bottom buckle can be noted in Figure 11. The definition of the SSS images allows to identify, at least, four different operational stages defined by the thermal cycles that the PDET pipeline were submitted from the beginning to the maximum operational condition. The surveys performed for furnishing data to Petrobras future pipeline design included two unplanned buckles foreseen in the thermo-mechanical design. Both unplanned buckles occurred during operation, having length and amplitude measured and presented in Table 3.

Regarding the planned buckles on dual sleeper triggers, Figure 12 presents SSS images in proximity to KP1.5 and KP34.6, where it is possible to identify the pipeline post-buckling configuration in maximum operational condition, as well as the sleepers on concrete mattresses at KP1.5 as designed. Table 3 presents length and amplitude of all planned buckles on dual sleepers measured in the images captured.

Recently Sinclair et al. (2009) published the design challenges and experience with controlled lateral buckle initiation methods, describing that there are no operational data available of distributed buoyancy as a method to control lateral buckling. In this paper planned buckles using distributed buoyancy modules as triggers were also mapped and the results concerning pipeline post-buckled configuration are presented in Table 3. Figure 13 illustrates this pipeline post-bucking configuration in proximity to KP12.7 and KP19.7 for maximum operational condition, where some buoyancy modules distributed along the buckle can also be observed due to resolution of the SSS image.

Table 3 – Lateral Buckle Mapped along the Pipeline

Location KP	Type	Buckle Length (m)	Buckle Amplitude (m)	Predicted Amplitude (m)
1.5	Dual Sleepers	~160	~12.8	7 to 10
3.9	Unplanned	~170	~8.7	6 to 9
5.1	Dual Sleepers	~140	~5.1	7 to 10
7.3	Dual Sleepers	~195	~13.5	7 to 10
8.8	Unplanned	~165	~9.0	6 to 9
10.2	Buoyancy	~175	~12.0	9 to 12
12.7	Buoyancy	~195	~12.0	9 to 12
13.8	Unplanned	~160	~8.5	6 to 9
15.8	Buoyancy	~180	~12.0	9 to 12
19.7	Buoyancy	~160	~12.1	9 to 12
23.7	Buoyancy	~195	~14.2	9 to 12
27.7	Buoyancy	~195	~13.4	9 to 12
29.6	Unplanned	~120	~7.2	6 to 9
31.4	Dual Sleepers	~160	~10.4	7 to 10
34.6	Dual Sleepers	~140	~9.0	7 to 10
38.3	Dual Sleepers	~115	~8.6	7 to 10
39.5	Unplanned	No identified in SSS image		7 to 9
42.5	Dual Sleepers	~115	~8.6	4 to 6
43.2	Unplanned	No identified in SSS image		7 to 9
46.5	Dual Sleepers	~150	~4.4	4 to 6
49.8	Dual Sleepers	No measurable in SSS image		4 to 6
54.4	Dual Sleepers	~110	~2.1	4 to 6

In general, the buckle amplitude results obtained in FEA during thermo-mechanical design varied between 7 and 10m at dual sleeper locations, between 9 and 12m at distributed buoyancy section locations and between 6 and 9m at unplanned buckle locations, according Table 2 and 3. These results are too compatible to the results presented in Table 3 mainly for the distributed buoyancy sections considered as the most reliable solution to control the lateral buckling behavior. Regarding the results using dual sleeper triggers, the values measured are slightly larger than the design results. The unplanned buckles due to the uncertainties regarding OOS and seabed profile presents amplitude values more conflicting, however these buckles (rogue buckles) occurred as foreseen showing the design robustness.

Regarding buckle modes, images presented in Figures 12 to 14 seem to indicate typical buckles formed in mode I, including the on-bottom buckle (Figure 12) where normally mode III would be expected. These post-buckle configurations must be better evaluated hereafter in order to confirm this conclusion.

This initial approach allowed to compare results related to post-buckled configuration of the design and observed during operation. Thus, it was possible to evaluate the pipeline as-built plus the operational pipeline configurations, in addition to assess the robustness of the design strategy applied to control the lateral buckling behavior. However, FEA considering the pipeline configuration in operation is required in order to analyze in details the lateral buckling results, mainly related to stresses and strains at the buckle apexes.

5. CONCLUSIONS

Regarding thermo-mechanical design of the PDET oil pipeline, the purposes of the detailed FEA were to assess the midline expansion that occurs in global lateral buckles, whether planned or unplanned, and determine whether code and project requirements were met. Such results showed that all requirements were met, and then the pipeline solution was deemed to be safe and adequate for the design life.

Concerning the selected solution developed during detailed design, the maximum stress, strain, and fatigue damage were fairly low at the buckle locations. Besides this, the stress and strain level and lateral deflection at unplanned buckle locations were less than ones found at the planned buckles. Therefore, the solution used to control the lateral buckling behavior assured a robust design of the pipeline.

The paper presented the thermo-mechanical design of the PDET oil export pipeline, performing a preliminary comparison between some results obtained in design and observed during operation. The planned buckles at dual sleepers and at distributed buoyancy modules, and the unplanned buckles (rogue buckles) verified in detailed FEA during design phase, also were observed in pipeline operational condition through the sidescan images available. Seven planned buckles and two unplanned buckles were mapped and analyzed, and the lengths and amplitudes of these buckles were compatible with the lateral buckles of the thermo-mechanical design.

Finally, it was recommended after an inertial pig run that FE retro-analysis to be carried out in order to compare more accurately the lateral buckling behavior between design and operational condition, also analyzing the stresses and strains in each buckle along the pipeline route. Thus, this will allow to obtain conclusions to be applied in Petrobras future designs.

6. NOMENCLATURE

AUV - Autonomous Underwater Vehicle
DNV - Det Norske Veritas
FEA - Finite Element Analysis
FPU - Floating Production Unit
FSHR - Free Standing Hybrid Riser
HP/HT - High Pressure and High Temperature
ILS - In Line Sled
JIP - Joint Industry Project
KP - Kilometer Post
LB - Lower Bound
OOS - Out-of-Straightness
PDET - Oil Flow Master Plan
PLEM - Pipe Line End Manifold
PLET - Pipe Line End Termination
SCR - Steel Catenary Risers
SSS - Side Scan Sonar
UB - Upper Bound
VIV - Vortex Induced Vibration

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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