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Subsea Pipeline Lateral Buckling Susceptibility Analysis

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Abstract: The research presents a detailed in-service lateral buckling analysis on the water injection (WI9) line of Angola Block 15/06 Agogo 2 Oil field located Development Project. The analysis was performed following the methodology given by the Flowline Global Buckling Design Premises. The study aims at the assessment of susceptibility to lateral buckling, calculation through detailed FE analysis (if necessary), the bending levels reached in the post-buckling configuration, design of corrective measures ensuring the safety of pipelines and the fulfillment of the pipe strength criteria, verification of stability of the curves for in-service conditions and assessment of the fatigue at buckle apex due to operating cycles. A detailed in-service lateral buckling analysis of the water injection Agogo phase 2 was performed through plenty stages namely, calculation of the axial force along the route using pressure and temperature profile and project specific pipe-soil interaction friction, assessment of lateral buckling susceptibility due to in-place loads under both hydrotest and operating conditions, examination of the rogue buckle at the peak compressive effective force location KP6, analysis of Friction combination BE/HE cases, performance of lateral buckling FE analyses by means of 1 mitigation device at KP6, and thus analyzing the Rogue buckle before and after sleeper, analyzing the buckle arrestor of 12 m between KP = 2194 m and KP = 2206 m to assess the impact on its FE models used for lateral buckling analysis, calculation of the bending moment levels originated in the post-buckling configuration with FE detailed analyses using ABAQUS 6.14 software, verification of the pipeline integrity depending on whether the flowline is in "Buckling" condition, then seabed is considered as even or moderately uneven seabed without trawling interference, only a displacement controlled check, based on the best estimate axial pipe-soil resistance and the high estimate lateral pipe-soil resistance. Therefore, the condition load effect factor of γc of 1.0 shall be used. The pipeline integrity check for local buckling is satisfied if DCC is satisfied.

Key words: lateral buckling, water injection pipeline, susceptibility, mitigation, FE analysis, KP6, seabed

1. Introduction

Due to the friction of the seabed, the frictional force increases against its expansion, which can cause a pipeline to buckle laterally. The axial expansion is caused by the internal working pressure and the temperature of the pipe wall, which is increased by the ambient temperature of the seabed. The compressive axial force, set up by seabed friction, is commonly referred to as the "effective axial force". The size of the initial out-of-straightness is an important parameter that governs the lateral buckling response. In practice, during pipelay on the seabed, a pipeline will have lateral imperfections resulting from the movement of the laying vessel. Thus, the effective axial force reaches the critical buckling load when the pipeline buckles only in the lateral direction. Buckling tends to occur, in the lateral direction, as the frictional forces are less than the submerged weight. The critical buckling load represents the maximum compressive axial load that a pipeline can sustain [1].

Pipeline buckling is usually seen as a structural instability and can be categorized as bifurcation buckling, described as a smooth transition of deflection under compressive loads from one direction to a different direction (e.g., from axial shortening to lateral deflection), or rather limits load buckling, meaning that the structure reaches a maximum load without any

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previous bifurcation with one deflection mode. One of the examples of limit load buckling includes Snap-through buckling. Buckling is provisioned to occur like a dynamic snap for small initial imperfections, therefore, a sudden jump from the equilibrium configuration to the next one including larger displacements, characterize a snap-through. A subsea pipeline snap-through happens when the temperature and the pipeline pressure increase to reach the critical buckling load. As stated, this type of loading undergoes bifurcation buckling under simple boundary conditions, and no snap-through occurs. Subsea pipeline boundary conditions, result in friction between the surface of the seabed and pipeline generating a non-linear boundary condition as the lateral force surpasses the static coefficient of friction. So, the creation of a loading scenario that can cause dynamic snap-through buckling is the non-linearity of the pipeline soil friction interaction. For a large initial imperfection, lateral buckling goes through a gradual deflection [2]. For the assessment of lateral buckling behaviour for a pipeline resting on a flat seabed, the two competing approaches used are as follows:

- Non-Linear Static Analysis.
- Non-Linear Dynamic Analysis.

