THE STUDY OF LATERAL BUCKLING MITIGATION METHODS FOR SUBSEA PIPELINES

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ABSTRACT

The present study introduces artificial buckling triggering features and then presents more description about snake pipe laying as the most common method for South Pars pipelines. Also the post buckling configuration and the strains resulting for single buckle and artificial buckles have been calculated with FEM program ANSYS. Limit states, as per DNV OS-F101 and SAFEBUCK Guideline are used for the verification of the buckling response.

INTRODUCTION

Compressive loads are commonly induced in pipelines by the frictional restraint of axial extension due to high temperature and pressure. The pipeline section that is virtually anchored could buckle either vertically (upheaval buckling), or horizontally (lateral buckling), this is caused by axial force near the initial imperfection. A single isolated unacceptable buckle would result in significant lateral bending moment and strains. The release of the effective axial compression into the multi artificial buckles would result buckling development in a controlled way with feed-in sharing between the different buckles.

EFFECTIVE AXIAL FORCE

If the expansion due to temperature and pressure is restrained in some way, for example by the frictional restraint of the seabed, then axial compressive force will develop in the pipeline, as illustrated in Figure 1.

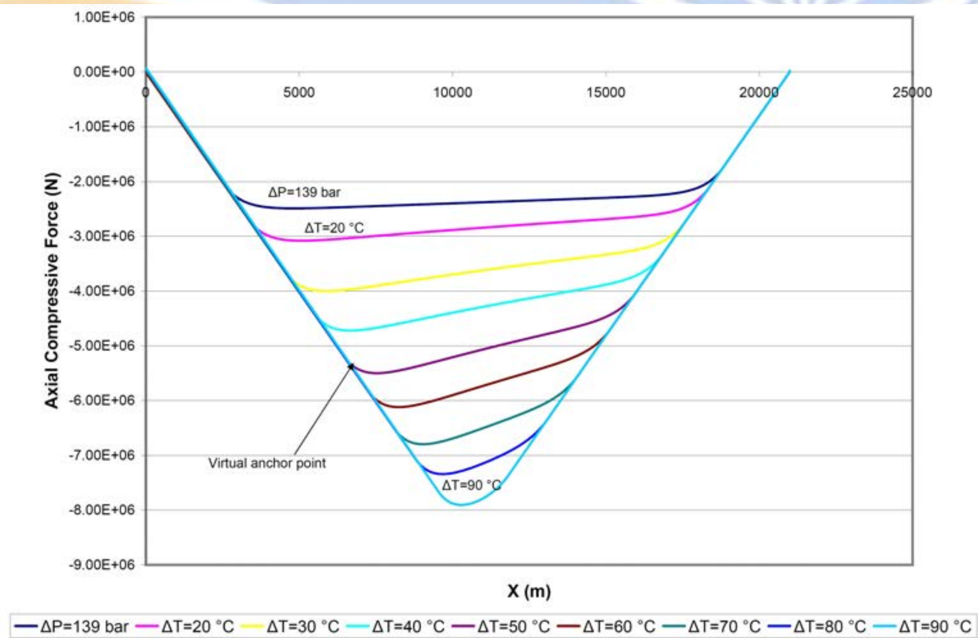

Figure 1: Axial compressive force along the straight pipeline in different conditions

Since pressure and temperature vary along the pipeline length, the fully constrained force also varies along the length as the pipe cools. This is shown in Figure 2 by the fall in the curve between x=0 and x=L.

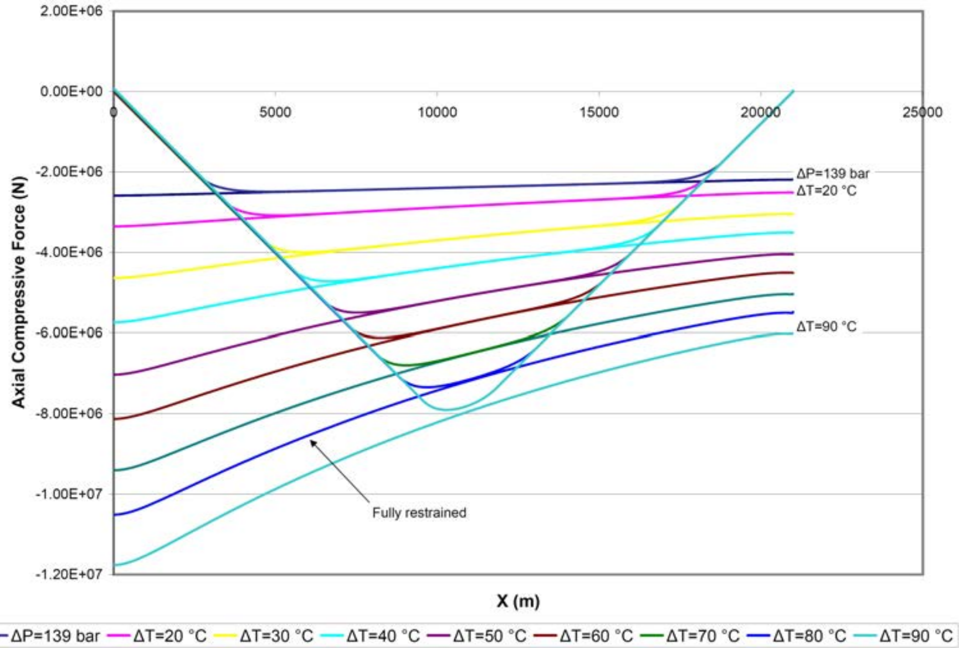

Figure 2: Axial compressive force along the fully restrained straight pipeline in different conditions

For a pipeline with free ends, the effective axial force gradually increases from zero at the ends, due to the frictional restraint of the seabed, until the force reaches full restraint. For a short pipeline, the overall length may be insufficient to reach full restraint.

