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International Journal for Scientific Research in Modern Engineering and Science

International Journal for Scientific Research in Modern Engineering and Science, 1(6): 25-35 (2020)

NUMERICAL AND ANALYTICAL ANALYSIS OF GLOBAL LATERAL BUCKLING OF OFFSHORE PIPELINE

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Abstract

An offshore pipeline laid on seabed is required to operate at high temperature and pressure. When this pipeline is operated at high internal pressure and temperature, it will attempt to expand and contract for differential temperature changes. For positive differential temperature it will be subjected to an axial compressive load and when this load reaches some critical value the pipe may experience relative movement. So buckling of offshore pipeline under thermal stress is one of the most important problems to be considered in pipeline design. The non-linear finite element analysis (FEA) is performed by modeling the soil-pipeline interaction by using finite element software package. The work further analyzes the lateral buckling of pipeline with out-of-straightness (OOS) (or say, initial imperfection) while applying operating temperature over a 250 m long pipeline model. The FEA model is verified by comparing the results with analytical solution.

Keywords: *Buckling; Pipeline; Force; Temperature; Seabed.*

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1. Introduction

Buckling of subsea pipeline is due to the relative movement of pipeline with respect to the surrounding soil. Global buckling mainly occur when pipeline is operated at high pressure and temperature due to which a high compressive axial force is built up in the pipe wall and when it exceed the critical value of load buckling occurs. Buckling leads to failure of the pipeline so it must be taken into consideration while designing the pipeline. While increase in temperature and pressure it is not easy to control the buckling behavior of pipeline. Offshore pipelines gradually become the main technique in the offshore engineering to transport gas and oil all around the world. As oil and gas industry moves farther into deep and ultra-deep waters, the subsea pipelines are being required to operate at ever higher temperature and pressure.

1.1 Global Buckling

Pipeline resting on seabed under operational conditions have a potential to buckle, walk and change configuration due to high temperature and pressure (HTHP) operational conditions. If the pipeline is restrained, a compressive axial force will be induced in the pipeline. According to Palmer and King(2004), this could lead to buckling of the pipeline if the compressive axial force induced reaches the critical buckling force. As a result of the induced force, the pipeline will tend to move upward or sideways to release the excessive axial force induced. The direction of the movement depends on the pipeline restrictions. As shown in Figure 1.1, large induced axial compressive force for trenched or buried pipeline will therefore lead to upheaval buckling (Upward) while exposed surface laid-pipeline leads to lateral buckling (sideways). This will endanger the integrity of the pipeline if not controlled.

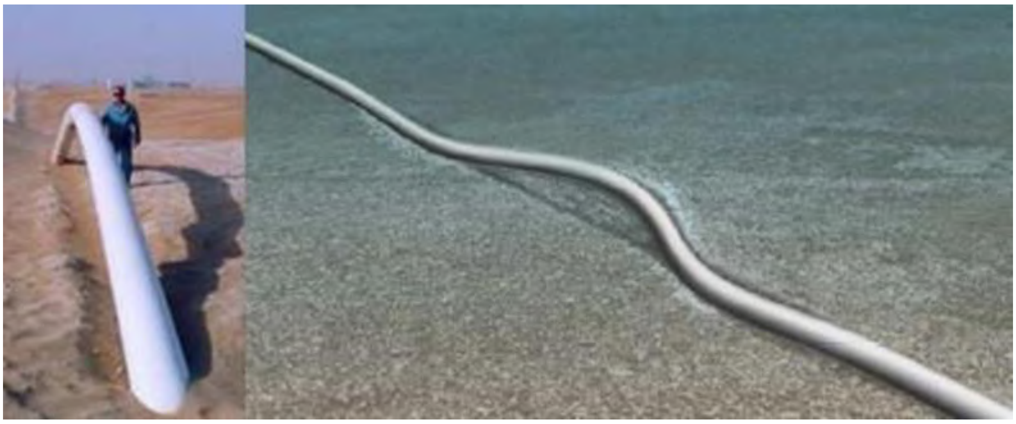


Figure1.1: Upheaval and Lateral Buckling

1.2 Local Buckling

Local buckling is normally the governing failure mode resulting from excessive material utilization (Almeida, 2001). It appears as wrinkling or as a local buckle on the compressive side of the cross section as shown in Figure 1.2. This failure mode could result in excessive material ovalisation and reduced cross-section area which reduces production efficiency or even cause full production stop in any event of pig getting stuck during pigging/inspection. A locally buckled pipeline cannot stand an increased bending moment in the pipeline. This also could lead to pipeline collapse or production lost time.