Static analyses are more used by pipeline engineers. There are different non-linear solution methods applied in commercial multi-purpose finite element software. The simulation of buckling and post-buckling can be achieved by using these solutions. Internal operating temperatures and pressures act on the pipeline with initial skew. The shortcoming with this method lies in, a) a large number of iterations that might be required to jump between two successive stable configurations, and b) numerical challenges involved in guiding the solution to overcome limit-point instability. Also, the static analysis does not take into consideration any of the dynamic responses, i.e., Therefore, kinetic energy transfer during a reaction cannot adequately evaluate the actual reaction. Dynamic analysis with implicit and explicit integration is available in commercially available general-purpose finite element software. The benefits of dynamic analysis are predetermined for pipeline snap-through problems. Additionally, it may be necessary to determine the axial and lateral velocities at the onset of buckling. These velocities are to be used as input for further soil laboratory tests. The paper aims to investigate the merits and limitations of static and dynamic lateral buckling for a pipeline resting on a flat seabed, with horizontal lateral out-of-straightness resulting from the pipelay. Sequences of numerical analyses are undertaken using ABAQUS. The paper studies the coated concrete weight thickness which is required to achieve the on-bottom stability under the influence of hydrodynamic waves and currents, and a 36-inch export pipeline resting on a flat seabed. In the finite element analysis, the contribution of the coating on the pipeline's structural behaviour is only related to its contribution to the submerged weight.

- Fishing: this activity, in the vicinity of the pipeline route, can present lateral out-of-straightness as the result of the interference between the pipeline and the on-bottom trawl gears.
- Motion of the installation vessel during pipe installation: The pipeline can move horizontally during pipeline installation due to the lateral sway movement of the vessel.

However, the main focus of this paper is only on a pipeline laid on a flat seabed in the lateral direction with initial out-of-straightness. The vessel motion that occurs during pipeline installation is the cause of this initial out-of-straightness. Therefore, the pipeline will buckle laterally at combinations of pressure, temperature, and given initial horizontal out-of-straightness. This is, partially, because the submerged weight of the pipeline is greater than the lateral resistance in the horizontal direction.

When the effective axial compressive force attains a critical load value, a pipeline will buckle, and then it will experience a large deformation into a new equilibrium shape to reduce the compressive load. At this phase, the pipeline is considered to have buckled. The load causing buckling is called the critical buckling load or just critical load. The lateral friction factor, the pipeline unit submerged weight, and the initial curvature of the initial lateral out-of-straightness determine the critical buckling of a pipeline.

2. Materials and Methods

2.1 Design Life and Pipeline Data

The field design life to be considered is 20 years. Table 1 below summarizes the main characteristic of the rigid line (pipe data) of the rigid line and the material data of the rigid line.

Table 1 Pipe data and material data.

Service (Water Injection)											
Item	Specified Minimum Yield Strength (SMYS)/ Tensile Strength (SMTS)	Young's Modulus (E)	Poisson Ratio (ν)	Steel Thermal Expansion Coef (α)	ND (In)	ID (mm)	WT (mm)	OD (mm)	Steel Density (ρ)	Corrosion allowance (mm)	Nominal length (m)
Flowline	SMLS	450 MPa/ 535 MPa	207 000 MPa	126.52	8" OD	188.9	15.1	219.1	7850 $kg.m^{-3}$	3	14112
Buckle [1] Arrestor	SMLS	450 MPa/ 535 MPa	207 000 MPa	126.52	8" OD	188.9	20	228.9	7850 $kg.m^{-3}$	3	12

2.1.1 Non-Linear Solution Methods

There are different non-linear solutions implemented in ABAQUS that are used when modelling the buckling and post-buckling behaviour of offshore pipeline under the influence of operating pressure and temperature.

ABAQUS that can be used to model the buckling and post-buckling behaviour of offshore pipeline under the influence of operating pressure and temperature. The static analysis is done using the Newton Method with artificial damping. Despite this, the non-linear and incremental/iterative technique are considered very cost effective. Lateral buckling in pipelines commonly include material non-linearity associated with plasticity or yielding and for the ABAQUS non-linear analysis, the material must be precisely chosen in terms of the stress versus strain relationship [1].

