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Lateral buckling critical force for submarine pipe-in-pipe pipelines

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ABSTRACT

The lateral buckling critical force of a submarine pipe-in-pipe pipeline with symmetrical initial imperfection on soft foundation is determined. The effects of initial imperfection shapes, out-of-straightness, soil parameters as well as lateral nonlinear pipe-soil interaction, and structure parameters (stiffness ratio of inner pipe to outer pipe and clearance between inner and outer pipes) are discussed. A simple formula considering the above factors is proposed to determine the lateral buckling critical force of submarine pipe-in-pipe pipelines based on dimensional analysis and numerical results. The accuracy of the presented formula is shown by a case study.

1. Introduction

Owing to the exceptional thermal insulation capability, submarine PIP (pipe-in-pipe) pipelines are widely used as the main means of transporting hydrocarbons in deep waters. The submarine PIP pipelines are often operated under high internal pressure and high temperature conditions which produces considerable axial force within pipelines. The pipeline cannot deform freely because of the restraint by the surrounding soil. Once the axial force reaches a certain value, referred to as critical force, global buckling of the submarine pipeline occurs.

Because of the large costs of burying a pipeline and the difficulties in detection and maintenance afterwards [1,2], the submarine PIP pipelines in deep waters are usually laid directly on the seabed or partly embedded in the soil. In this case, lateral buckling is the main buckling type. Collapse, buckling propagation, or even fracture may occur [3] because of excessive bending caused by lateral buckling. Therefore, lateral buckling is an important problem in the design of submarine PIP pipelines. The critical force is a key design parameter for submarine pipelines which has attracted a lot of researchers' attention.

Based on theoretical analysis and experiments of lateral buckling of a pipe, Palmer and Baldry [4] correctly interpreted the reason why lateral buckling can occur in a pipe and proposed an analytical formula for the critical pressure. Hobbs [5] studied the lateral buckling of a perfect straight pipeline on the basis of related work on railroad track and proposed five buckling modes which may occur in the process of lateral buckling. Analytical formulas for critical force, wavelength and amplitude corresponding to every buckling mode are also presented. However, the initial imperfections of submarine pipelines were not considered in the above studies, and this factor was proved to be crucial for the critical force of lateral buckling [6–9]. Taylor and Gan [6] considered the initial imperfections and proposed analytical formulas for critical forces of lateral buckling corresponding to mode 1 and mode 2. Finite element (FE) analysis was used to study the lateral buckling responses of submarine pipelines [10–12], some formulas were proposed to calculate the critical force of lateral buckling. The initial imperfection parameters (initial wavelength and maximum amplitude) are included in these formulas.

Zhang and Duan [13] focused on the effect of initial imperfection shapes on the critical force of upheaval buckling and found one characteristic parameter of initial imperfection shapes which has a great influence on the critical force. A three-parameter formula for critical force which includes the complete initial imperfection parameters was proposed. Other analysis methods were used to study the lateral buckling problem, such as isolated half-wavelength method [14,15], bifurcation analysis method [16], mode analysis method [17,18], and experimental tests [8,19,20].

These research results made the design of submarine pipelines more reliable and reasonable. However, as a large amount of offshore oil and gas have been explored and the hydrocarbon resources in shallow water become scarce, the offshore oil exploration and exploitation have to move from shallow waters to deep waters. In deep waters, the design of submarine pipelines faces great challenges. For instance, a typical design requires the operation temperature up to 177°C and pressure 44.8 MPa [21]. In these situations, single-walled submarine pipelines which have been discussed in the above studies are not available any more. PIP pipelines are well suited for the transportation of hydrocarbons in deep waters and lateral buckling may also occur in the submarine PIP pipelines.

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Nomenclature

C	Coefficient function for r_0 and β
D_i	Diameter of inter pipe
D_o	Diameter of outer pipe
EI_i	Flexural rigidity of inner pipe
EI_o	Flexural rigidity of outer pipe
EI_s	Integrated flexural rigidity
E	Young's modulus
F_c	Lateral buckling critical force
$f(u)$	Nonlinear lateral resistance, per unit length
G	Integrated coefficient function
h	Separate distance of inner pipe and outer pipe
J	Coefficient function for imperfection
L	The total length of pipe
L_0	The initial wavelength of imperfection
N_i	Interpolation function
q_e	Equivalent soil resistance
r_0	Clearance between inner pipe and outer pipe
t_i	Wall thickness of inner pipe
t_o	Wall thickness of outer pipe
u	Lateral displacement
u_m	Mobilization distance
$w_0(x)$	Initial imperfection shape function
w_{0m}	Maximum deviation of initial imperfection
ρ	Curvature radius
β	Stiffness ratio of inner pipe to outer pipe