The effective axial force in the pipeline is calculated according to following formula;

$$\begin{cases} F_{eff} = -\varepsilon_f \, E \, A_{stc} & if \quad L \le L_{AC} \\ F_{eff} = -(\varepsilon_E + \varepsilon_\nu + \varepsilon_T) E \, A_{stc} & if \quad L > L_{AC} \end{cases} \tag{1}$$

F_{eff} : Effective axial force

ε_E : Strain due to end cap effect; $\varepsilon_E = \dfrac{P_i A_i}{A_{stc} E}$

ε_ν : Strain due to Poisson effect; $\varepsilon_\nu = -\upsilon \left[P_i \left(\dfrac{D-2t}{2tE} \right) \right]$

ε_T : Strain due to thermal effect; $\varepsilon_\nu = \alpha \Delta T$

ε_f : Strain due to mobilisation of friction; $\varepsilon_f = \dfrac{\mu_{ax} W_s L}{A_{stc} E}$

A_{stc} : Steel pipe cross section

A_i : Pipe bore area

L_{AC} : Active length

L : Distance of pipeline from free end

W_s : Submerged weight of pipe

μ_{ax} : Axial friction coefficient

E : Modulus of elasticity for steel

υ : Poison's ratio for steel

D : Pipe outside diameter

t : Pipe wall thickness

ΔT : Temperature difference

α :Thermal expansion coefficient

P_i : The design pressure plus the internal hydrostatic head

MITIGATION OPTIONS FOR HIGH PRESSURE OR HIGH TEMPERATURE PIPELINES

Mitigation of the buckling problem can be broadly divided into three categories:

1. Techniques to reduce the effective force in the pipeline to avoid buckling or reduce buckling loads that include:
    - Installing a cooling spool at pipeline inlet;
    - In-line expansion spools;
    - Installing the pipeline while hot.
2. Techniques to constrain the effective force and prevent buckling that typical include:
    - Trenching the pipeline
    - Trench and backfill
    - Trench, backfill and spot rockdump
    - Trench and blanket rockdump
    - Blanket rockdump
3. Techniques to relieve the effective force and allow buckling that include:
    - Snake-lay;
    - Reduced Download;
    - Vertical upset;
    - Zero radius bend.

ARTIFICIAL BUCKLING TRIGGERING FEATURES

The design strategy of relieving effective force will involve a buckle initiation technique, to guarantee the formation of regular buckles. By this strategy more than one buckles form in the anchored pipeline. Between adjacent buckles there must be a virtual anchor point at which the direction of pipe expansion changes. This effectively divides the pipe up into more than one short pipeline anchored at each end and discrete series of isolated buckles between anchor points.

Each buckle initiation method is detailed in the following sections.

Snake Lay

The most common buckle initiation approach adopted to date is snake lay. In snake-lay, the pipeline is laid in a series of gentle curves, as illustrated in Figure 3.

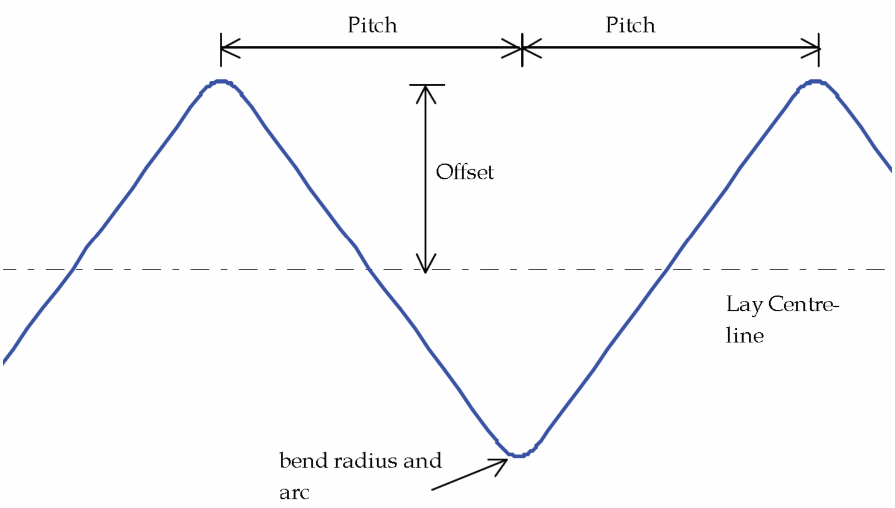

Figure 3: Typical Snake Lay Configuration (exaggerated vertical scale)

Figure 3 shows the key parameters in the snake lay configuration. The snake **pitch** is the half-wavelength, defined as the distance between successive snake crowns. The **offset** is the distance from the lay centre-line to the crown of the snake and the **bend radius** is the average lay radius around the bend.
Clearly, the propensity for buckling is controlled by the bend radius of the snake. The radius is designed to act as the buckle initiator, with the aim of developing a lateral buckle at some point on the curve. This is a true localised lateral buckle, not a benign expansion of the snake crown. Decreasing the bend radius increases the likelihood of buckling (although this is ultimately limited by the minimum lay radius capability of the lay vessel for the given water depth and seabed). However, it is also influenced by the snake pitch and offset. The frequency of buckling can be increased by reducing the snake pitch; although this is limited by the potential for buckles to interact, localise, feed-through and coalesce. The approach does give the designer some degree of control and by a careful choice of these parameters the success of the snake lay can be maximised.

Local Weight Reduction
The download caused by the pipeline submerged weight can be locally reduced by either adding buoyancy or, in the case of a large concrete coated export pipeline, by reducing the concrete weight coat thickness or density. Using the distributed buoyancy approach, discrete lengths of typically 60m to 200m of the pipeline are installed with additional buoyancy on them; these lengths are the intended buckle initiation sites as illustrated in Figure 4.