2.2 Geotechnical Data

The Water Injection friction factors adopted through Empty Installation and Hydrotest/Operating for the WI9 pipeline were analysed through the following aspects:

- Axial Residual – Drained, Axial Residual – Undrained, Lateral Peak, Lateral Residual.
- Axial and lateral residual friction factors are used in the FEA calculations to estimate the post-buckling pipeline loads if any.
- For the AGOGO 2 project, the minimum BE axial residual between undrained (0.24) and drained conditions (0.47) and the maximum LE residual (1.16) highlighted in green are used for the FE global model in accordance with the Fatigue Design of Offshore Steel Structures.
- For AGOGO 2 project, maximum BE axial residual (0.24) and LE lateral Peak friction factors (1.28) highlighted in red are used in the lateral buckling susceptibility assessment in hydrotest and operating conditions.
- Axial mobilization distance is taken as 1% of the pipe's outer diameter.
- Lateral mobilization distance is taken as 17% of the pipe's outer diameter.

2.2.1 PLETs Resistance

PLET sliding resistance considered in the calculations is 68 kN for Sangos and 82 kN for Agogo on water injection In Service Buckling Analysis Water Injection Lines Report.

2.2.2 Seawater Temperature and Density

The following values are assumed for the entire Agogo area:

- Seawater temperature: 4°C at sea bottom.
- Seawater density: 1035 kg/m^3.

2.2.3 Analytical Buckling Susceptibility

Lateral buckling assessment is based on the following assumptions:

- The consideration of design temperature profile with incidental pressure for operating conditions.
- Best Estimate axial friction (maximum between drained and undrained values).

Low Estimate Peak lateral friction.

- Minimum OOS radius from laying equal to 1000 m.
- 49 kN residual lay tension has been considered.
- Slope effect has been considered.
- PLET sliding resistance of 68kN for Sangos and 82 kN for Agogo.
- Pipe is considered to be installed empty.

Best Estimate axial residual friction (minimum between drained and undrained values); high Estimate residual lateral friction; 49 kN residual lay tension has been considered; slope effect has been considered; PLET sliding resistance of 68kN for Sangos and 82 kN for Agogo; the pipeline is considered to be installed empty; the pipeline is considered conservatively fully corroded at the first operating cycle for the pipeline integrity check.

3. Methodology

3.1 FE Global Analysis

The Finite element modelling was used in this research by utilising Abaqus FE [3].

Two cases have been considered for the lateral buckling analyses:

- Case 1: Design temperature with associated pressure.
- Case 2: Packing pressure with associated temperature.
- Because Case one is more conservative, the results will further on illustrate Case 1.

3.2 Operating Temperature and Pressure Profiles

The following temperature and pressure profiles have been considered for operating conditions:

- Maximum design temperature and associated pressure profile as Case 1.

The graphs below illustrate the Pressure and temperature profile as shown in Fig. 1.

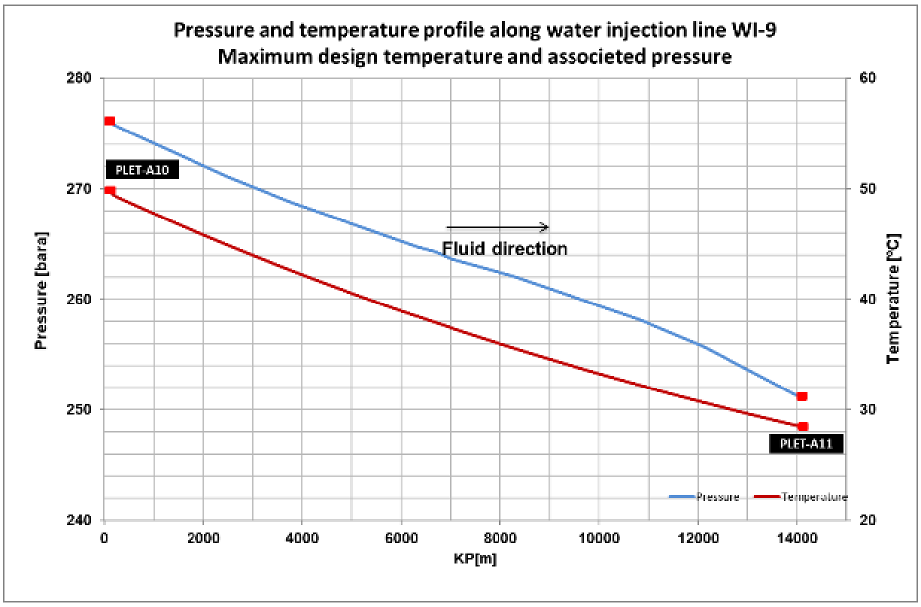

Fig. 1 Pressure & Temperature Profiles along Water Injection Line WI 9.