The lateral buckling behavior of a submarine PIP pipeline is more complicated than that of a single-walled submarine pipeline because of the interaction between the inner and outer pipes. Taking the temperature gradient, pressure, soil resistance and the interaction forces between the inner and outer pipes into consideration, Harrison et al. [22] proposed an analysis method for the thermal expansion of an insulated PIP system and gave the calculating formulas for expansion length, stress, and strain. Vaz and Patel [23] proposed an analytical formula of the coupled lateral buckling instability of a PIP system based on beam theory. Their results show that the stiffness ratio of the inner pipe to the outer pipe and the number of centralizers affect the form of lateral buckling. However, since the imperfections and the friction between the seabed and the outer pipe were neglected, their analytical formula cannot be used for practical PIP design directly.

Zhao et al. [24] pointed out that it is difficult to obtain analytical formulas considering all factors such as initial imperfections, pipe-soil interaction, and interaction between inner and outer pipes, making the FE method convenient to study the lateral buckling problem of PIP pipelines. Sun and Jukes [25] performed FE simulations for high pressure and high temperature PIP systems using ABAQUS. In their simulations the beam elements were used to model the inner and outer pipes and the pipe-soil interaction elements were utilized to model interaction between the soil resistance and the pipeline displacement. Haq and Kenny [26] developed finite element modeling procedures based on the enhanced seabed friction model and performed a numerical parameter study on the lateral buckling response of submarine PIP pipeline. The parameters include the pipe embedment, pipe out-of-straightness (OOS), soil shear strength, soil peak force, soil residual force and mobilization distance, variation in soil properties, and external pressure.

The design challenges of submarine PIP pipelines were identified by various investigators. For example, Carr et al. [27] pointed out that the pipeline walking and the interaction between walking and lateral buckling are challenges that are often overlooked, Kristoffersen et al. [28] pointed out that the assessment of free span is another important part of the design of PIP pipelines. Some engineering measures were proposed to control the lateral buckling, as for instance, the sleeper method [29], the distributed buoyancy method [30] and the snaked lay method [31].

In conclusion, lateral buckling response of submarine PIP pipelines is complicated and is affected by many factors. The critical force of lateral buckling is essential to estimate the behavior of PIP pipelines and is also important for the design of PIP pipelines. However, until now, there is no a clear formula to accurately calculate it. The lateral buckling critical force of submarine PIP pipelines still lacks an integrated study.

In this paper, three dimensional (3D) FE models are established to study the lateral buckling response of imperfect submarine PIP pipelines on the basis of 3D beam elements, 3D tube-to-tube elements and 3D PSI (pipe-soil interaction) elements. Parameter studies are performed to investigate the effects of initial imperfection shape, OOS, soil conditions as well as nonlinear pipe-soil interaction, and structural parameters (stiffness ratio of inner pipe to outer pipe and clearance between inner and outer pipes) on the critical force of lateral buckling. A formula including the above parameters is proposed to calculate the lateral buckling critical force for submarine PIP pipelines on the basis of dimensional analysis and discussion of the results. A case study is carried out to verify the formula. The result demonstrates the accuracy of the formula.

2. Model and parameterization

2.1. Structure and model of PIP pipelines

Fig. 1 illustrates a typical structure of submarine PIP pipeline systems. The PIP pipeline system is composed of an inner pipe, an outer pipe, some insulation material, and a series of centralizers and bulkheads. The inner pipe is used to convey hydrocarbons and the outer pipe is used to withstand the external pressure and to protect the inner pipe. The centralizers are fixed with the inner pipe and used to avoid load crushing of the thermal insulation material. Since the outer pipe is separated from the centralizers, the inner pipe and the centralizers can move freely inside the outer pipe and transfer forces and displacements through the contact between the centralizer and the outer pipe. The insulation materials, between the inner and outer pipes, are used to provide thermal barrier to reduce heat loss. The end bulkheads are

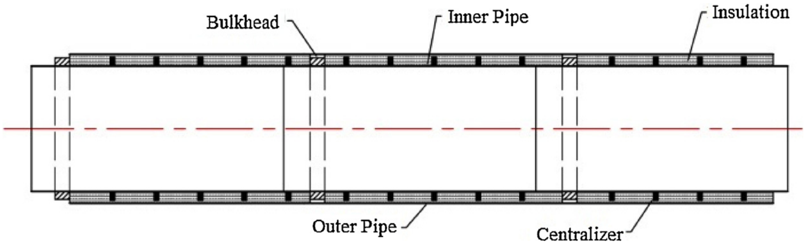

Fig. 1. Typical structure of a PIP pipeline.