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Numerical studies on global buckling of subsea pipelines

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ABSTRACT

Subsea pipelines buckle globally because of their movement relative to surrounding soil. Global buckling is often triggered by high operational temperature of the oil in pipelines, initial imperfections in the pipeline, and/or a combination of both. Pipeline global buckling is a failure mode that must be considered in the design and in-service assessment of submarine pipelines because it can jeopardize the structural integrity of the pipelines. Global buckling is increasingly difficult to control as temperature and pressure increase. Therefore, location prediction and buckling control are critical to pipeline design. Finite element analysis (FEA) is often used to analyze the behavior of pipelines subject to extreme pressures and temperatures. Four numerical simulation methods based on the finite element method (FEM) program ABAQUS, i.e., the 2D implicit, 2D explicit, 3D implicit, and 3D explicit methods, are used to simulate pipeline global buckling under different temperatures. The analysis results of the four typical methods were then compared with classical analytical solutions. The comparison indicates that the results obtained using the 2D implicit and 2D explicit methods are similar and the results obtained using the 2D implicit method are closer to those obtained using traditional analytical solutions. The analysis shows that the results of the 3D implicit and 3D explicit methods are similar, but the results obtained using the 3D methods are significantly different from those obtained using the analytical solution. A novel method to introduce initial pipeline imperfections into the FEA model in global buckling analysis is also presented in this paper.

1. Introduction

Pipeline design faces numerous engineering challenges as oil and gas resources are being obtained from deep waters. One of these challenges is pipeline global buckling. Pipelines are being required to operate at increasing temperatures and pressures in deep water. Thermal lateral buckling is a typical global buckling mode of deep-water pipelines because pipelines are typically laid directly on the seabed rather than being trenched and buried. In-service hydrocarbons must be transported at a high temperature and pressure to ease the flow. Thus, the thermal stress induced by the difference between the operational and ambient temperatures coupled with the Poisson effect causes a pipeline to expand longitudinally. However, the pipeline cannot expand freely because the surrounding soil restricts it. Axial compressive stress builds up on the wall of a pipeline approximately one kilometer long, and sudden deformation occurs when the compressive load reaches or exceeds the soil foundation constraint to release the internal stress accumulated on the pipe wall. Uncontrolled buckling can have serious effects on pipeline integrity.

Studies on thermal buckling in pipelines can be traced back to the early 1970s. Hobbs (1981, 1984) derived analytical solutions to the buckling and post-buckling behavior of a heated pipeline by assuming a pipeline buckling curve. He established the relationship between buckling temperature and buckling length in consideration of axial pipe–soil interaction. Taylor and Gan (1986) derived an analytical solution to the global buckling of an initially imperfect pipeline based on the analytical solution obtained by Hobbs (1984) to lateral buckling in an ideal pipeline. They assumed that the shape of a deformed pipeline is symmetrical and similar to that of an initially imperfect. The seabed trench bottom deformation are neglected and the soil resistance force is fully mobilized per unit length acting against the lateral buckling mechanism. Solving the total potential energy equation with special boundary conditions, Taylor and Gan (1986) obtained the analytical solution of buckling force, buckling amplitude, and maximum compressive stress. A sophisticated finite element method (FEM) that considers all of the pertinent pipeline operation data has been applied to pipeline buckling analysis with the development of modern computers. FEM studies on subsea-pipeline global buckling can be classified into two categories. One focuses on the interaction between a pipeline and its subsoil because a reliable pipe–soil resistance assessment plays a significant role in pipeline global buckling analysis. Several researchers

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over the past 30 years have paid particular attention to pipe–soil interaction in the analysis of on-bottom pipeline strength and stability behavior. Numerous excellent research studies have been conducted, and several useful achievements have been adopted for practical use, such as those of Lyons (1973), Friedmann (1986), Schaminee et al. (1990), Palmer et al. (1990), Hesar (2004), Merifield, White, and Randolph (2007, 2009), Bruton et al. (2008), Wang et al. (2013) and Bruton et al. (2011). The other category simulates pipeline global buckling under high-pressure and high-temperature conditions. Numerical pipeline global buckling analysis tools, such as PIPLIN-III (Structural Software Development Inc., 1981), PlusOne (Palmer and Associates, 1995), PIPSOL (Nixon, 1994), ABP, and UPBUCK (Klever et al., 1990) have been used in different situations over the past 30 years. Shaw and Bomba (1994) have developed a finite element (FE) analysis method that considers both nonlinear geometry and material effects to examine pipeline response to upheaval buckling. Case studies show that the temperature difference corresponding to pipeline buckling with nonlinear material behavior is smaller than that in the elastic model. Andreuzzi and Perrone (2001) present a mathematical model that considers soil resistance to beam lateral deflections by introducing linear spring resistance to beam lateral displacement, and report that FE and finite differences may generate errors in the results because of the discretization related to the modeling of the various axial compressive forces in the elements. A formula to analyze initially imperfect underground pipelines has been developed, and an issue regarding a 2D, initially imperfect, buried pipeline has been analyzed by Villarraga et al. (2004). All of these programs are based on pipe beam elements and elastic–plastic soil springs. Using simplified analytical models has been a standard approach to analyze upheaval buckling of high-temperature and high-pressure pipelines.