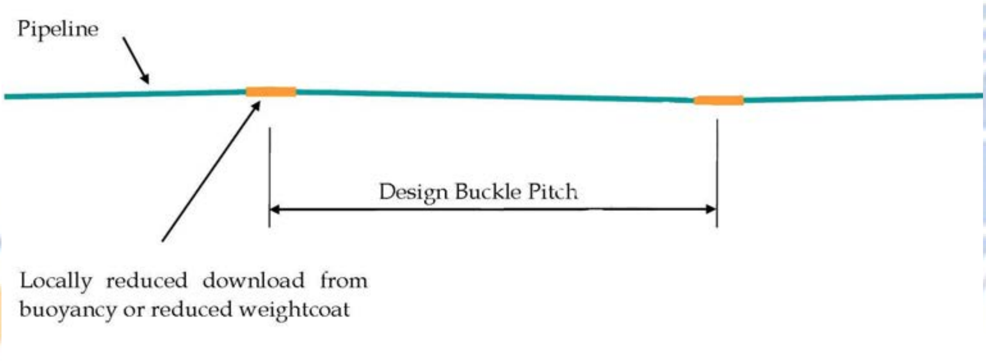

Figure 4: Buckle Initiation Using Buoyancy

Vertical Upset
Pipeline buckling can be initiated in either the horizontal or the vertical direction. If the pipeline is laid on an uneven seabed, then an initial vertical movement is highly likely to develop into a lateral buckle. This approach takes advantage of this fact. The technique works by deliberately introducing significant vertical out of straightness (OOS) at a number of points along the pipeline. Two techniques have been employed:

- Sleepers
- Gravel dump berms

The sleeper technique employs several large diameter pipe joints welded together and laid perpendicular to the lay route to provide the vertical OOS. The sleepers are installed prior to pipe lay at the appropriate spacing, as illustrated in Figure 5.

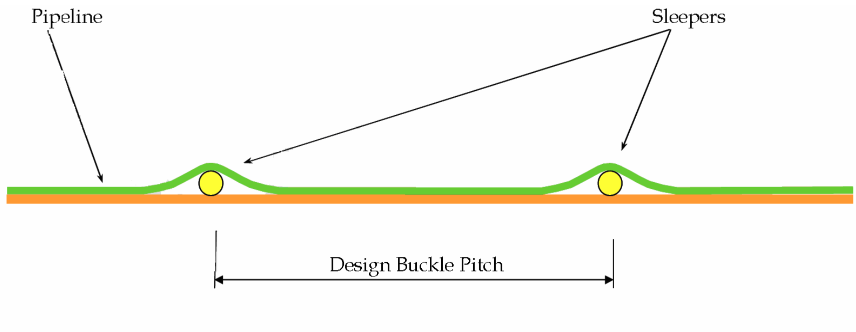

Figure 5: Buckle Initiation Using Sleepers

In the gravel dump option, the sleeper is replaced by a gravel berm which does not give the same level of reduction in the lateral restraint; otherwise, the concept is identical.

Zero Radius Lay

When using snake lay, the propensity for buckling is controlled by the bend radius of the snake. The radius is designed to act as the buckle initiator, with the aim of developing a lateral buckle at some point on the curve. Decreasing the bend radius increases the likelihood of buckling although for snake lay, this is ultimately limited by the minimum lay radius capability of the lay vessel for the given water depth and seabed. When using the zero radius lay method, the smallest bend radius achievable is limited by the flexural rigidity of the pipeline only. The method is referred to as 'zero radius' because the lay vessel manoeuvres apply the entire change of direction in one operation, as if it were laying a bend with zero radius, although the flexural rigidity of the pipeline results in a pipeline bend of greater than zero radius.

The pipeline is laid alongside a preinstalled counteract as shown in Figure 5.4; the vessel then moves laterally and deviates the route with a single change in direction. The presence of the counteract ensures the bend remains in the pipeline as the lay vessel continues to lay away from the counteract without relying wholly on pipe-soil friction to ensure the target bend radius is achieved. However it is not necessary for the pipeline to contact the counteract if the pipe-soil friction is great enough to allow installation of the minimum bend radius.

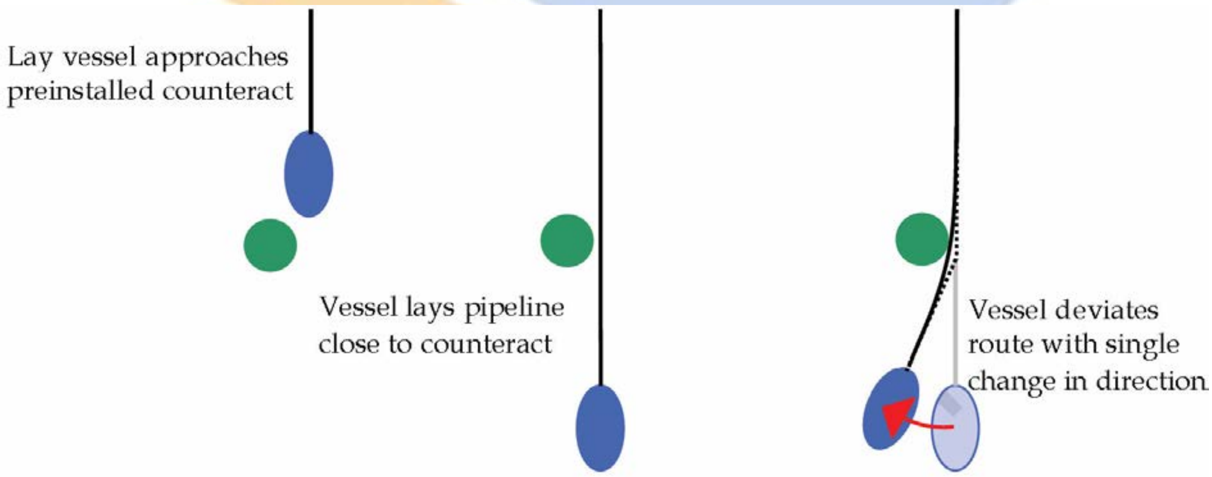

Figure 6: Zero Radius Lay Schematic

FINITE ELEMENT ANALYSIS METHODOLOGY

Different cases of straight and snaked pipeline have been modeled by finite element analysis (ANSYS) to study stress and strain of the pipeline under expansion loads in large displacement condition. A pipeline with 21 km has been considered for both straight and snaked pipeline. The straight pipeline is long enough to be anchored virtually.

