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Controlling lateral buckling of subsea pipeline with sinusoidal shape pre-deformation

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ABSTRACT

It is common for subsea pipelines to operate at high pressures and high temperatures (HPHT) conditions. The build-up of axial force along the pipeline due to temperature and pressure differences from as-laid conditions coupled with the influence of the seabed soil that restricts free movement of the pipeline can result in the phenomenon called 'lateral buckling'. The excessive lateral deformation from lateral buckling may risk safe operation of the pipeline due to local axial strains that potentially could be severe enough to cause fracture failure of welds or collapse of the pipeline. Engineered buckles may be initiated reliably during operation by using special subsea structures or lay methods which are expensive. This paper introduces and exemplifies a novel method that involves continuously deforming the pipeline prior to or during installation with prescribed radius and wavelength to control lateral buckling that could be a valuable modification of the practical design of offshore pipelines. Previous published work has shown that installation of a pipeline with such continuous deformations is feasible. The results from an example pipeline case described here show that the pipeline can be installed and operated safely at elevated temperatures without the need for other expensive buckle initiation methods.

1. Introduction

The demand for gas in recent times has driven the offshore industry into exploration and production at extreme conditions, due primarily by high pressure high temperature (HPHT) drilling. An accepted HPHT definition is when a gas reservoir temperature exceeds 300 °F (149 °C) and pressure exceeds 10,000 psi (690 bar) (Shadravan and Amani, 2012). This often implies that subsea pipelines, used to transport hydrocarbons, are also required to operate at HPHT conditions.

When a subsea pipeline, carrying a hydrocarbon gas, is operated at high temperatures and pressures there is a consequential tendency for the pipeline to expand longitudinally. The longitudinal expansion is resisted by the axial friction mobilised against the seabed soil, creating high compressive axial forces.

When the compressive axial forces increases in the pipeline to a certain level, the pipeline has the natural tendency to move laterally on the seabed to reduce the axial force and to achieve a lower strain energy state. Similar to beam or column buckling, the lateral deflection of the structural member as a result of axial compressive force leads to bending of the column, i.e. change of mode, due to the instability of the member.

Buckling can occur quite suddenly and the large lateral displacements induced by this uncontrolled phenomenon, sometimes called 'global buckling', may result in high local stresses and strains in the pipe wall that exceed code limits such as those specified in DNV OS F101 (Det Norske Veritas, 2013). Cyclic fatigue and fracture of girth weld between pipeline joints may also be at risk of failure due to pipeline lateral buckling caused by conditions that cycle between start-up and shutdowns during the pipeline's design life.

In order to understand the lateral buckling of subsea pipelines, it is required that we understand the concept of effective axial force. The concept of effective axial force is the heart of subsea pipeline design and has been extensively discussed (Fyrileiv and Collberg, 2005; Sparks, 1984). Effective axial force (taking compression as negative) is the pipeline steel wall force augmented by the pressure induced force as shown in Eq. (1):

$$S_{eff} = N - P_i A_i + P_e A_e \quad (1)$$

where:

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N = pipeline axial steel-wall force
P_i = pipeline internal pressure
A_i = pipeline internal cross-sectional area
P_e = pipeline external pressure
A_e = pipeline external cross-sectional area

It is generally accepted that global buckling of pipelines is governed by the effective axial force (Det Norske Veritas, 2013). Following installation of a pipeline on the seabed, the steel-wall force of the pipeline is simply the residual lay tension and the external pressure force, P_eA_e. When the pipeline is operated, the steel-wall force is given by the restrained thermal expansion ($-A_s\alpha\Delta TE$) and the longitudinal stress due the hoop stress and Poisson's effect ($\nu\sigma_hA_s$) during the application of the gas temperature and pressure. As the external pressure of the pipeline due to the hydrostatic pressure of water depth is the same for as-laid and operation conditions, the external pressure term is cancelled. Substituting the steel-walled force into Eq. (1), the fully restrained pipeline effective axial force can be defined using Eq. (2).

$$S_{eff} = H - \Delta P_i A_i(1-2\nu) + A_s E\alpha\Delta T \tag{2}$$

where

H = residual lay tension
ΔP_i = internal pressure difference relative to as-laid
ν = Poisson Ratio
A_s = cross-sectional area of the pipe
E = Young's Modulus of Elasticity
α = thermal coefficient of expansion
ΔT = temperature difference relative to as-laid

The fully restrained force is shown as Case A in Fig. 1. In practice, a pipeline on the seabed is not fully restrained from expansion movement. Axial movement during operation is restrained by the seabed soil and the axial resistance force over a length L of a pipeline is given by Eq. (3).

$$F_{ax} = \mu_a W_s L_x \tag{3}$$

where

μ_a = axial friction coefficient
W_s = pipeline submerged unit weight
L_x = length along pipeline