3.3 Axial Friction Factor

The lognormal distribution used during the study is obtained as the best fit to:

- Residual BE friction with a cumulative distribution probability of 50%
- Residual LE friction with a cumulative distribution probability of 5%.

3.3.1 PLET Reaction Forces

End reactions are considered in such a way that the number of buckles is not overestimated on analysis results. The approach considers that regular buckle formation is desirable since it allows the feed-in length to be shared among buckles resulting in lower loads at each buckle. Thus, end reaction forces have the effect of increasing the effective axial force development along the flowline and thus increasing line propensity to global buckling [6].

The buckle Formation Assessment analyses are performed as presented below, with regards to end reaction forces.

- First run – Equipment resistance of 68 kN for Sangos and 82 kN for Agogo.

3.4 Main Results and Associated Criteria

For the Probabilistic Buckling Formation Assessment, the main results and associated criteria are presented in Table 2.

3.5 Uniform Strain Capacity

The longitudinal strain should not approach the uniform strain capacity of the material, i.e., the strain corresponding to the ultimate tensile strength of the material. The maximum equivalent strain developed in the buckle should therefore be limited to:

Table 2 Probabilistic buckle formation assessment result list.

Assessment Result	Definition	Criteria
Min. Number of Buckles	The Min. No. of buckles with occurrence probability above criteria	1%
Probable VAS	The Maximum VAS with probability of exceedance less or equal to criteria	1%

$$\varepsilon_q \leq \frac{\varepsilon_{US}}{\gamma}$$

$$\varepsilon_{US} = 0.5.\left(1.04 - \alpha_h\right)$$

$$\gamma_{US} = \max\left(2.5\ ,\ 4.1\ .\ \left(2\alpha_h - 1\right)\right)$$

$$\varepsilon_{eq} = \varepsilon_{eq}^{p} + \frac{\sigma_{eq}}{E}$$

Where YT is the maximum specified yield to tensile ratio, $\varepsilon eq\ p$ is the equivalent plastic strain (PEEQ output from Abaqus); and σeq is the von Mises equivalent stress.

3.6 Cyclic Plasticity Limit State

Cyclic plasticity should be avoided. In the Subsea structures geotechnical design [12], the maximum axial stress range, σR, for both internal and external overpressure should comply with:

$$\frac{\sigma_R}{f_y} \leq 2 \times \alpha_B \times \sqrt{1 - \frac{3}{4} \times \left(\frac{\sigma_h}{f_y}\right)^2}$$

Where αB is the Bauschinger factor which is equal to 0.8 for seamless pipe. σh is the maximum absolute value of the hoop stress that could occur during operation.

3.7 Fatigue

The detailed general methodology used for the fatigue is presented in Water Injection Flowline in Place Fatigue Analysis Report. Only fatigue verification at buckle apex due to operating cycles according to Submarine Pipeline Systems is assessed in this report. The results discussed within this report exclude installation and VIV fatigue, which are treated in dedicated reports [9].

The selected S/N curves used for the fatigue analysis of AGOGO phase 2 water injection are given in the following Table 3 as per Water Injection Flowline in Place Fatigue Analysis Report complemented with Subsea geotechnical design structures.

Table 3 S/N curves for water injection fatigue analyses [11, 12, 18].

Flowline	Weld Location	S/N Curve	Stress Concentration Factor
WI-9	Weld root on internal pipe surface	F1 in air	1.143 as per DNVGL-RP-C203
	Weld toe on external pipe surface	D in air	1.229

From the table above, it can be concluded that as per Flowlines Design Basis, 8 mm is the width of the weld cap (outer side) of the pipe girth weld, and 5 mm is the width of the weld root (inner side) of the pipe girth weld. A Knock Down factor (KDF) of 4 is used for the inner surface fatigue damage calculation, and a Knock Down factor (KDF) of 9 is used for the outer surface fatigue damage calculation [8]. The standard split between the different phases of the design fatigue life and the allowable damage to be used for the operation phase are shown in Table 9.

4. Results

4.1 Lateral Buckling mitigation – BE/HE – Rogue Buckle at KP 10500 m and 1 Sleeper at KP 6000 m

FEA global model analysis has been performed with an imperfection of 0.8 m at KP = 10500 m with a lateral buckling mitigation device at KP6000. The results for FEA water injection are summarized below in Table 4. Furthermore, the results were plotted graphically from (Fig. 2 to Fig. 5), based on the Lateral displacement for Water Injection, Pipeline Lateral Curvature, Lateral bending moment for Water Injection and Axial displacement for Water Injection with RB.