Element description

The pipeline is modeled using plastic pipe element type: PIPE20 in ANSYS 11.0. The PIPE series element has typical beam properties but allows in addition to consider the constant hoop stress caused by the external/internal pressure loadings. Therefore, this element is well suited for pipeline analysis under operating conditions. The FE model used in the analyses for the pipeline has elements with a constant length of 1m.

The plasticity behavior of the pipeline is included in the pipeline modeling. For more that 50°C of Pipe temperature the stress and strain curve is changed according the Stress De-Rating curve (Figure 5-1) of DNV-OS-F101

The seabed is modeled as a 2D rigid flat surface (target surface in ANSYS). The surface is large enough to ensure the pipeline-seabed contact throughout the operation condition. In this study, rigid-rigid contact pairs are manually defined between individual pipeline node (termed contact node) and seabed surface.

It is assumed that the pipeline is in perfect contact with the seabed over the entire length. The ends of the pipeline are free to move.

ANSYS 11.0 introduces a feature that allows orthotropic friction to be modeled between contacts. The frictional contact using Coulomb's model expressed using contact pressure and friction stress.

ANALYSIS RESULTS

Three design cases have been considered to illustrate analysis results for different pipe laying shape. Two snake shape with different pith length and one straight pipeline including imperfection (imperfection is necessary to initiate buckle) are three cases that are shown in Table 1.

Table 1: Design Cases

	Pipe laying shape	Pitch (m)	Offset (m)	Bend radius (m)
Case 1	Straight	-	-	-
Case 2	Snake	3500	100	1500
Case 3	Snake	2500	100	1500

Design Data

The main design data for all cases are presented in Table 2. These data typically are same as South Pars Pipelines design data.

Table 2: Design Data

Pipe nominal diameter	32 inches
Pipe wall thickness	20.6 mm
Installation temperature	13 °C
Maximum operation temperature	90 °C
Maximum external pressure	8.5 barg
Maximum internal pressure	139 barg
Specified Minimum Yield Strength (SMYS)	450 Mpa
Specified Minimum Tensile Strength (SMTS)	535 Mpa
Submerge weight in operation case	2230 N/m
Concrete Coating Thickness	55 mm
Axial friction factor	0.36
Lateral friction factor	0.53

Load Step Description

During pipeline installation external pressure and during operation internal pressure is applied to pipeline.

During the Heat-up process, the 32” Pipeline is heated to maximum operating temperature of about 90°C starting from 13°C surrounding temperature.

Maximum temperature and pressure at the start of pipeline are decreased along pipeline according to temperature and pressure profile.

Limit States

In lateral buckling design, high stresses and strains can be developed at buckle crowns. The limit states associated with these local buckling, strain capacity and fatigue loads are based on the SAFEBUCK Guideline. In the very sour environment experienced by the South Pars pipelines, high tensile loads can lead to an increased risk of stress corrosion cracking. In order to minimize the risk of stress corrosion cracking, the lateral buckling design shall limit the maximum tensile mechanical axial strain in the pipeline to 0.2%.

Straight Pipeline (Case 1)

In this case a straight pipeline with length of 21 km has been modeled to show single buckle strain.

For a perfectly straight pipeline or pipeline with large laying radius, the loading on the pipeline is perfectly in-plane (that is, axial stresses only), the out-of-plane deflections necessary to initiate buckling will not develop, and the analysis will fail to predict buckling behavior. In reality out of straightness will be induced to pipeline due to the barge movements and seabed characteristics. In the ANSYS model, out of straightness (displacement imperfection) has been applied in the middle of the 21 km straight pipe. The imperfection point has enough distance from virtual anchor point to ensure that feed line is enough for buckling.

Figure 7 shows axial compressive force along the straight pipeline with a single buckle. The pipeline buckles when the maximum temperature passes 20 °C. After buckling in the buckle zone, axial force drops and temperature growing up doesn’t have significant effect on axial force.

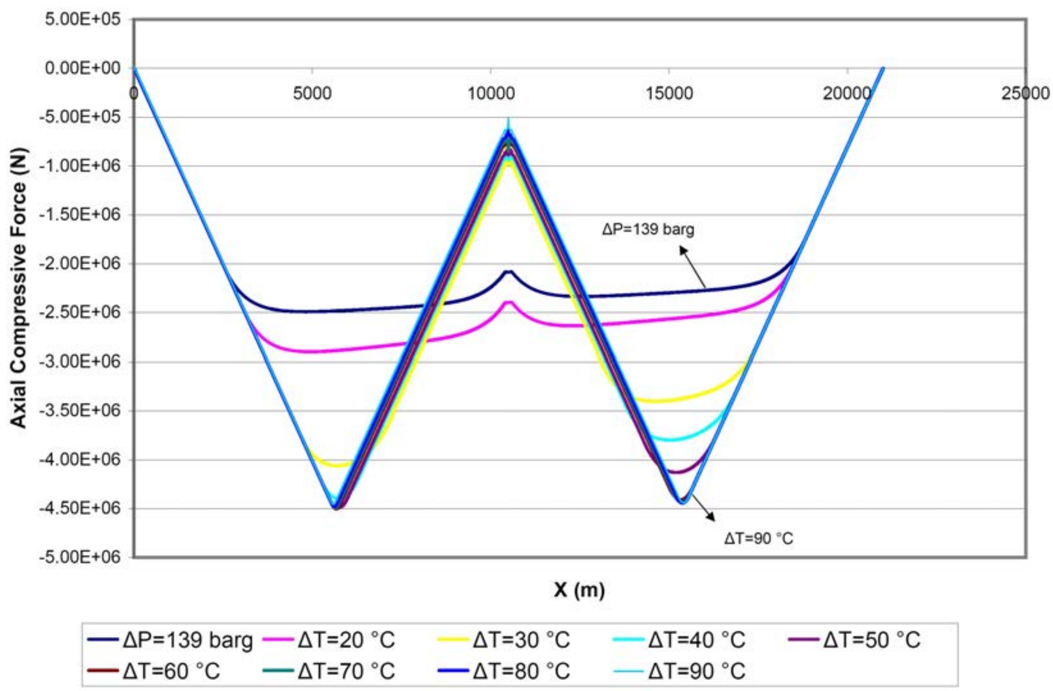

Figure 7: Axial compressive force along straight pipeline with a single buckle (Case 1)

