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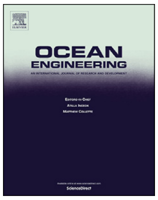

Analytical solution for lateral buckling of unburied subsea pipelines with distributed buoyancy section

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ABSTRACT

Unburied subsea pipelines operating under high temperature and high pressure (HT/HP) conditions tend to relieve their axial compressive force by forming lateral buckles. Uncontrolled lateral buckling can lead to pipeline failure. In order to control lateral buckling phenomenon, distributed buoyancy method is employed as buckle initiation technique. In this study, analytical solutions for lateral buckling of unburied subsea pipelines with distributed buoyancy section are derived. Fitting method is used to get the relationship between the equivalent axial compressive force and the half-length of the buckled section. The influence of the length and the weight of the distributed buoyancy section over typical behaviors of lateral buckling is illustrated and analyzed. The results show that increasing the length of distributed buoyancy section or decreasing the weight of distributed buoyancy section can all be used to decrease the minimum critical temperature difference and reduce the maximum axial compressive stress. However, the corresponding lateral displacement amplitude increases. The best selection of the weight of distributed buoyancy section is about half reduction of the original weight of pipeline.

1. Introduction

Unburied subsea pipelines operating under high temperature and high pressure (HT/HP) conditions are subject to relatively high axial compressive force induced by axial thermal expansion. Long unburied subsea pipelines tend to relieve their axial compressive force by forming lateral buckles. Such lateral deformations are uncontrolled, which will lead to undesirable stresses and strains along the pipeline. Moreover, the locations of lateral buckles are very uncertainty. Thus, uncontrolled lateral buckles can lead to pipeline failure, such as local buckling, collapse, low cycle fatigue or fracture at girth welds (Bruton, 2005).

An appropriate strategy is deliberately to induce the pipeline to buckle laterally at several planned locations in a controlled manner, rather than to allow it to suffer an uncontrolled, large buckle at one location only (N, 2013; Shi and Wang, 2015). At these planned locations, a sufficient number of lateral buckles should be triggered at a sufficiently low axial compressive force.

In order to control lateral buckling phenomenon, several buckle initiation techniques, which are briefly described by Sinclair et al. (2009). are recently developed to ensure that regular buckles form along the pipeline. The buckle initiation techniques will be artificially installed at some planned sections throughout the length of the pipeline in order to induce buckle formation at these sites.

Three methods are commonly adopted to promote the reliable formation of lateral buckles and control the buckle spacing and operating loads, which are snake-lay, vertical upset and local weight reduction of distributed buoyancy (Urthaler et al., 2012). A related method to distributed buoyancy is to use discrete buoyancy, such as buoyancy bags, to aid buckle initiation (Harrison et al., 2003; Peek and Yun, 2007; Shi and Wang, 2015). In this method, a discrete buoyancy, such as an air bag, is only used to initiate lateral buckling, which will be removed once the lateral buckle formation has occurred. Another buckle initiation technique is zero radius bend technique, which is proposed by Peek (Peek and Kristiansen, 2009). For the zero radius bend technique, a vertical trigger is pre-installed on the seabed and the pipeline is initially laid straight towards it. All of these initiation techniques are employed to improve the reliability of buckle formation through lowering the critical buckle initiation force. The critical buckle initiation force is governed by (i) out-of-straightness (OOS) features and (ii) lateral breakout resistance (Sinclair et al., 2009). The buckle initiation techniques are used to modify one or both of these parameters. The snake-lay method is to introduce OOS in the horizontal plane. And the vertical upset and local weight reduction method bring in vertical OOS and also reduce the lateral soil resistance around the vertical upset region, although pipe-soil

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Nomenclature

P_0	is the axial compressive force induced by high temperature and high pressure along the pipeline, where no axial expansion happens
P	is the axial compressive force within the buckled section
EI	is the flexural rigidity
λ	is the equivalent axial compressive force
w_1	is the deformed configuration of pipeline with distributed buoyancy section
w_2	is the deformed configuration of pipeline without distributed buoyancy section
l_1	is half-length of the buckled section
l_b	is half-length of the distributed buoyancy section
l_s	is half-length of the feed-in zone
x	is the distance measured along the X axis
W_b	is the submerged weight per unit length of the pipeline with distributed buoyancy section
W_p	is the submerged weight per unit length of the pipeline without distributed buoyancy section
$k = W_b/W_p$	is a ratio coefficient
f_b	and f_{Ab} is the lateral and axial soil resistance per unit length for pipeline with distributed buoyancy section respectively
f_1	and f_{A1} is the lateral and axial soil resistance per unit length for pipeline without distributed buoyancy section respectively
ϕ_L	is the lateral friction coefficient between pipeline and seabed
ϕ_A	is the axial friction coefficient between pipeline and seabed
A	is the cross-sectional area of the pipeline,
E	is Young's modulus of the pipeline,
D	is the external diameter of pipeline,
p	is the internal pressure of pipeline,
υ	is Poisson ratio, generally equal to 0.3
t	is the wall thickness of pipeline,
α	is the coefficient of linear thermal expansion
w_m	is the lateral displacement amplitude along the pipeline,
M_m	is the maximum moment along the pipeline,
σ_m	is the maximum axial compressive stress along the pipeline,
$A_1 \sim A_4$ and $B_1 \sim B_4$	are constant coefficients

