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Analytical study of third-mode lateral thermal buckling for unburied subsea pipelines with sleeper

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ABSTRACT

Unburied subsea pipelines operating under high-temperature and high-pressure conditions tend to relieve their axial compressive force by forming lateral buckles. In order to manage lateral buckling, a sleeper is often employed as a buckle-initiation technique to ensure pipeline integrity. In this study, analytical solutions of third-mode lateral buckling for unburied subsea pipelines with sleeper are derived. The analytical solution is compared with experimental data in the literature and shows good agreement. The stability of the buckled pipeline is investigated by means of an energy analysis and it is found that third-mode lateral buckling has lower energy than first-mode buckling, which means that third-mode buckling is more likely to happen in practice. The influence of sleeper height and sleeper friction on lateral post-buckling behaviour is illustrated and analysed, with particular attention paid to the minimum critical temperature difference, lateral displacement amplitude and maximum stress. Our results show that increasing the height of the sleeper or decreasing the friction between pipeline and sleeper can both be used to decrease the minimum critical temperature difference, but their influence on the maximum stress is opposite.

1. Introduction

Subsea pipelines are increasingly being required to operate under high-temperature conditions to ease the flow and prevent solidification of the wax fraction in deep water. Due to the constraint of seabed foundation, excessive axial compressive force will be accumulated, which may lead to lateral thermal buckling for unburied subsea pipelines. Such uncontrolled lateral buckling may lead to fracture, fatigue or local buckling [1]. Therefore some engineering measures have been taken to prevent subsea pipeline buckling, such as trenching, burying and rock-dumping, or to relieve the stress with in-line expansion spools [2]. However, these methods are becoming more and more expensive as the operating temperature increases and as hydrocarbon development moves into deeper water [3].

Thus, an effective and inexpensive method is proposed for the relief of thermal induced axial compressive force, which is to accommodate thermal expansion by artificially inducing the pipeline to buckle in a controlled manner at several controlled locations, rather than to allow it to suffer an uncontrolled, large buckle at one location only. Thermal expansion can be evenly divided into a number of buckles, none of which is subject to too much feed-in from thermal expansion [4]. At these planned locations, a sufficient number of lateral buckles should be triggered at a sufficiently low axial compressive force [5,6]. Several buckle initiation techniques, which are briefly described by Sinclair et al. [7], have recently been developed to ensure that regular buckles form along the pipeline. Three methods are commonly adopted to promote the reliable formation of lateral buckles and to control the buckle spacing and operating loads, which are snake-lay, vertical upset (sleeper) and local weight reduction through distributed buoyancy [8]. The advantage in the use of these engineered buckle initiation techniques is that the planned post-buckling configuration is generally more benign than uncontrolled lateral buckles. Consequently, the integrity of pipelines within the buckle will be improved.

Lateral and upheaval buckling have been studied previously by researchers within a theoretical framework by modelling the pipeline as a beam resting on a rigid seabed [9–16] or on a soft seabed [17–19]. Nonlinear localised lateral buckling of straight pipelines was investigated analytically by Zhu et al. [20] and Wang and van der Heijden [21] without making assumptions about the shape of lateral deformation. The research in [21] suggests that the deformed shape and the buckling path can be predicted accurately by using the assumption of a third-mode for a pipeline without sleeper, so this assumption is employed in this paper. Small-scale model tests were conducted in [22,23] to understand the mechanism of upheaval buckling of buried pipelines.