Axial force has been relieved in the buckle and cussed unacceptable strain in the pipeline. According DNV-OS-F101 accumulative plastic strain should be less than 0.3%. Figure 8 shows equivalent plastic strain near the buckle. The plastic strain is too big and shows that a rupture has been occurred in the pipeline.

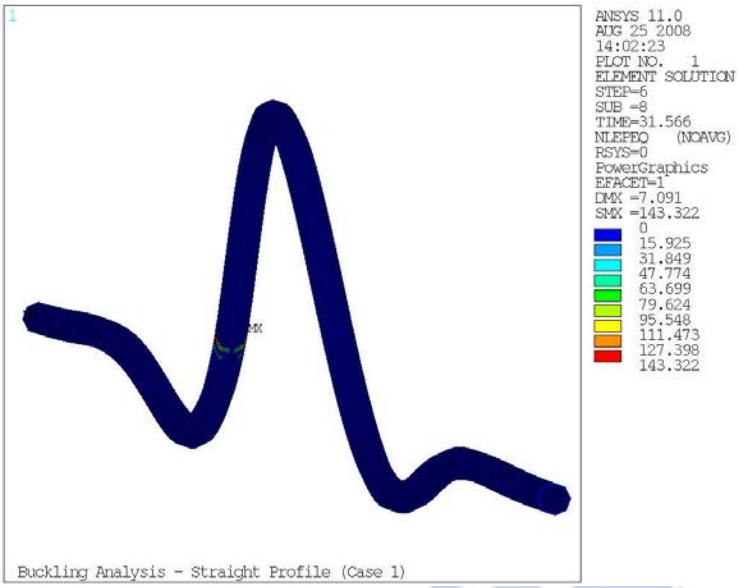

Figure 8: Equivalent Plastic Strain near the single buckle (Case 1) (exaggerated vertical scale)

The results show that lateral buckling mitigation shall be applied to this pipeline to prevent unacceptable buckle.

Snake Lay – Long Pitch (Case 2)

For the first try to mitigate pipeline buckling, design case 2 has been considered. Axial compressive force in different conditions is shown in Figure 9. As it is shown in Figure 9 buckle initiates when the maximum pressure passes 90 barg. Compared with straight pipeline, buckle initiates in the lower compressive force. It causes the smoother buckle without any rupture in the pipeline.

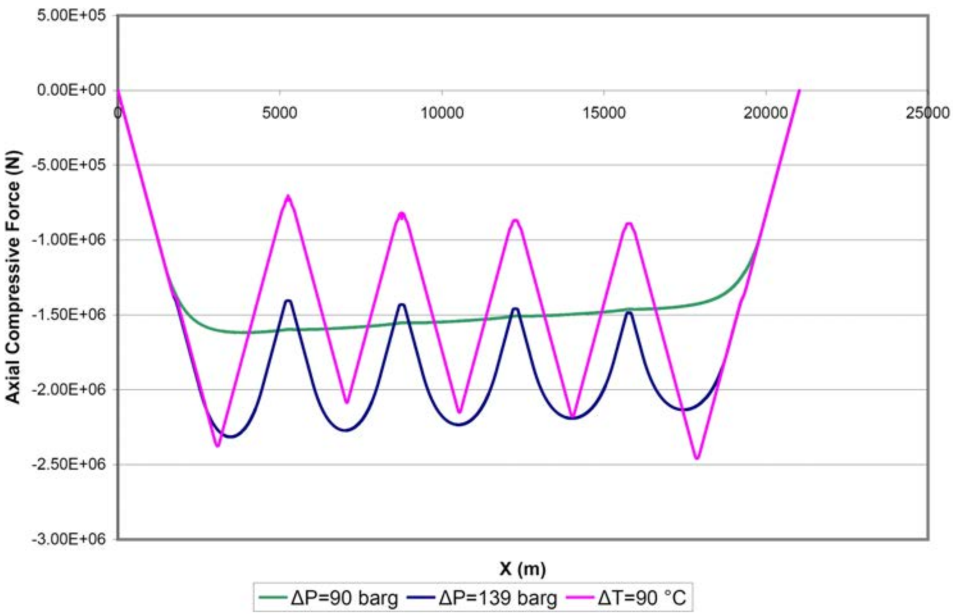

Figure 9: Axial compressive force in the snake laid pipeline with long pitch (case2)

In Figure 10 is shown equivalent plastic stain in the crown of the first buckle. According to Figure 10 maximum equivalent plastic strain in the maximum pressure and temperature is 0.32% that is more than DNV-OS-F101 limit state.