Table 4 FEA results for water injection with 0.8 m RB at KP = 10500 m and 1 Sleeper at KP 6000 m (case 1).

Summary Results FE model BE_HE				
Description	**Unit**	**Hydrotest**	**Operating**	**Shut-Down**
Max lateral displacement	m	4.774	8.005	5.281
Max lateral bending moment	kNm	223.18	275.33	114.66
Effective Axial force at max bending moment	kN	-173.61	-76.98	-26.63
Max. compressive mechanical strain	%	-0.459	-0.820	-0.658
Max. tensile mechanical strain	%	0.445	0.789	0.620

Result attained from FEA global model analysis are illustrated as follows:

- when performed with an imperfection of 0.8 m at KP = 10500 m to find the Lateral displacement for Water Injection as shown in Fig. 2.
- when performed for case 1 with 1Sleeper at KP = 600 m to find the Lateral displacement for Water Injection as shown in Fig. 3.
- when performed with RB at KP = 10500 m and 1Sleeper at KP 6000 m (case 1) to find the Axial displacement for Water Injection as shown in Fig. 4.
- when performed with RB at KP = 10500 m and 1Sleeper at KP 6000 m (case 1) to find the Axial displacement for Water Injection as shown in Fig. 5.

4.2 In-Service Curve Stability

Table 6 presents the curve stability assessment of the minimum expected radius based on the current pipeline layout.

The maximum effective tensile forces during shutdown condition are extracted and compared against the minimum allowable radius based on LE peak lateral friction for operating weight.

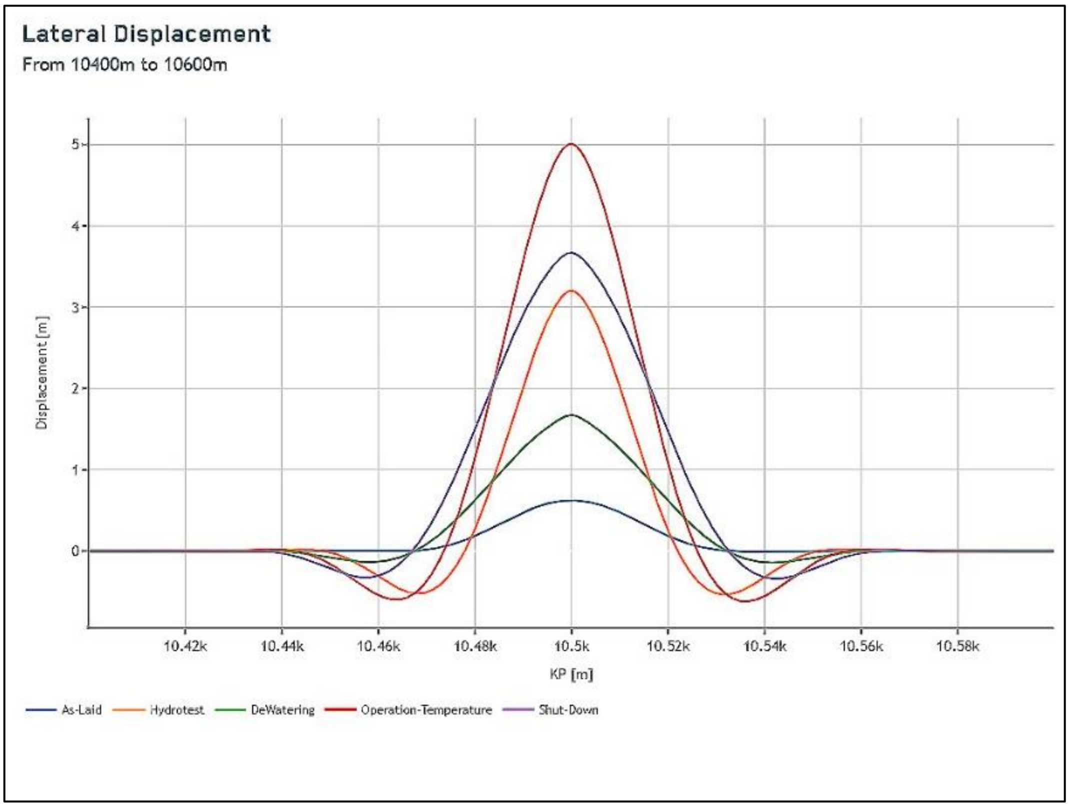

Fig. 2 Lateral displacement for water injection with 0.8 m RB at KP = 10500 m (case 1).