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Nomenclature

P_0	is the axial compressive force induced by high temperature and high pressure in sections of the pipeline where no axial expansion occurs
P	is the axial compressive force in the span region
E	is the elastic modulus
I	is the moment of inertia of the cross-section
f_A	is the axial soil resistance per unit length
l_s	is the half-length of the feed-in zone
v	is the vertical deflection
q	is the submerged weight per unit length of the pipeline
l_1	is half the span length
F	is the shear force at the contact point between sleeper and pipeline
F_{st}	is the supporting force from the sleeper
v_{om}	is the sleeper height
F_t	is the point contact force between the pipeline and the seabed at the touchdown point
$\overline{P}(x)$	is the axial compressive force distribution
μ_A	is the axial friction coefficient between pipeline and seabed
f_{At}	is the axial friction force induced by the contact vertical force F_t
w_1, w_2 and w_3	are lateral deflections
A_1–A_4, B_1–B_4, C_1–C_4 and D_1–D_4	are constant coefficients
f	is the lateral friction force
μ_L	is the lateral friction coefficient
l_2	is the half-length of the primary lobe
l_3	is the half-length of the buckled region
λ	is the equivalent axial compressive force
f_{ow}	is the lateral shear force induced by the lateral friction force between pipeline and sleeper
μ_s	is the friction coefficient between pipeline and sleeper
x	is the distance measured along the X axis
f_t	is the lateral concentrated friction force at the touchdown point
f_2	is the point force at $x = l_3$
T_0	is the temperature difference between the fluid flowing inside the pipe and the environment
u_1	is the length of axial expansion within the pipeline section $0 < x < l_s$ due to high pressure and high temperature
u_2	is the geometric shortening, which allows for the additional length introduced by the lateral displacement
A	is the cross-sectional area of the pipeline
D	is the external diameter of the pipe
$\Delta\overline{P}(x)$	is the amount of decrease of axial compressive force along the pipeline after the pipeline buckles
α	is the coefficient of linear thermal expansion
u	is the axial deformation of the pipeline
w_m	is the maximum lateral displacement along the pipeline
M	is the bending moment along the buckled pipeline
M_m	is the maximum bending moment
σ_M	is the bending stress along the buckled pipeline induced by the bending moment
σ_{Mm}	is the stress induced by the maximum bending moment
σ_P	is the axial compressive stress
σ_m	is the maximum stress along the pipeline induced by the axial compressive force and the maximum bending moment
P_a	is the axial compressive force at the virtual anchors between two buckles
l_a	is the maximum axial feed-in length
T_m	is the minimum critical temperature difference
V	is the total potential energy relating to the buckled pipeline
V_i	is the total potential energy of the straight pipeline namely before buckling
V_1	is the bending strain energy
V_2	is the energy loss due to lateral soil resistance
V_3	is the energy loss due to axial soil resistance
V_4	is the axial compressive strain energy

Experimental and numerical investigations were carried out to investigate the buckle interaction between propagation buckling and upheaval or lateral buckling in subsea pipelines by Karampour et al. [24,25]. Many finite-element analyses have also been performed to investigate lateral and upheaval buckling [26–32]. All these works studied lateral or vertical buckling rather than how to control it.

In recent years, several researches about lateral buckling of unburied subsea pipelines with an initiation technique have been carried out. Simple analytical solutions were given for triggering lateral buckles by applying buoyancy to the pipeline by Peek and Yun [33], which are valid for a single-point buoyancy load, a two-point buoyancy load and a distributed buoyancy load over a specified length. The single-buoyancy method was further studied by Shi and Wang [5]. Analytical solutions were derived based on the first lateral buckling mode by Wang et al. [34] and on the third lateral buckling mode by Li et al. [35] and Wang et al. [36] for a pipeline section with a distributed buoyancy section. An analytical solution for controlled lateral buckling of unburied subsea pipelines was studied by Wang et al. with the consideration of interaction between adjacent buckles [4]. Moreover, experimental investigations were carried out by Silva-Junior et al. [37] and de Oliveira Cardoso et al. [38] to study the effect of distributed buoyancies and sleepers on lateral buckling. As to the study of lateral buckling for pipeline with sleeper, Wang et al. [39] derived an analytical solution based on the first lateral buckling mode. Bai et al. [40] studied the applications of dual sleepers as lateral buckling initiators through finite-element modelling. Wang et al. [41] also used finite-element modelling to analyse the buckling behaviour of pipelines with sleeper. Equations for buckling displacement, critical buckling force and buckling stress were proposed using genetic programming.

In order to verify the effect of a sleeper in controlling pipeline lateral buckling, a survey was conducted by Sinclair et al. [7] collecting operating data on the behaviour of nine pipelines employing sleepers as buckle initiators. Their results show that the sleeper initiation technique can induce both symmetric (mode 1 or 3) and asymmetric (mode 2) buckles (in the classification of Hobbs [9]). For mode 1, there is only a primary lobe in the positive direction, while for mode 3 there are, in addition, two adjoining secondary lobes in the negative direction. The actual mode is driven by the local imperfection introduced during pipe lay. Consequently, it is not possible to predict the buckling mode. Mode 1 has been studied analytically by Wang et al. [39]. The aim of this paper is to derive the analytical solution for the third lateral buckling mode and to compare results. First we validate our analytical model by comparing its predictions with the experimental data reported in [38], finding better agreement with our third-mode assumption than is obtained with a first-mode assumption. Then we analyse the stability of the lateral buckling solutions by computing the total energy of the pipeline. The energy of the third mode is found to be lower than that of the first mode for both pipelines with and without sleeper. Finally, parameter studies are carried out to study the effect of sleeper height and sleeper friction on the lateral buckling behaviour.

2. Analytical solution

In the process of thermal buckling within a pipeline section that is