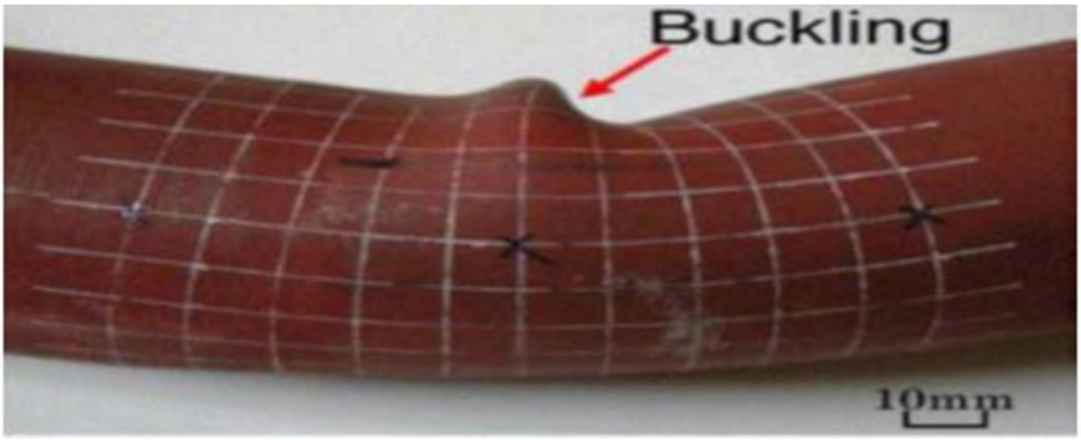


Figure1.2: Example of a local buckled Pipe

The increased cell temperature result in an increase in short circuit current and decrease in the open circuit voltage. Decrease in the open circuit voltage is more prominent than the increase in short circuit current. Therefore, as shown in figure 1, the power output and efficiency of solar cell and module decreases with increase in its operating temperature [1]. The current increase with temperature is due to the decrease in the band gap of Si and voltage decrease with temperature due to the increase in the carrier recombination.

2. Literature Review

In the late eighties and early nineties analytical tools were superseded in many circumstances due to the request to consider the plastic capacity of the pipe section. When the stresses exceed the elastic limit, a more sophisticated nonlinear analysis is required to account for the nonlinear state of stress. As the problems increased in their complexity, numerical models took the place of the analytical tools in the preference of engineers. Commercial finite element software package makes a significant role in modeling the nonlinear pipe-soil interaction and post buckling behavior of pipeline.

These examples highlight the vulnerability of pipelines to these buckling modes and the resulting disastrous human, environmental and economic consequences. One of the first experimental and analytical studies on upheaval buckling of an axially compressed frictionless strip was conducted by Allan (1968) who observed the sensitivity of the problem to initial imperfections.Lyons, (1973) discovered that traditional Coulomb friction model can be used to represent the force of sand on the pipeline, but it cannot be applied to soft clay when the pipeline buckles on the lateral plane. In the early eighties, pipeline technology started to account for in-service buckling. A decade later, a number of studies motivated by lateral buckling of railway tracks were presented by Kerr (1978) and Tvergaard and Needleman, (1981) who accounted for buckle localization and the nonlinear force–displacement relationship of the track foundation.

Guo et al. (2016) studied the lateral buckling analysis of submarine Pipeline with one arch initial Imperfection. According to him one arch initial imperfection is main form of imperfection of offshore pipeline. Pipeline with imperfection easily get failed due to overall buckling under thermal stress and internal pressure. The analysis of pipeline with imperfection shows that the temperature difference decreases with the increase in the buckling amplitude. The buckling topology of the pipeline changes with increase of imperfection amplitude. The critical temperature difference increases with the increase in soil friction coefficient. The axial load also increases with increase in soil frictional resistance.

3. Methodology

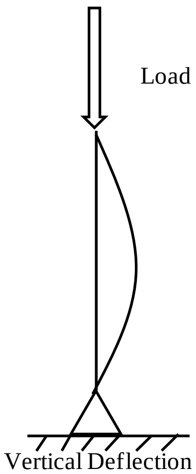
3.1 Theoretical Background

Buckling occurs physically when a structure becomes unstable under a loading configuration and mathematically when a bifurcation occurs in the solution to equation of equilibrium.