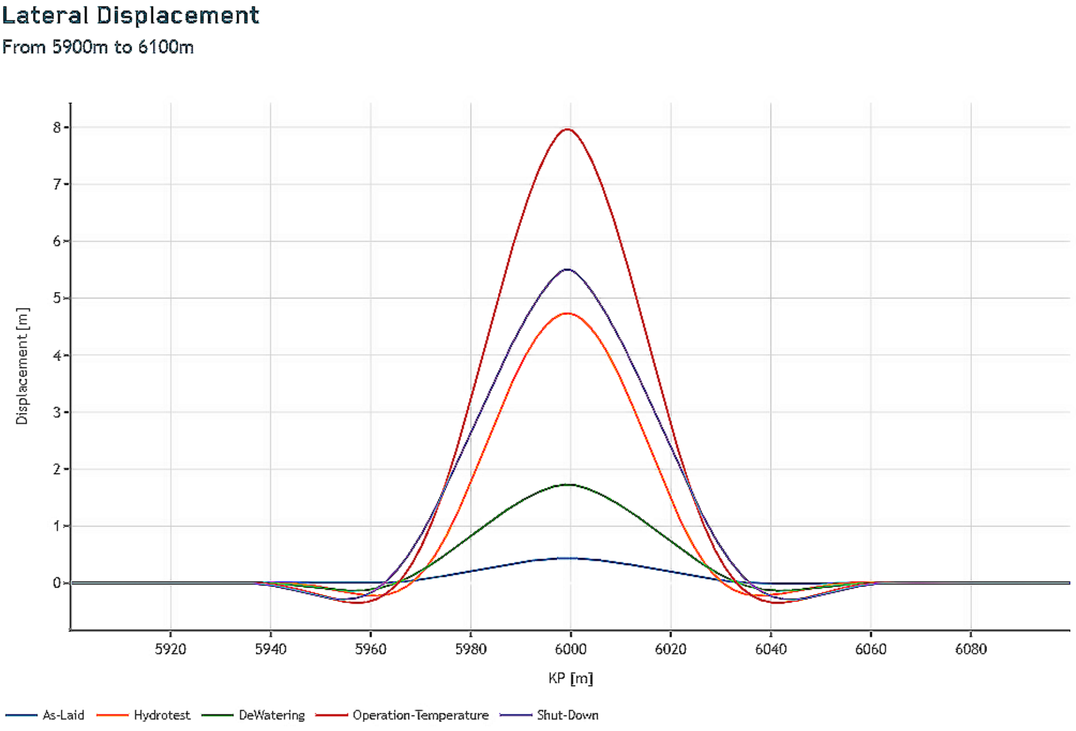

Fig. 3 Pipeline lateral curvature for WI9 with 0.8 m RB at KP = 10500 m (case 1).