However, simplified approaches may be excessively conservative because they may fail to identify vulnerable features and underlying upheaval buckling risks that can result in severe economic consequences (Zhang and Tuohy, 2002). Therefore, understanding pipeline response to various loading conditions is critical in increasing pipeline design efficiency. Zhang and Tuohy (2002) conduct a global-buckling analysis case study on a trenched but unburied 6.0-inch production flowline using the commercial FEM program ANSYS (Kohnke and Peter, 1999). The results show that FE technology can be adopted as an effective tool to evaluate potential offshore flowline buckling behavior. ABAQUS (Hibbitt et al., 2000) also incorporates pipeline beam elements, soil–pipe interaction, and large displacements to model considerable pipeline length and predict overall structural behavior under different load conditions. Jukes et al. (2009) report the advantage of the FE analysis tools, which can be used in the design and simulation of subsea pipelines and their components. SIMULATOR, a highly nonlinear FE program, has been developed using ABAQUS as the FE engine. Case studies show that the developed program can be applied to complex pipeline design cases, such as global analysis, local modeling, and pipeline route selection. The case study results also imply that the advanced numerical tools are suitable for pipeline design and simulation, particularly of deep-water pipelines. These tools are also suited to extreme conditions because they can simulate highly non-linear cases quickly and efficiently. Wang et al. (2009) and Jukes et al. (2009) developed the FE tool as a SIMULATOR component. The in-house pipeline analysis package designed by Kenny, which has been developed using the ABAQUS platform, can simulate global buckling with different pipeline configurations under various conditions. Global pipeline FE analyses have been widely used to investigate complex practical problems associated with lateral pipeline buckling and the walking pipeline phenomenon (Jukes et al., 2008; Jukes et al., 2009; Sinclair et al., 2009; Cumming et al., 2009; Cumming and Rathbone, 2010; Jin et al., 2010; Bruton et al., 2011; Sun et al., 2011). Literature reviews have shown that the existing 3D, thermal-pipeline-buckling finite element analysis (FEA) method, which collectively considers temperature field and stress fields, initial imperfections in a pipe, and soil/pipe interaction, is inefficient, although the FEA of offshore pipeline upheaval buckling has progressed rapidly in recent years.

In this study, four typical FEA methods, namely, the 2D implicit, 2D explicit, 3D implicit, and 3D explicit methods, are used to analyze subsea-pipeline global buckling under high temperature and high pressure conditions. Initial pipeline imperfection as a result of fabrication or installation and seabed undulation is also considered in the FE analyses using a novel method. The analysis results obtained using the four typical FEA methods are then compared with analytical solutions derived by Taylor and Gan (1986).

2. Global buckling analysis methods

2.1. Establishment of 2D and 3D FEA models

A global buckling analysis model is characterized by the long axial direction of the pipeline and the relatively small pipeline cross-section. Therefore, the beam element is highly suitable for pipeline structure simulation. The moment distribution along the pipeline can be obtained easily. The 2D FEA model can be adopted to simplify the study on one-direction global buckling under thermal stress conditions. The 2D FEA model offers a trustworthy solution to exposed pipelines on an even seabed, and it allows the pipeline to move both axially and laterally. The 2D FEA model not only can assess thermal expansion and longitudinal thermal loading, but also can investigate lateral and upheaval buckling. The horizontal 2D FEA model can be built as shown in Fig. 1.

The 2D FEA model employed in this study uses ABAQUS as the underlying FE engine. PIPE32H beam elements and dimensions represent the pipeline in this model. The expansion coefficient of the pipeline material is also defined to determine the role of thermal stress induced by temperature. The pipeline is modeled using linear elastic material, and the seabed is assumed to be a rigid foundation. Contact elements are created between the pipeline and the rigid foundation, and these contact elements are positioned in two areas: one is perpendicular to the plane of the foundation soil, which displays normal contact behavior and has a "hard" contact parameter, and the other is parallel to the foundation soil surface/plane, which displays tangential contact behavior and has a penalty function parameter. This form of contact cannot determine pipeline settlement deformation as a result of self-weight, but it can simulate the increasing resistance of the foundation soil to the increasing weight of the submerged pipeline. The friction length effect cannot be extended to both ends of the pipeline because the pipeline is long ($\geq$ 500 m). Both ends of the pipeline are completely fixed, and the boundary conditions of the soil resist both laterally and axially. The bottom boundary of the soil is completely fixed as well. The following three steps have been adapted in the simulation: (1) introduction of the initial curved pipeline section to simulate the initial imperfection generated in the manufacturing process and placement of the pipeline

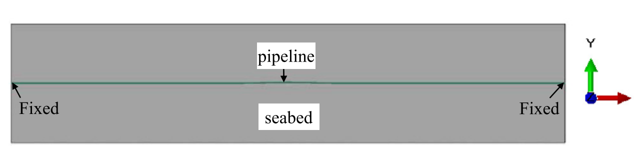

Fig. 1. 2D FEA model.