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Numerical study on critical axial forces of upheaval buckling for initially stressed submarine pipelines on uneven seabed

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A R T I C L E I N F O

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A B S T R A C T

For pipelines on uneven seabed, upheaval buckling may occur if the axial compressive force reaches the critical force of upheaval buckling. The critical axial force is sensitive to the seabed undulation, However, the effect of the seabed undulation on the critical force has not been completely discussed. Moreover, effect of the initial stress which accumulates in the pipe wall when the pipeline conforms to the seabed undulation under self-weight has been rarely examined. This paper mainly focuses on the effect of the initial stress. Using numerical tools developed with the Vector Form Intrinsic Finite Element (VFIFE) method, effect of the initial stress is proved significant. Subsequently with the theory of dimensional analysis, a formula of the critical axial force is derived. This formula covers the dimensionless undulation length and the Out-of-Straight (OOS) of the seabed undulation. Considering three seabed undulation shapes, coefficients in the formulas are determined with numerical results from the VFIFE simulations. Finally, the proposed formulas are proved applicable for pipes with different properties and within the error range of ±10% for pipelines in continuous contact with the seabed in a large dimensionless scope.

1. Introduction

When a pipeline is laid on topography with uneven seabed, it may buckle vertically once the axial compressive force is larger than a value called the critical axial force of upheaval buckling (Guijt, 1990; Liu et al., 2012a, 2012b; Palmer et al., 1990; Wang et al., 2015). Upheaval buckling is a failure mode and may result in cross-sectional distortion or rupture of the pipe (Croll, 1997; Liu et al., 2014b). And because of the economic losses and environmental damage resulted from possible pipeline leaks, upheaval buckling must be considered in design and in-service assessment of pipelines. As upheaval buckling happens only when the axial compressive force of the pipeline reaches the critical value, designers could prevent its happening by keeping the axial force smaller than the critical axial force of upheaval buckling (Xu and Lin, 2017c). Therefore, it will help much in practice if the critical axial force could be predicted with a great precision.

For pipelines on uneven seabed, the seabed undulation may trigger upheaval buckling of the pipeline. For a pipeline on seabed with undulation, two situations are considered: the situation with initially unstressed pipe (Fig. 1(a)) and the situation with initially stressed pipe (Fig. 1(b)). Fig. 1(a) corresponds to local undulation in the pipe itself with a conforming seabed. The undulation of the pipeline profile may result from the residual curvature in the pipe-laying process (Liu et al., 2012a; O'Grady and Harte, 2013) or the snaked-laying of the pipeline (Guan et al., 2007; Liu et al., 2012b). Fig. 1(b) represents the undulation in the seabed with a bending pipeline, which is initially straight and has to bend under submerged weight to conform to the seabed undulation (Liu et al., 2012a). For a typical seabed undulation, the maximum cross-sectional stress contours of the pipeline segments are also shown in Fig. 1. It is illustrated that there is no initial stress in an initially unstressed pipe, while in an initially stressed pipe, the initial stress is significant.

Many researches have been conducted to study the critical upheaval bcukling forces of submarine pipelines. Yun and Kyriakides (1985) studied the upheaval buckling of buried pipelines through a large deflection extensional beam nonlinear formulation. They found the critical axial forces are sensitive to undulation of the pipeline profile. Taylor et al. (Taylor and Gan, 1986, 1987; Taylor and Tran, 1993, 1996) studied the upheaval buckling of unstressed pipelines through theoretic analysis and experiments. They manifested the undulation length L and

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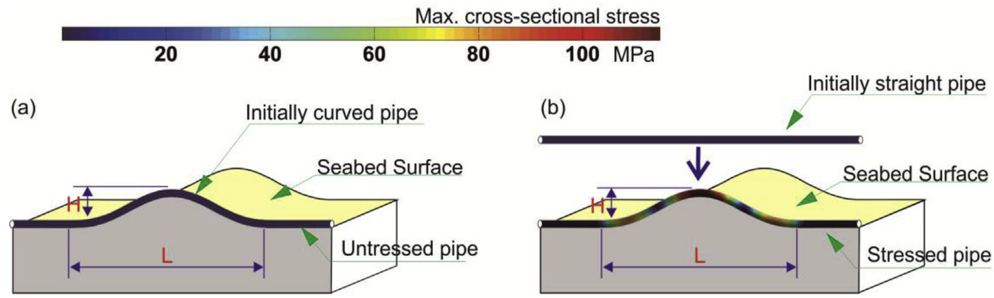

Fig. 1. Schematic diagram of (a) an initially unstressed pipeline, and (b) an initially stressed pipeline, laid on seabed with undulation.