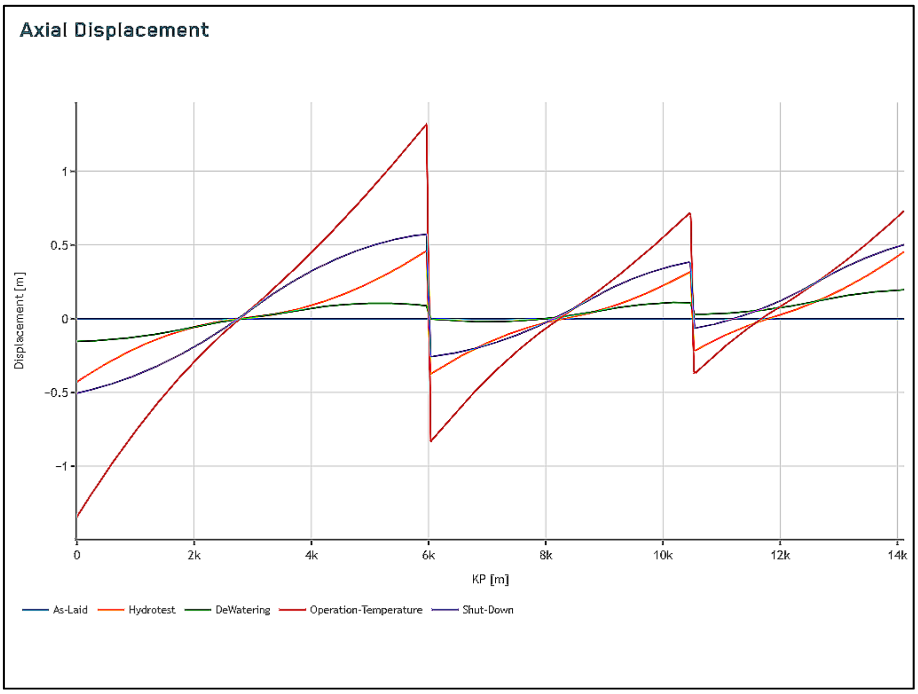

Fig. 4 Axial displacement for water injection with RB at KP = 10500 m and 1Sleeper at KP 6000 m (case 1).

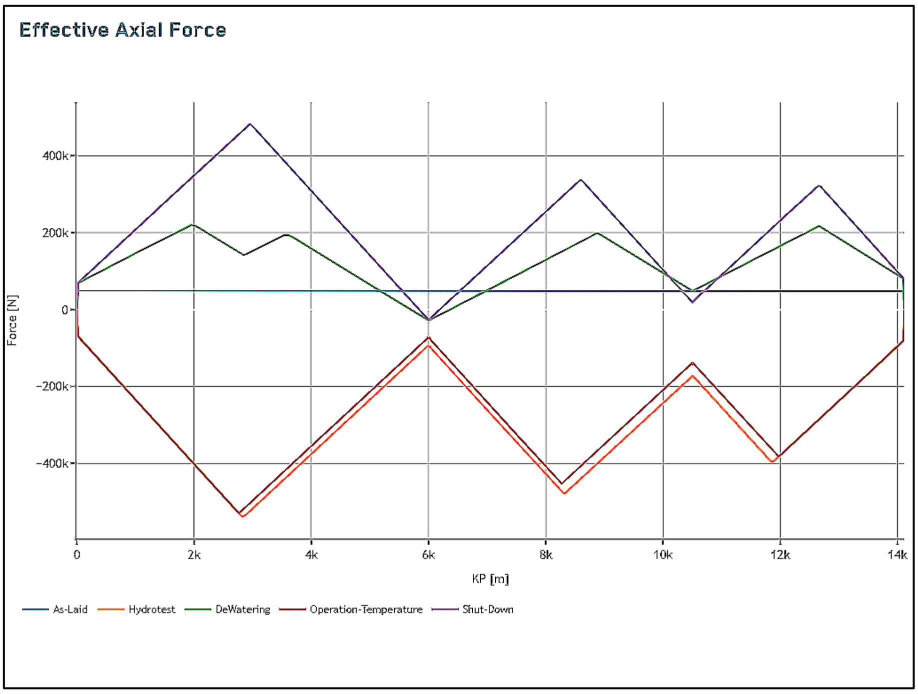

Fig. 5 Effective axial force for water injection with RB at KP = 10500 m and 1Sleeper at KP 6000 m (case 1).

Table 6 DCC and LCC Unity check for Water Injection with RB at KP = 10500 m and 1Sleeper at KP 6000 m (case 1).

Condition	Internal Pressure (Bar)	External Pressure (Bar)	Axial Compr. Strain [%]	DNV DCC Check without SNCF	DNV LCC Check
Hydrotest	605.767	158.267	-0.459	0.06 [1]	0.973
Operating	265.284	147.491	-0.82	0.359	2.547
Shutdown	147.491	147.491	-0.658	0.448	0.44

4.3 Fatigue Results

The cumulative fatigue damage for buckled flowline under operational load cycles is calculated considering the maximum loads generated at buckle by fluctuations of pressure and temperature between start-up and full shutdown conditions [17] as described below:

- For start-up conditions, the flowline is conservatively considered at maximum operating temperature and the associated operating pressure profiles.

For shutdown conditions, it is assumed that the internal pressure is equal to the fluid internal column and the internal temperature is the same as the external 4°C.

The maximum bending and true axial force ranges coming from FE analyses are used to calculate the stress range at the inner and outer pipe surfaces, considering half-corroded wall thickness.

Using the parameters reported in Section 5.6 and Water Injection Flowline in Place Fatigue Analysis Report, cumulative fatigue damages have been calculated for the inner and outer surfaces.