The present section discusses the theoretical background and basic scientific principle relating to pipe-soil interaction with respect to lateral buckling. This will vary from the driving factors of high temperature and pressures, breakout resistance to thermal buckling.
The basics of the study were generated by the principle of buckling phenomenon in a simple bar element. The same principle is applied for a subsea pipeline installed on a seabed.

Figure 4.1.a and Figure 4.1.b illustrate the bifurcation buckling and the load response in the bucking. This is a situation where the elastic stiffness of the structure is cancelled by the effects of compressive stress within the structure. If the effect of this causes the structure to suddenly displace a large in a direction normal to the loading direction, then it is a classical bifurcation buckling.

If there is a sudden large movement in the direction of the loading it is called a snap-through buckling. According to Robert "This occurs in structures experiencing limit point instability, when the load is increased infinitesimally beyond the critical load, the structure undergoes a large deformation into a different stable configuration which is not adjacent to the original configuration.



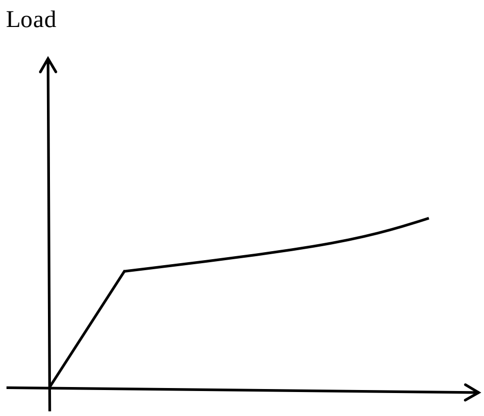


Figure 4.1: Bifurcation Buckling Figure 4.2: Load Response in Buckling

For pipeline with small initial imperfection, the buckling is expected to occur as a snap through buckling jumping from a particular equilibrium of smaller displacement to another equilibrium position of higher displacement while for those with large initial imperfection; it will undergo a gradual displacement.

Consider a beam section of length, L and Flexural rigidity, EI and compressive axial force, P.

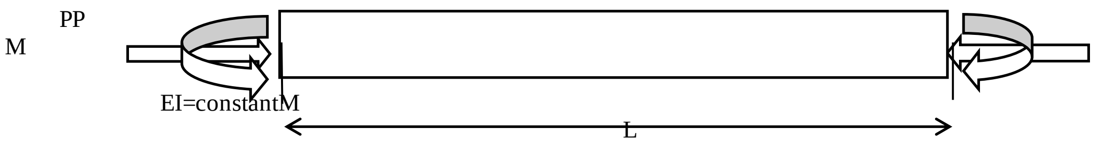


Figure 4.3: Beam Section under Loading

Buckling is said to occur if the combined bending and compressive stresses reaches the Critical Buckling load P_{cr} . By considering the equilibrium of lateral forces and bending moments acting on the beam section. The dynamic equation of motion for the beam section exposed to an axial compressive force P is given as:

$$\mathrm{EI}\frac{\partial^4 \mathrm{w}}{\partial \mathrm{x}^2}+\mathrm{P}\frac{\partial^2 \mathrm{w}}{\partial \mathrm{x}^2}=0 \tag{1}$$

From the homogeneous equation above, taking $\mathrm{w}=\mathrm{e}^{\lambda \mathrm{x}}$

Substituting the function $\mathrm{w}=\mathrm{e}^{\lambda \mathrm{x}}$ in equation (1), we have

$$\lambda^4+\frac{\mathrm{P}}{\mathrm{EI}}\lambda^2=0 \tag{2}$$

From equation (2) the solution for λ becomes a complex number

$$\lambda=\pm\sqrt{\frac{\mathrm{P}}{\mathrm{EI}}}\,\mathrm{i}$$

Hence general homogeneous solution becomes:

$$\mathrm{w}=\mathrm{A}\sin\sqrt{\frac{\mathrm{P}}{\mathrm{EI}}}\mathrm{x}+\mathrm{B}\cos\sqrt{\frac{\mathrm{P}}{\mathrm{EI}}}\mathrm{x}+\mathrm{C}+\mathrm{Dx} \tag{3}$$

Considering the case of a simply supported beam and, invoking the boundary condition we have:

$\mathrm{W}(\mathrm{x}=0)=0$, no deflection at support

$\mathrm{M}(\mathrm{x}=0)=\mathrm{EI}\frac{\partial^2 \mathrm{w}}{\partial \mathrm{x}^2}=0$, no bending at support