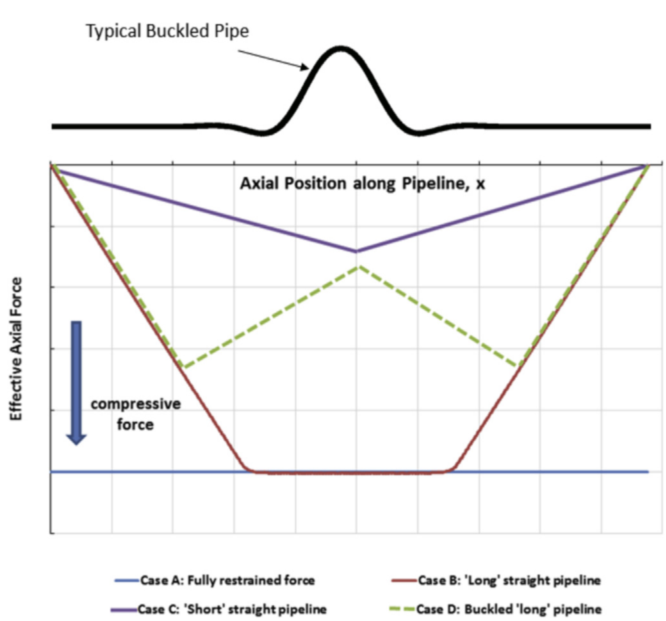

Fig. 1. Pipeline lateral buckling phenomenon.

The pipeline ends are usually free to expand, for example through the provision of low-friction mechanical sliders on the termination structure (see the case study in Jayson et al., 2008; for example). This means that the effective axial force for a pipeline at the free-ends is zero and gradually increases due to the axial friction resistance force between the pipeline and the seabed. Given sufficient length of the pipeline, there will be a limiting position along the pipeline where the axial friction force equals the expansion force of the pipeline. This position is called the anchor point where the axial strain of the pipeline is zero and the force at this point is the fully restrained force given in Eq. (2). This behaviour of the effective axial force is represented by Case B in Fig. 1 and is called 'long pipeline' is called 'long pipeline' behaviour. If however, due to low axial friction resistance between seabed and pipeline, or if the length of pipeline is insufficient, the pipeline does not attain the fully restrained condition. This is shown in Fig. 1 as Case C and is called 'short pipeline' behaviour. The anchor point is then formed at the mid length of the pipeline. The effective axial force in the pipeline may be well below the fully constrained force but it could be sufficient to buckle the pipeline.

A pipeline is susceptible to lateral buckling when the compressive effective axial force exceeds the 'critical buckling force' above which the pipeline becomes unstable laterally. The critical buckling force is highly dependent on the lateral pipe-soil resistance and to the local out-of-straightness (OOS) of the installed pipeline. When a pipeline buckles, the pipeline axial force decreases significantly with the axial expansion feeding into the buckle. This is shown as Case D in Fig. 1. A 'long pipeline' is more susceptible to lateral buckling due to high effective axial force than a 'short pipeline'.

An important aspect to be considered by pipeline engineers is to determine this critical buckling force that could cause lateral buckling. Early studies carried out by Hobbs (Hobbs, 1981; Hobbs and Liang, 1989) have proved an analytical solution for the critical buckling force, P_o for a perfectly straight pipeline laid on a rigid flat seabed shown in Eq. (4) for a mode 3 buckle, which is a commonly encountered mode of subsea pipeline buckling:

$$P_o = \frac{34.06.E.I}{(L)^2} + 1.294.\mu_a.w_s.L.\left[\left(1 + 1.668x10^{-4}\frac{E.A_s.\mu_l^2.w_sL^5}{\mu_a.(E.I)^2}\right)^{0.5} - 1\right] \tag{4}$$

The buckle amplitude is calculated using Eq. (5) (Hobbs, 1981; Hobbs and Liang, 1989).

$$y = \frac{1.032x10^{-2}\,.\mu_l.W_s}{E.I}L^4 \tag{5}$$

where

L = buckle length
I = Second Moment of Pipe Area
μ_a = axial friction coefficient
μ_l = lateral friction coefficient
y = buckle amplitude

If the pipeline effective axial force exceeds the Hobbs critical buckle initiation force, lateral buckling will occur. This method however has two major limitations; the first is that Hobbs equations are for an idealised, or perfect pipeline buckling phenomena which does not account for any initial out-of-straightness; secondly, pipe-soil friction is assumed to be fully mobilised throughout the analysis.

In practice, a perfectly straight pipeline does not exist as a practical pipeline would inherit imperfections from the processes of pipe manufacturing, pipe laying and also the seabed topography. Taylor and Gan (1986) modified the Hobbs formulation for Mode 1 and 2 conditions to include the effect of imperfection in lateral buckling of pipeline and