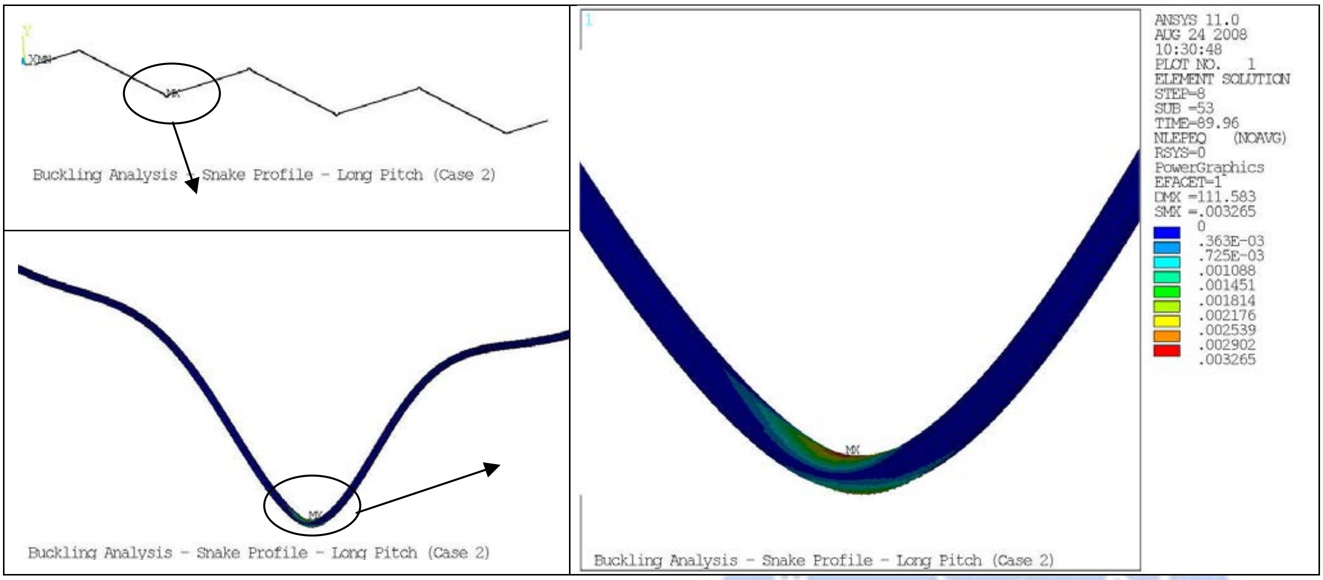

Figure 10: Equivalent Plastic Strain in the first buckle (Case 2) (exaggerated vertical scale)

Due to decreasing of pipeline temperature and pressure strain will decrease in next buckles. In Figure 11 and Figure 12 are shown the total axial strain distributions in the pipe section at 0deg and 180deg (see Figure 13 for details on pipe transversal section).

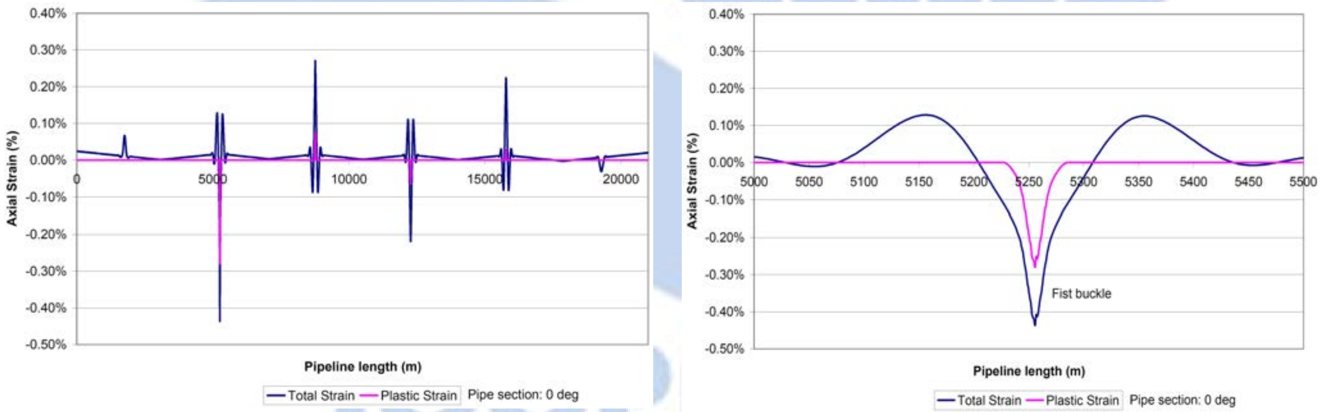

Figure 11: Total axial strain distribution in the pipe section at 0deg (Case 2)

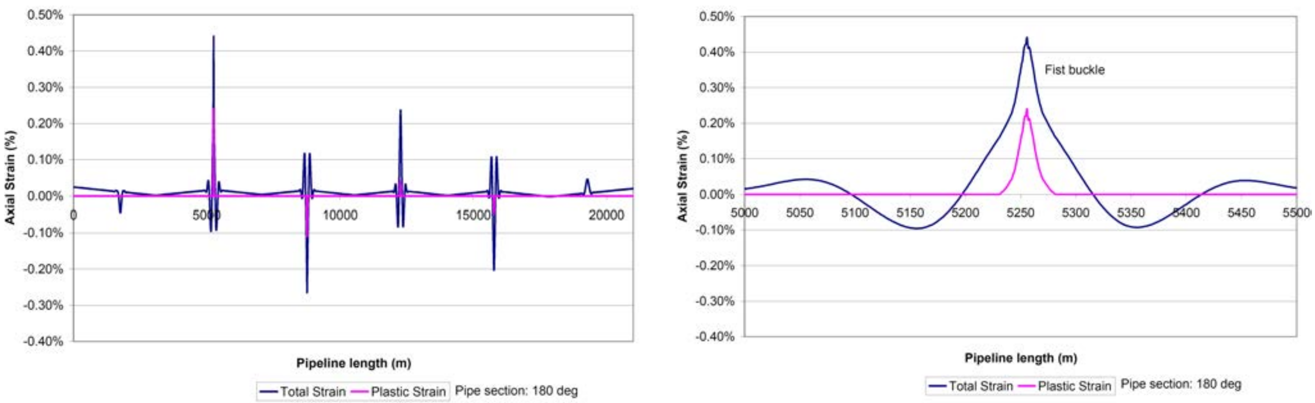

Figure 12: Total axial strain distribution in the pipe section at 180deg (Case 2)

As shown in Figure 11 and Figure 12 the maximum axial strain occurs in the first buckle. For pipe section at 0deg, compressive axial strain is 0.43% and for pipe section at 180deg tensile axial strain is 0.44% that both of them are two times bigger than SAFEBUCK limit state.