$\mathrm{W}(\mathrm{x}=\mathrm{L})=0$,no deflection at support

$\mathrm{M}(\mathrm{x}=\mathrm{L})=\mathrm{EI}\frac{\partial^2 \mathrm{w}}{\partial \mathrm{x}^2}=0$, no bending at support

From the above we can decide that B=C=D=0

Therefore we have

$$\mathrm{AP}\ \sin\sqrt{\frac{\mathrm{P}}{\mathrm{EI}}}\mathrm{L}=0$$

Hence A and P cannot be zero, so we conclude that …….. $\sin\sqrt{\frac{\mathrm{P}}{\mathrm{EI}}}\ \mathrm{L}=0$

Therefore $\sqrt{\frac{\mathrm{P}}{\mathrm{EI}}}\ \mathrm{L}=\mathrm{n}\pi$

The critical buckling that must exceed for buckling to occur becomes:

$$\mathrm{P}_{\mathrm{cr}}=\frac{\mathrm{n}^2\pi^2\mathrm{EI}}{\mathrm{L}^2} \tag{4}$$

For n=1, $\mathrm{P}_{\mathrm{cr}}=\frac{\pi^2\mathrm{EI}}{\mathrm{L}^2}$

For n=2, $\mathrm{P}_{\mathrm{cr}}=\frac{4\pi^2\mathrm{EI}}{\mathrm{L}^2}$

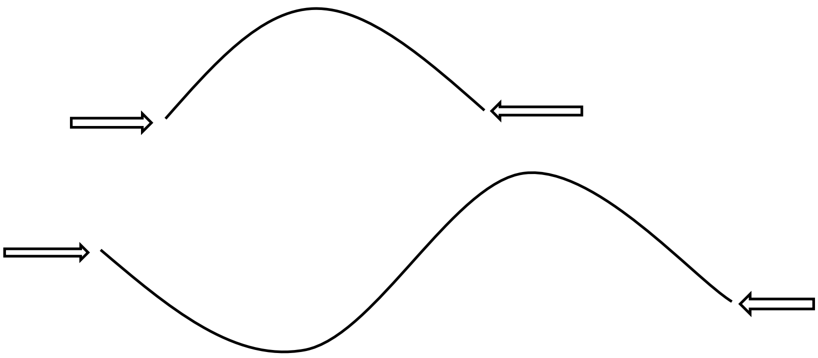


Figure 4.4: Lateral Buckling Mode-I and Mode-II

4. Result and Discussion

4.1 Critical Buckling Temperature (Analytical- Method)

The fully restrained axial force in the pipeline is

$$P_0 = 80.76\frac{EI}{L^2}\left[1 - \frac{R_1}{75.6}\left(\frac{L_0}{L}\right)^2\right]$$

$$+\left[1.59766 \times 10^{-5}\frac{\varphi_A\varphi_L q^2 A}{I}(L^7 - L_0^7) - \left(\frac{\varphi_A qL}{2}\right)^2\right]^{\frac{1}{2}}$$

Where,

$$R_1 = 4.6031\left\{\sin\left(4.493\frac{L_0}{L}\right) + 2.3061 \times \left[\frac{\sin 4.4934\left(1+\frac{L_0}{L}\right)}{\frac{L}{L_0}+1} + \frac{\sin 4.4934\left(1-\frac{L_0}{L}\right)}{\frac{L}{L_0}-1}\right]\right\}$$

Now, $L = \left[\frac{2.7969\times10^5\times(EI)^3}{(\varphi q)^2\times AE}\right]^{0.125} = 40.76\text{ m}$

Now use the value of buckle length 0.5L to 2L up to 20 values to compute safe design temperature change for first buckling mode. After taking 20 values of buckle length a graph of buckle length versus fully constrained axial force is plotted.

