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Analytical study of lateral thermal buckling for 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. Uncontrolled lateral buckling may lead to pipeline failure. In order to control lateral buckling, a sleeper is often employed as a buckle-initiation technique. In this study, analytical solutions of lateral buckling for unburied subsea pipelines with sleeper are derived. An energy analysis is employed to investigate the stability of the buckled pipeline. The influence of sleeper height and sleeper friction on pipeline buckled configurations and typical lateral buckling behaviour is illustrated and analysed. The results are shown to be in very good agreement with experimental data in the literature. We also discuss the effect of imperfections and conduct an error analysis of one of the main assumptions of the proposed analytical method. Our results show that increasing the height of the sleeper or decreasing the friction between pipeline and sleeper can all be used to decrease the minimum critical temperature difference. However, only the sleeper height is effective in substantially reducing the maximum compressive stress.

1. Introduction

For the exploitation and transportation of energy resources, 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. The excessive axial compressive force induced by the increase in temperature may lead to lateral buckling for unburied subsea pipelines. Such uncontrolled lateral buckling would cause serious damage to the safety of the pipelines. Consequently, some engineering measures have been employed to prevent subsea pipeline buckling, such as trenching, burying and rock-dumping; or relieving the stress with in-line expansion spools [1]. However, these methods are becoming more and more expensive as the operating temperature increases and as hydrocarbon development moves into deeper water [2].

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. At these planned locations, a sufficient number of lateral buckles should be triggered at a sufficiently low axial compressive force [3,4]. Several buckle initiation techniques, which are briefly described by Sinclair et al. [5], 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, sleeper and local weight reduction through distributed buoyancy [6]. A method related to distributed buoyancy is to use discrete buoyancy, such as buoyancy bags, to aid buckle initiation [3,7,8]. In this method, a discrete buoyancy, such as an air bag, is only used to initiate lateral buckling, and will be removed once the lateral buckle formation has occurred. Another buckle initiation technique is the zero-radius bend technique proposed by Peek et al. [9]. 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 is improved.

Lateral and upheaval buckling have been studied by previous researchers in the theoretical framework by modelling the pipeline as a beam resting on a rigid seabed [10–17] or on a soft seabed [18–20]. Nonlinear localised lateral buckling of straight pipelines was investigated analytically by Zhu et al. [21] and Wang [22] without the assumption of lateral deformation. On the other hand, small-scale model tests were conducted to understand the mechanism of upheaval buckling of buried pipelines [23,24] and the properties of man-made initiation techniques to control lateral buckling [25,26]. Experimental and numerical investigations were carried out to investigate the buckle interaction between propagation buckling and upheaval or lateral

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buckling in subsea pipelines by Albermani and Karampour [27,28]. Moreover, many finite-element analyses have been performed to investigate lateral and upheaval buckling [29–35]. All these methods are employed to investigate lateral buckling or vertical buckling behaviour rather than how to control them.

In recent years, several researches about lateral buckling of subsea pipelines with an initiation technique have been carried out. Simple analytical solutions were given for triggering lateral buckles through applying buoyancy to the pipeline by Peek and Yun [7], which could be applied to a single-point buoyancy load, two-point buoyancy load and distributed buoyancy load over a specified length. Furthermore, the single buoyancy method was further studied by Shi and Wang [3]. The single buoyancy load required to trigger lateral buckles along a pipeline was investigated through analytical methods by Shi and Wang [3]. Analytical solutions were derived based on the first and third lateral buckling mode for a pipeline section with a distributed buoyancy section by Wang et al. [36], Antunes et al. [37] and Li et al. [38].

The use of sleepers as buckle initiation technique does not seem to have attracted much work in the literature. Sinclair et al. [5] conducted a survey of the effect of a sleeper in controlling pipeline lateral buckling and collected operating data on the behaviour of nine pipelines employing sleepers as buckle initiators. Experiments on a scaled-down model were carried out by Silva-Junior et al. [26] and de Oliveira Cardoso et al. [25]. Their studies compare displacements and critical buckling loads of various artificial buckle triggers, including sleepers. Bai et al. [39] studied the applications of dual sleepers as lateral buckling initiators through finite-element modelling. No analytical work appears to exist. Here we propose an analytical model for the study of lateral buckling of subsea pipelines with sleeper.