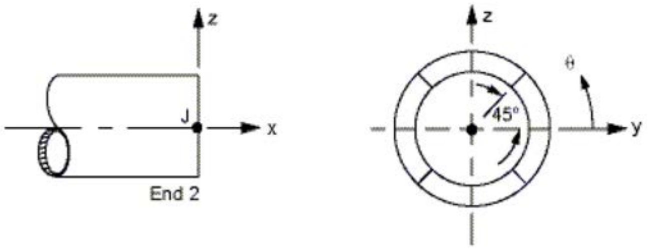

Figure 13: PIPE 20 configuration and its coordinate system

Snake Lay – Short Pitch (Case 3)

By decreasing of straight route, axial force will decrease and consequently feed-in to buckles will decrease. Figure 14 shows axial compressive force in different condition for short pitch case (Case 3). By comparing axial force in case 2 and case 3 it is clear that maximum axial force in case 3 is less than case 2. Bend radius in Case2 and Case3 is the same therefore both cases buckle in the same axial force level.

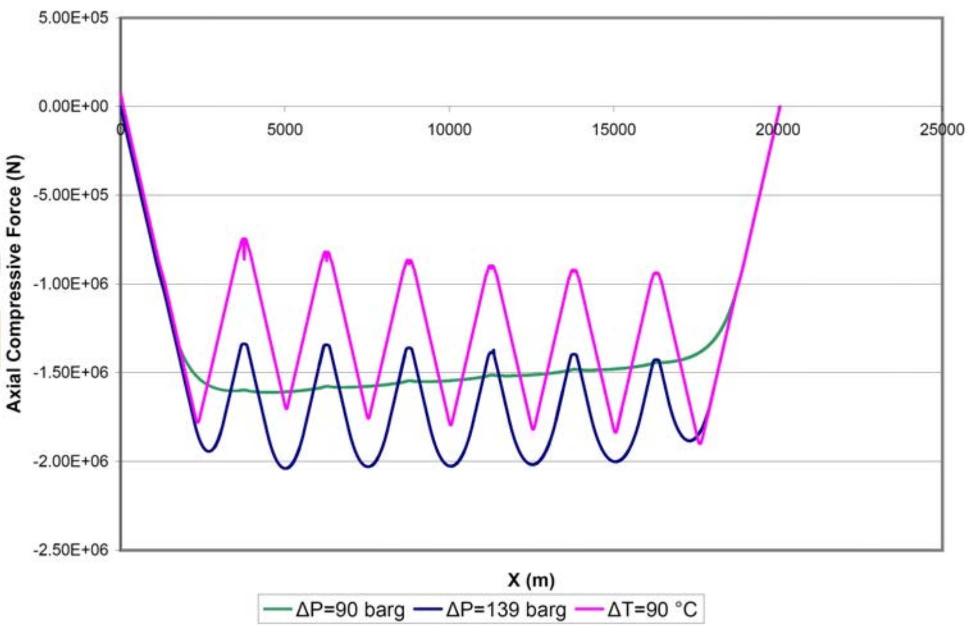

Figure 14: Axial compressive force in the snake laid pipeline with short pitch (case3)

Equivalent plastic stain in the crown of the first buckle for case 3 is shown in Figure 15. Maximum equivalent plastic strain in the maximum pressure and temperature is 0.11% that is allowable according to DNV-OS-F101.

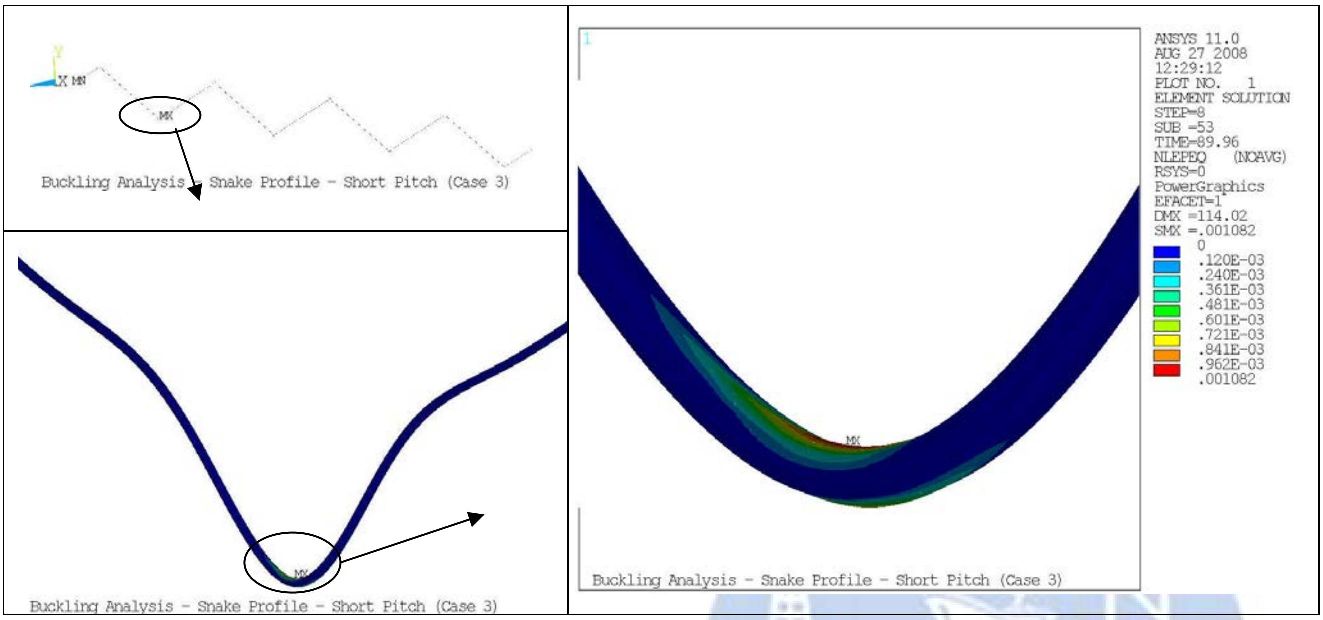

Figure 15: Equivalent Plastic Strain in the first buckle (Case 3) (exaggerated vertical scale)

Figure 16 and Figure 17 are shown the total axial strain distributions in the pipe section at 0deg and 180deg.