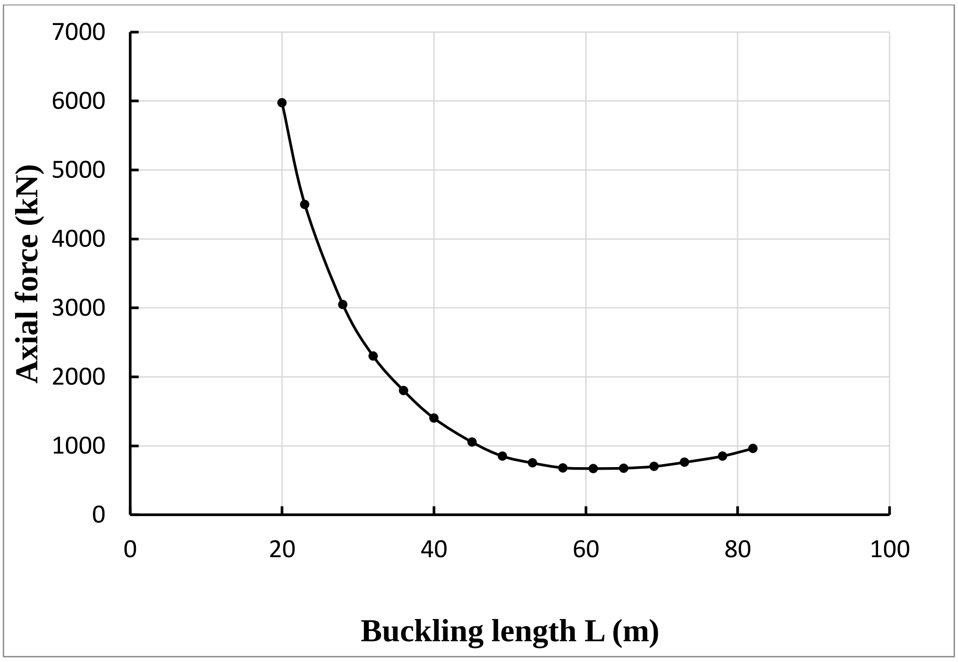


Figure 5.1: Buckling length versus axial force curve

From the above curve it is found that the safe axial force is about 664.28kN.

So safe temperature rise is calculated as

$$\frac{AE\alpha\Delta T}{\left(1+\frac{2AE}{LK}\right)} = 664.28 \times 10^3$$

$$\Delta T = 33.56°C$$

4.2 Numerical Analysis Results

To calculate critical buckling temperature according to finite element analysis, a pipeline model is run in ABAQUS to compare the result of analytical solution. A length of 250 m was run the parameter of pipeline and seabed soil was taken. The initial imperfection or out of straightness is taken as 150 mm and the initial imperfection wavelength is taken as 25m. An axial soil spring is attached to both the ends of the pipeline and other end of the spring is fixed.

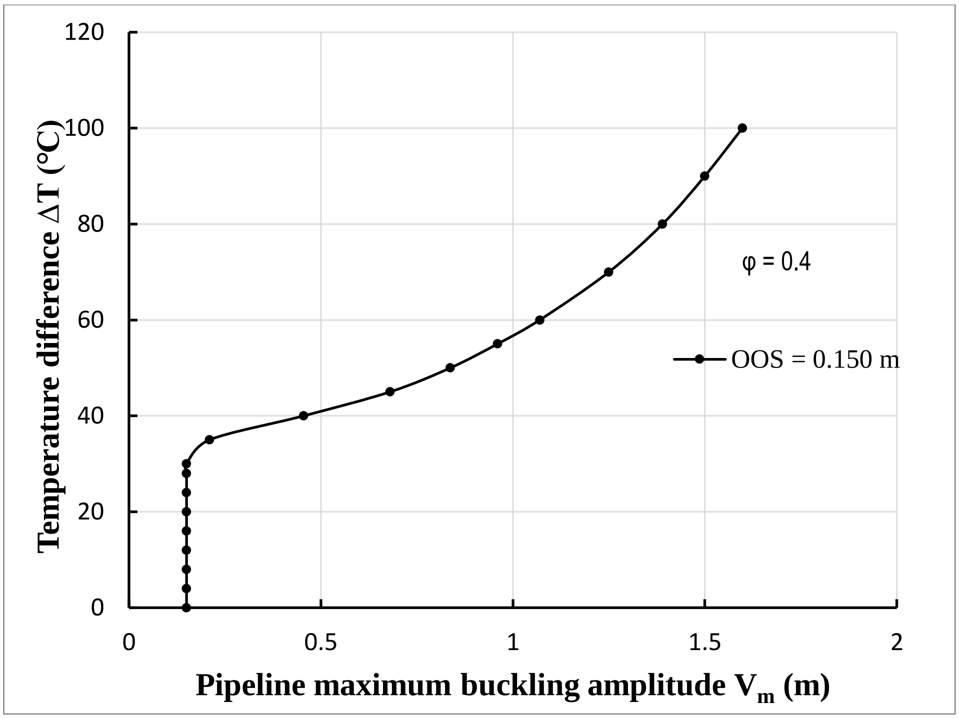


Figure 5.2: Pipeline maximum buckling amplitude versus temperature difference

From the above graph it is found that the triggering temperature difference is almost 34℃ which is nearly equal to the above analytical solution. Triggering temperature is also called as safe temperature difference. Once the temperature difference is higher than this value, the global buckling will happen continuously until the stress in the pipe wall reaches the yield stress. And the pipeline would not suffer the global buckling failure if the design temperature difference is lower than the triggering temperature difference.