The survey in [5] shows that the sleeper initiation technique can induce both symmetric (mode 1 or 3) and asymmetric (mode 2) buckles (in the classification of Hobbs [10]). The actual mode is driven by the local imperfection introduced during pipe lay. Consequently, it is not possible to predict the buckling mode. However, mode 1 is the most commonly considered lateral buckling mode for pipelines with sleeper according to the surveyed results of Sinclair et al. Thus, the aim of this paper is to derive the analytical solution of the first lateral buckling mode for unburied subsea pipelines with sleeper. Stability of the lateral buckling solutions is analysed by computing the total energy of the pipeline. Parameter studies are carried out to study the effect of sleeper height and sleeper friction on the lateral buckling behaviour. We validate our analytical model by comparing its predictions with the experimental data reported in [25], finding very good agreement.

2. Analytical solution

In the process of thermal buckling within a pipeline section that is initially immobilised by axial friction against the seabed a small central segment of pipe will mobilise. As pipe feeds into the buckle the compressive force in the pipe drops, pulling more pipe into the buckle. If the soil resistance for axial movement is constant, say f_A, then a compressive force will build up in the pipe, increasing linearly with the distance from the touchdown point between pipeline and seabed. At some point this compressive force is sufficient to satisfy the requirement of additional length introduced by the lateral displacement. The end points of this segment are called virtual anchor points. Fig. 1 shows the feed-in region of length $2l_s$ within the larger immobilised section of the pipeline together with the typical compressive force variation. l_s is sometimes called the slip-length. P_0 is the axial compressive force at the virtual anchor points.

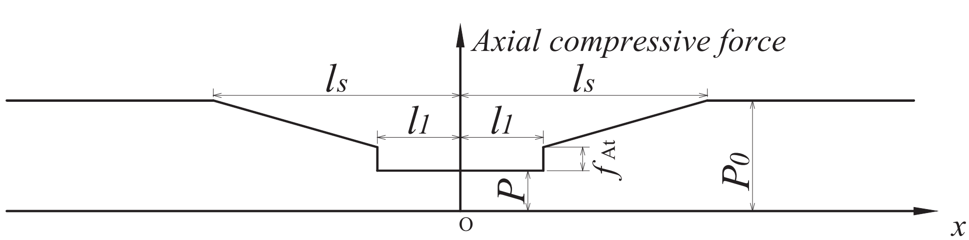

Fig. 1. Axial compressive force distribution.

In practice multiple (independent) localised buckles may form in the immobilised pipe section, especially if it is long. In the following we present a theory for a single localised buckle that applies to each such buckle individually. Fig. 2 illustrates the configuration and load distribution of the first lateral buckling mode for unburied subsea pipelines with sleeper. In the analytical formulations of this mode presented in this section the pipeline is modelled using linear beam-column theory valid for small deflections. The vertical and lateral deflections are therefore essentially independent, coupled only by friction, and we consider each individually.

2.1. Analytical solution in the vertical plane

For exposed subsea pipelines the vertical resistance of the seabed is usually greater than the lateral resistance; therefore, the seabed is assumed rigid as a feasible approximation, even for soft soils. Consider a sleeper laid at the middle of the span, as shown in Fig. 2a. The governing equation for the configuration of the pipeline with sleeper in the vertical plane is

$$EI\frac{d^4v}{dx^4} = -q \quad 0 \le x \le l_1 \tag{1}$$

where v is the vertical deflection, q is the submerged weight per unit length of the pipeline, E is the elastic modulus, I is the moment of inertia, l_1 is the half span length. Only half of the pipeline needs to be considered owing to the symmetrical configuration and load distribution in the vertical direction.

The general solution of Eq. (1) is

$$v = -\frac{q}{24EI}x^4 + C_1x^3 + C_2x^2 + C_3x + C_4 \tag{2}$$

By symmetry, the slope of v at $x = 0$ must be zero, while the shear force F at $x = 0$ comes from the supporting force $2F$ by the sleeper. In addition, the displacement, slope and moment at $x = l_1$ must be zero as well. So the boundary conditions at $x = 0$ and $x = l_1$ are

$$\begin{cases} \frac{dv}{dx}(0) = 0 \\ \frac{d^3v}{dx^3}(0) = \frac{F}{EI} \\ v(l_1) = 0 \\ \frac{dv}{dx}(l_1) = 0 \\ \frac{d^2v}{dx^2}(l_1) = 0 \end{cases} \tag{3}$$

Combining Eq. (2) and Eq. (3), $C_1 - C_4$ and F can be obtained as

$$C_1 = \frac{ql_1}{9EI},\ C_2 = -\frac{ql_1^2}{12EI},\ C_3 = 0, C_4 = \frac{ql_1^4}{72EI}, F = \frac{2}{3}ql_1 \tag{4}$$

Thus, the vertical deflection is

$$v = \frac{ql_1^4}{72EI}\left(-3\frac{x^4}{l_1^4} + 8\frac{x^3}{l_1^3} - 6\frac{x^2}{l_1^2} + 1\right) \tag{5}$$