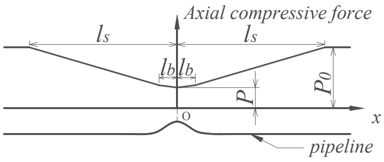

Fig. 1. Axial compressive force distribution.

interaction at the touch-down points is enhanced. The advantage in the use of these engineered buckle initiation techniques is that the planned post-buckling configuration is generally more benign than that for an uncontrolled lateral buckles. Consequently, the integrity of pipelines within the buckle is improved.

The lateral and upheaval buckling have been studied by previous researchers in theoretical framework through assuming the pipeline as a beam resting on the rigid seabed (Hobbs, 1984; Hong et al., 2015b; Ju and Kyriakides, 1988; Karampour et al., 2013; Liu et al., 2014a; Taylor and Gan, 1986; Taylor and Tran, 1993) and on the soft seabed (Shi et al., 2013; Wang et al., 2011; Zeng and Duan, 2014). Small-scale model tests were conducted to understand the mechanism of upheaval buckling of buried pipelines (Maltby and Calladine, 1995a, b) and the properties of man-made triggers to control lateral buckling (de Oliveira Cardoso and Solano, 2015; Silva-Junior et al., 2009). Moreover, FE analyses have been performed for lateral and upheaval buckling (Hong et al., 2015a; Liu et al., 2015; Liu et al., 2014b; Wang et al., 2015a; Wang et al., 2015b; Zeng et al., 2014; Zhang and Duan, 2015).

Simple analytical solutions were given for triggering lateral buckles through applying buoyancy to the pipeline by Peek and Yun, which could be applied to a single-point buoyancy load, two-point buoyancy load and distributed buoyancy load over a specified length (Peek and Yun, 2007). They assumed that the pipeline was uplifted over a length $2L$ within the buckled section. So the lateral soil resistance was zero within the buckled section. And the bifurcation load to initiate lateral buckling was derived for pipelines with the buoyancy section. However, in some cases, the pipeline was not fully uplifted off the seabed. Thus, the effect of buoyancy section was partially to reduce lateral soil resistance, which was not reduced to zero. This situation was considered in this paper. Furthermore, the single buoyancy method was further studied by Shi and Wang (2015). The single buoyancy load required to trigger lateral buckles along a pipeline was investigated through analytical methods by Shi and Wang (2015). The pipeline was divided into three zones in the horizontal plane: the span zone, in which the pipeline was uplifted by the buoyancy force, and two contacting zones, in which the pipeline contacts the seabed. The lateral soil resistance within the span zone was zero, which was assumed elastic within the contacting zones. They concluded that the flotation design was significantly influenced by the seabed condition. Analytical solutions were derived based on third lateral buckling mode for a pipeline section with distributed buoyancy section by Antunes (Antunes et al., 2010), which could be employed in the preliminary design to assess the influence of buoyancy sections on lateral buckle configuration, feed-in length, tolerable Virtual Anchor Spacing, etc.

In order to verify the effect of buoyancy on pipeline lateral buckling, a survey presented by Urthaler was conducted on a pipeline system with single and dual buoyancy section in the Gulf of Mexico (Urthaler et al., 2012). The surveyed results showed that six of the ten surveyed buckle sites formed mode one configuration and four of the buckle sites formed mode two configuration. Seven of these surveyed sites were the dual buoyancy configuration, which were designed to buckle in mode two. However, three of them formed mode one under operational conditions. All three surveyed buckle sites intended to buckle in mode one formed mode one. Thus, mode one configuration is the most common configuration for pipelines with single buoyancy section or dual buoyancy section. In this paper, analytical solution is derived for mode one lateral buckling of unburied subsea pipelines with single distributed buoyancy section.

2. Analytical solution

The analytical formulations presented within this section are derived considering one-order lateral buckling mode for unburied subsea pipelines with distributed buoyancy section. The pipeline is modelled as an elastic beam with axial compressive force due to high temperature and high pressure. Assume that the soil foundation provides a constant resisting force when the pipeline deforms laterally. Fig. 2 illustrates the configuration and loads distribution of the one-order lateral buckling mode for unburied subsea pipelines with distributed buoyancy section after lateral buckling happens. And initial imperfection is not considered. In this paper, only the situation $l_b < l_1$ is considered. The axial compressive force $\overline{P}$ has the profile sketched in Fig. 1, i.e., $\overline{P} = P$ at the centre of the pipe and $\overline{P} = P_0$ at the end of the mobilized buckling region. We now