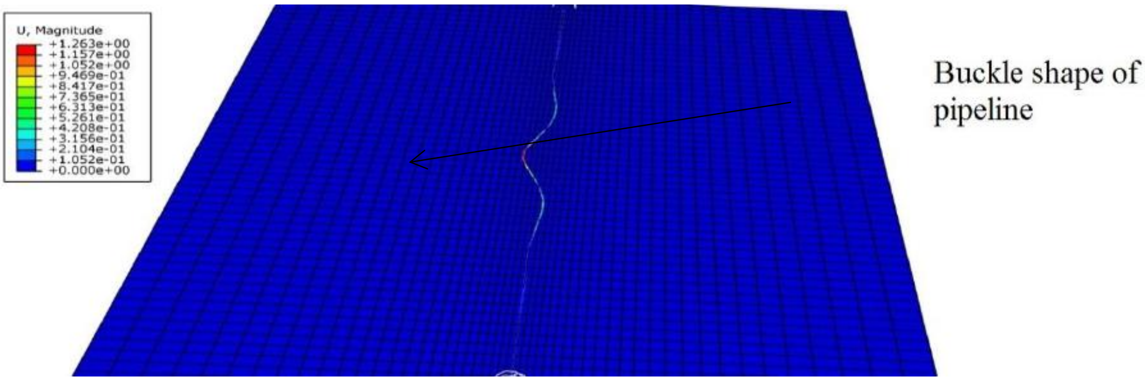


Figure 5.3: Pipeline deformation at operating temperature with 150mm OOS resting on deformable seabed

Above figure shows the result of finite element analysis using FEA software Abaqus. It shows the buckling of offshore pipeline resting on deformable seabed operating at different temperature difference. The maximum amplitude value after applying an operational temperature difference of 70℃ is 1.263 m.

4.3 Impact of Temperature on Pipeline Global Buckling

The effect of temperature on global lateral buckling shape of pipeline with considering soil spring at end boundary condition is obtained from numerical analysis is shown in Fig 5.4. The figure shows the variation of pipeline length and amplitude with respect to temperature change. The x-coordinate denotes the horizontal distance from end point of pipeline and y-coordinate denotes buckling amplitude. We can see that the buckling starts at initial imperfection segment. There is opposite movement of pipeline with respect to initial imperfection on both sides when the amplitude increases with increase in temperature difference.