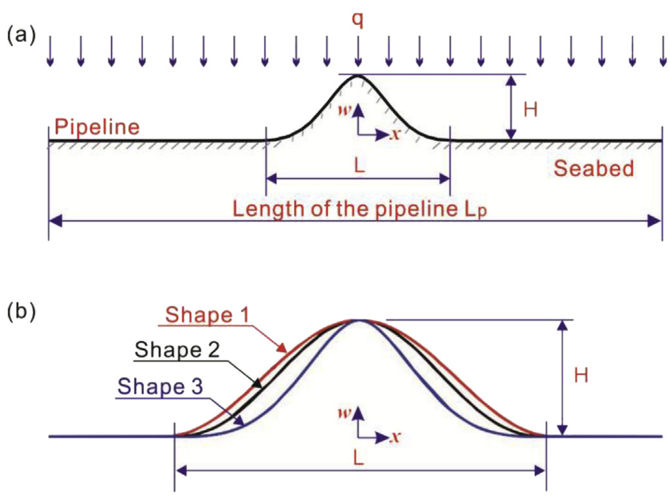

Fig. 2. (a) The analytical model, and (b) diagram of three typical seabed undulation shapes.

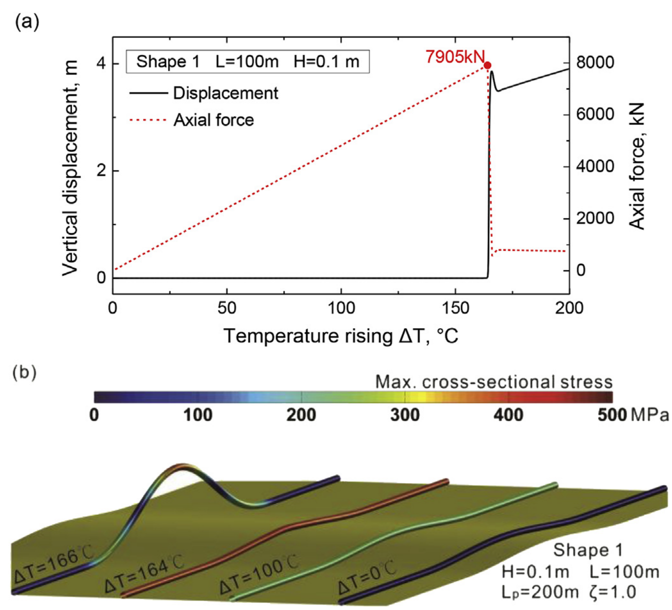

Fig. 3. (a) Temperature rising versus the vertical displacement and axial force; (b) the maximum cross-sectional stress and deformation contour plot at different temperatures (shape 1, $H = 0.1$ m, $L = 100$ m, $\zeta = 1.0$).

Table 1
Parameters of the studied pipe.

Property	Value
The outer diameter, D (mm)	457
The thickness of the steel pipe wall, t (mm)	14.3
The Young's modulus, E (GPa)	207
The Poisson's ratio, υ	0.3
The equivalent cross-sectional moment of inertia, I (m^4)	4.88×10^{-4}
The equivalent cross-sectional area, A (m^2)	0.0199
The distributed load on pipelines, q (N/m)	1 500
The thermal expansion coefficient, α_s (/°C)	1.17×10^{-5}

hight H can influence the critical axial force. Richards (1990) studied the influence of undulation shape on upheaval buckling behavior of initially unstressed pipeline and proved this influence is significant. Based on this, he pointed out the seabed profile survey is important for the pipeline design process. Assuming the buckling mode of a pipeline segment is the growth of the periodic initial mode, Maltby and Calladine (1995a,b) proposed formulas for the critical axial force including the undulation amplitude. Croll (1997, 1998) deduced analytical expressions of the upper and lower bounds of the critical axial force, while the length and height of the undulation are separating in the equations.

Palmer et al. (1990) introduced a semi-empirical simplified design method and presented the general form of the critical force formulas. They proved the specific undulation shape only affects the coefficients of the formulas, while the general form of the formulas keeps unchanged. This provided basis for the using of the theory of dimensional analysis in this problem. With the theory of dimensional analysis and finite element analysis, Zeng et al. (2014) studied the influences of the Out-of-straightness (OOS) and the undulation shape for initially unstressed pipelines. Again, it was proved that the form of the critical axial force formulas is the same for different undulation shapes. However, effect of the imperfection size was not systematically considered in Zeng et al. (2014). To account for this size effect, Xu and Lin (2017c) proposed a new dimensionless parameter, the dimensionless imperfection length, which combines the effects of the imperfection length, the bending stiffness and vertical load of the pipeline. Moreover, approximation formulas covering the dimensionless imperfection length and the OOS were proposed by Xu and Lin (2017c). However, in the study of Xu and Lin (2017c), pipelines are assumed to be initially curved and with no initial stress.

Although the stressed pipeline and the unstressed pipeline are both common in practice, there are few researches about initially stressed pipeline, for which the bending stress caused by the seabed undulation must be considered. For a long-distance pipeline through sand-wave topography, Xu and Lin (2017b) studied the influence of the initial stress caused by real seabed undulations and found the stress is considerable and could significantly influence behaviors and internal forces of free-spanning pipelines. Karampour et al. (2013) derived a tabulated analytical solution based on a long heavy elastic beam resting on a rigid seabed for both stressed and unstressed pipelines. They found the critical axial force of initially stressed pipeline is larger than that of the initially unstressed pipeline. This indicates it may be over-conservative to directly adopt the results of the initially unstressed pipeline in the initially stressed situation. Nevertheless in previous studies, effects of the initially