Results are reported for 20 years of life at KP2.2 (rogue buckle location) in Table 7.

Table 7 Fatigue results summary — Base case fatigue split (10%, 10%, 80%) [11, 17].

<table>
<tr><th>Fiber Position</th><th>Friction Cases</th><th>S-N curve</th><th>SCF</th><th>Lateral Bending Moment Range [kN.m]</th><th>True axial force range [kN]</th><th>Outer Stress [MPa]</th><th>Inner Stress [MPa]</th><th>Membrane Stress [MPa]</th><th>Fatigue Stress [MPa]</th><th>UC = Total Damage/ Allowable Damage</th></tr>
<tr><td>Inner Pipe Surface</td><td>BE-HE</td><td>F1 in Air</td><td>1.143</td><td>197.513</td><td>126.52</td><td rowspan="2">479.5</td><td rowspan="2">421.8</td><td rowspan="2">450.7</td><td>486</td><td>0.290</td></tr>
<tr><td>Outer Pipe Surface</td><td>BE-HE</td><td>D in Air</td><td>1.229</td><td>197.513</td><td>126.52</td><td>583</td><td>0.385</td></tr>
</table>

A common split between installation, as laid, and operation of respectively 10%, 10% and 80% leads to short standby times. To improve these standby times at an acceptable level, installation proposed the following split 50%, 5% and 45%, and relevant results are given below in Table 8.

Table 8 Fatigue results summary — Proposed optimized fatigue split (50%, 5%, 45%) [11, 17].

<table>
<tr><th>Fiber Position</th><th>Friction Cases</th><th>S-N curve</th><th>SCF</th><th>Lateral Bending Moment Range [kN.m]</th><th>True axial force range [kN]</th><th>Outer Stress [MPa]</th><th>Inner Stress [MPa]</th><th>Membrane Stress [MPa]</th><th>Fatigue Stress [MPa]</th><th>UC = Total Damage / Allowable Damage</th></tr>
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<tr><td>Outer Pipe Surface</td><td>BE-HE</td><td>D in Air</td><td>1.229</td><td>197.513</td><td>126.52</td><td>583</td><td>0.684</td></tr>
</table>

The proposed split is acceptable as fatigue damages are below the limit. Therefore, no fatigue issues are envisaged using this adjusted split for the Water Injection line.

- Half-corroded pipe is considered for fatigue verification.
- Fatigue stresses are calculated in accordance to Global Buckling of Submarine Pipelines Due to High Temperature/High Pressure [10].
- The RB at KP2.2 before the sleeper at KP6 has been identified as the most stringent location in terms of fatigue.

- A KDF of 4 has been considered for the inner surface, and a KDF of 9 has been considered for the outer surface.
- For 20 years of design life, 84 cycles are considered
- The allowable damage considered in the UC calculation is 80% (operating)/DFF = 26.66% as the base case.
- The allowable damage considered in the UC calculation for optimized fatigue split is 45% (operating)/DFF = 15%.

Fatigue damages are below the limit; therefore, no fatigue issues are envisaged for AGOGO phase 2 water injection pipelines, considering one mitigation located at KP6 [5].

- The accumulative fatigue damage level of the pipe is within its allowable limit during operation cycles considering 20 years' design life, a KDF of 4 for the inner surface, and a KDF of 9 for the outer surface;

5. Conclusions

The results show that the water injection line is susceptible to lateral buckling under hydrotest and operating conditions.

The results show a rogue buckle is not safe as the pipeline fails all criteria (DCC, uniform strain capacity) for that reason, lateral buckling mitigation is required. According to probabilistic results, 1 (one) LBMS is required and the best position is KP6.

The results discussed within this report exclude installation and VIV fatigue, which are treated in dedicated reports.

From the lateral buckling analysis results the following conclusions are made:

- The Agogo phase 2 water injection pipeline is susceptible to lateral buckling under operation conditions and hydrotest.
- When a rogue buckle (no mitigation) happens at the peak effective force location, the line fails both the LCC and DCC check;
- 1 Mitigation measures are required to reduce the compression force, stresses, bending moments, and strains to acceptable levels;
- Considering 1 mitigation, the cyclic longitudinal stress range, and the equivalent plastic strains are well within their cyclic plasticity limits as per Submarine Pipeline Systems;

The route curve has been found stable during operation and shut-down.

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