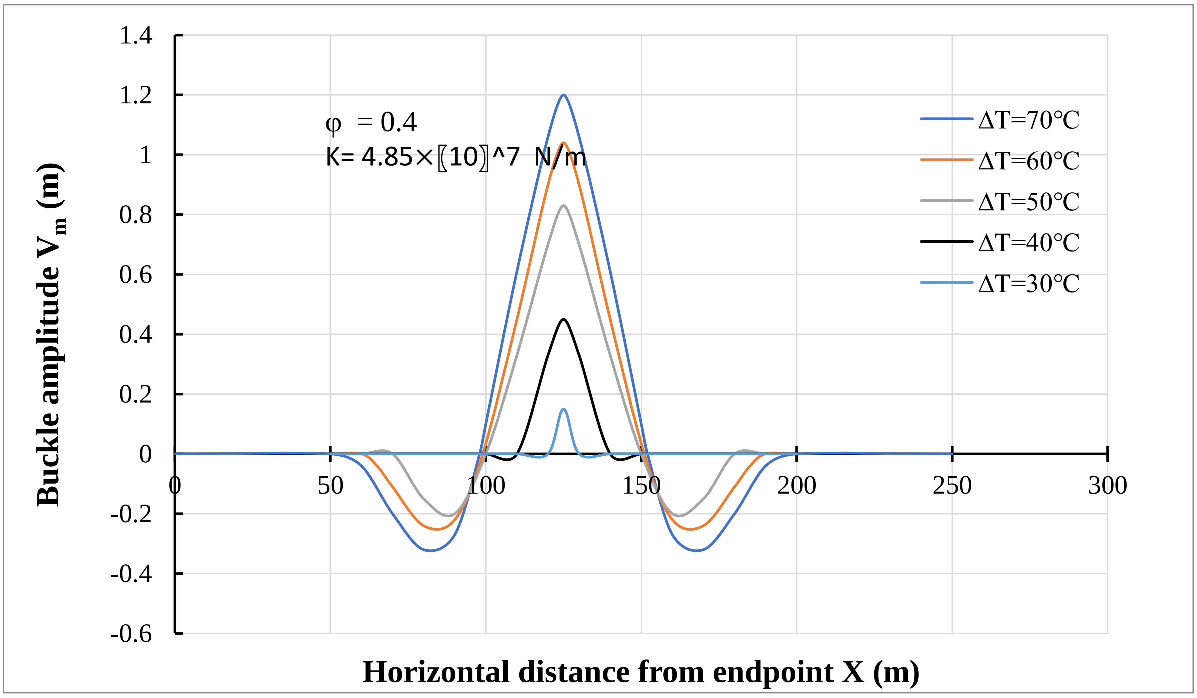


Figure 5.4: Horizontal distance from endpoint versus buckling amplitude (Soil spring end condition).

Above figure shows when the temperature difference is 30°C there is no increase in the buckling amplitude. After increase in temperature difference of 30°C there is increase in buckling amplitude.

At temperature difference of 40°Cthe buckling amplitude is 0.455 m. However, at temperature difference of 50°C the buckling amplitude increases to 0.837 m which is approximately two times larger as compared to the previous value. Now at temperature difference of 60°C and 70°Cthe buckling amplitude is 1.04 m and 1.263 m respectively. Which shows that after exceed in temperature difference from 50°C there is slow increase in amplitude. The maximum value of buckling amplitude is 1.263 m. The maximum temperature difference is taken as 70°C.

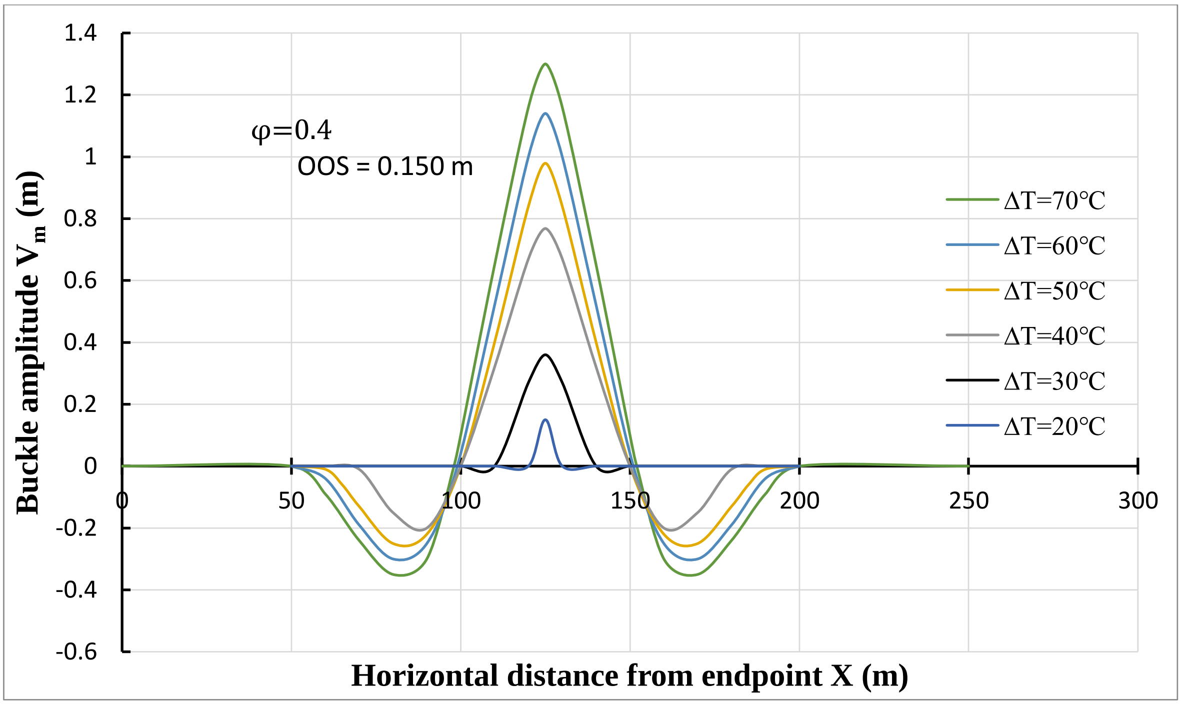


Figure 5.5: Horizontal distance from endpoint versus buckling amplitude (Fixed end condition).