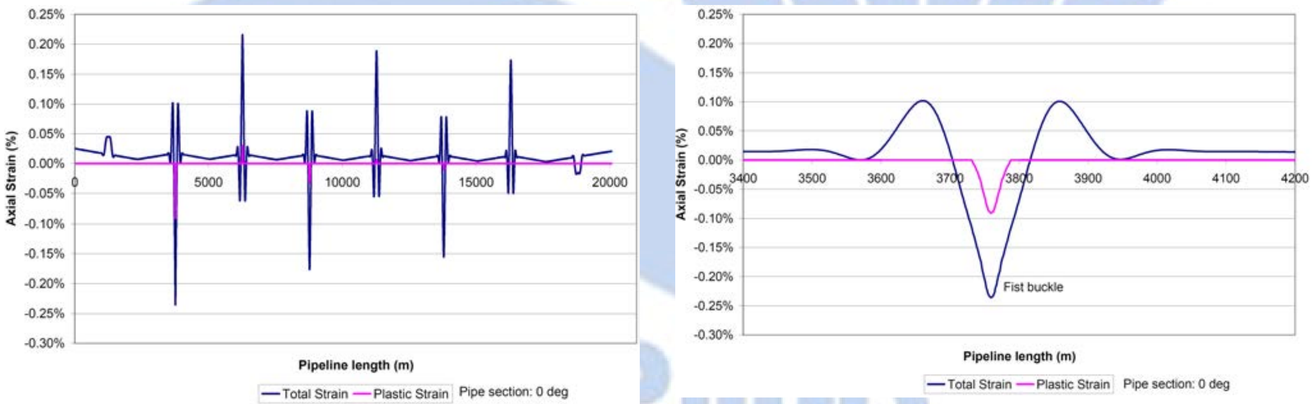

Figure 16: Total axial strain distribution in the pipe section at 0deg (Case 3)

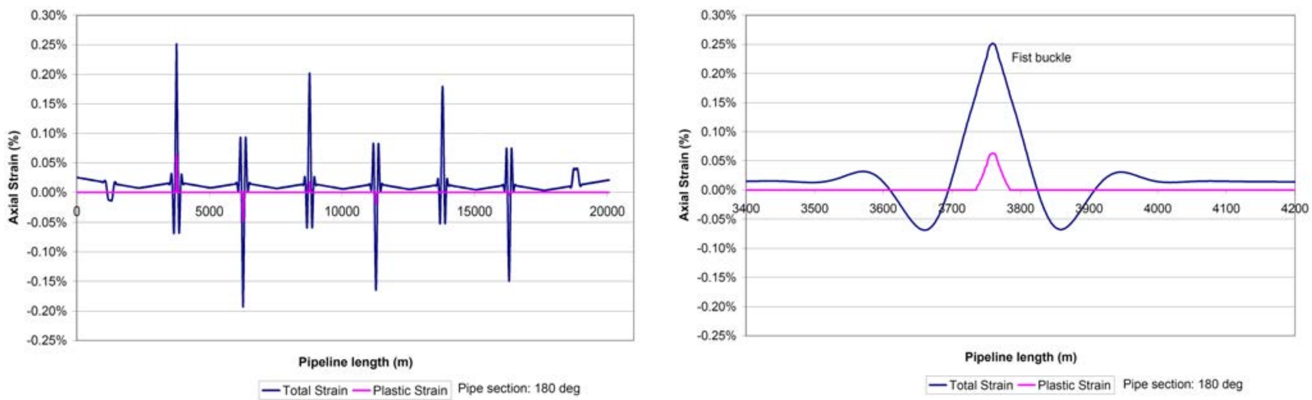

Figure 17: Total axial strain distribution in the pipe section at 180deg (Case 3)

As shown in Figure 16 and Figure 17 the maximum axial strain occurs in the first buckle like case 2. For pipe section at 0deg, compressive axial strain is 0.22% and for pipe section at 180deg tensile axial strain is 0.25%. All axial strains except axial strain of first buckle are below SAFEBUCK limit state. In this regard by changing of snake lay profile (using shorter pitch) or changing of concrete coating thickness (increasing submerge weight) or other mitigation methods first buckle could become in limit state range.

CONCLUSION

Buckle initiation in the lower axial force causes a plane buckle and relieves force smoothly that it depends on bend radius and submerge weight in the bend.

The results of the buckle formation probability analysis for the 32” pipeline show that 55(mm) concrete coating thickness and a nominal bend radius of 1500 m lead to a reliable buckle.

Comparing of case 2 and case 3 shows that 2500 m is the maximum acceptable pitch for the hot section of line.

Axial force growing up in the straight part increases feed-in to buckle and consequently increases strain in the buckle crown. Thicker concrete restrains force and prevents unacceptable buckle. Strain in the crown of first buckle of case 3 could be improved by this method.

REFERENCES

[1] "Pipeline Buckling Caused by Axial Loads", Hobbs, R.E., J of Constructional Steel Research 1980

[2] Offshore Standard DNV-OS-F101 Submarine Pipeline System

[3] "Lateral Buckling And Pipeline Walking, A Challenge for Hot Pipelines" M. Carr; D. Bruton; D. Lenslie, Offshore Pipeline Technology Conference 2003 Amsterdam

[4] "Safe Design of Pipelines with Lateral Buckling, Design Guideline", SAFEBUCK JIP, Boreas Report No. BR02050/SAFEBUCK/B, August 2004.