Fig 5.5 shows the global lateral buckling shape of the pipeline at different temperature changes considering the pipeline ends are fixed. In case of fixed end condition buckling starts after temperature difference increases from 20°C. As we can see in Fig 5.5 that at temperature difference of 30°C the buckling amplitude is 0.368 m.At maximum temperature difference of 70°C buckling amplitude increases to 1.304 m.

Now comparing both the curves we can see that pipeline with fixed end has high buckling amplitude with respect to pipeline with soil spring at end at same temperature difference. The decrease in buckling amplitude is because some amount of energy is absorbed by the soil spring due to which there is reduction in axial compressive load in pipeline.

From above curves it is shown that buckle shape is symmetrical to the initial imperfection provide to the pipeline. After temperature difference greater than the triggering temperature the length and amplitude increases simultaneously. However this increase is not uniform with the uniform increase in temperature difference.

5. Conclusion

The present work carries the analysis of offshore pipeline lateral buckling with initial imperfection resting on two different seabed conditions. The pipeline is operated at different temperature changes and the effect of temperature changes on buckling amplitude is studied. The finite element method is used to model and analyze the subsea pipeline. This work carries an important role for future design of offshore oil and gas pipeline, where high temperature and pressurized oil and gas passes. For this kind of pipeline it is very essential to know the triggering temperature difference to occur pipeline buckling.

From the detailed study of the work and by examining the results obtained during the analysis of the work, the following conclusions were drawn.

For the global lateral buckling mode, with the increase of temperature difference, the buckling amplitude and length increase. However this kind of increase is not uniform, buckling amplitude and length increases slowly when the temperature is less than a certain value. Once the temperature difference exceeds this value, the buckling amplitude and length increases rapidly with increase of temperature difference. This value of temperature difference to initiate buckling of pipeline is called as triggering temperature difference.

Pipeline with soil spring at ends has lower buckling amplitude when compared to that of pipeline with fixed boundary condition.The decrease in buckling amplitude is because some amount of energy is absorbed by the soil spring due to which there is reduction in axial compressive load in pipeline.

Pipeline with higher initial imperfection amplitude shows lower triggering temperature difference than the lower one.For initial imperfection of 100 mm amplitude a sharp turning point is visible on the curve of temperature difference vs. buckling amplitude. However it disappears slowly for higher values of initial imperfection amplitude.In case of pipeline with soil spring at ends has lower buckling amplitude and higher triggering temperature difference when compared to those of fixed ended pipeline.

Changing the D/t ratio of pipeline leads to change in cross-sectional area of the pipeline due to which magnitude of axial stressbuilt up within the pipe wall changes. For decrease in D/t ratio buckling amplitude increases due to increase of wall thickness. However in case of fixed end condition the lateral buckling profile and amplitude has no large variation with respect to different D/t ratios. But for soil spring end condition the variation of buckling amplitude is more as compared to pipeline with fixed end condition.

The effect of pipe-subsoil friction coefficient on pipeline global buckling behavior, as the value of friction coefficient increases the buckling amplitude and length deceases. However for pipeline with fixed end have uniform change in buckling amplitude and length. But pipeline with soil spring end condition the change in buckling amplitude and length are not uniform. There is sudden decrease in buckling amplitude when coefficient of friction value increases to 0.5.

Considering the impact of seabed on buckling behavior, it shows that in case of rigid seabed the buckling tendency of pipeline is more as compared with deformable seabed. For rigid seabed condition only frictional soil resistance is acting on pipeline to resist its movement. But in case of deformable seabed the pipeline movement is resisted by the combined effect of soil friction as well as lateral earth pressure resistance due to settlement. It leads to increase in triggering temperature difference and decrease in buckling amplitude of the pipeline as compared to pipeline resting on rigid seabed.

There is lot of future scope on the study of pipe soil interaction. Future work will focus to generate a better analytical expression for the pipeline subjected to lateral earth pressure when resting on deformable seabed. Also there is requirement of mathematical expression for effect of different soil layer on pipeline buckling analysis

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