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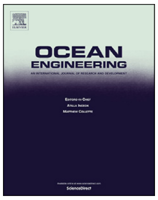

Effective design of submarine pipe-in-pipe using Finite Element Analysis

Facheng Wang

Department of Civil Engineering, Tsinghua University, Beijing, 100084, PR China

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ABSTRACT

Submarine pipe-in-pipe flowline have become a common pipeline arrangement to achieve a significant thermal insulation capacity. A pipe-in-pipe system generally contains four structural components: jacket pipe, carrier pipe, spacers and bulkheads. Global response of the system depends on both the behaviour of each constituent part and interactions between them. Existing design approaches to consider this system are either too simplistic resulting in loss of accuracy or significantly complicated Finite Element Analysis demanding expensive highly skilled manpower. This paper proposes cost effective design methods which provide accurate prediction with minimum increase in modelling complexity through simplified Finite Element Analysis models. Pipe-in-pipe system S-lay, thermal expansion and spool arrangement design have been investigated. ABAQUS or AutoPIPE based methods have been proposed to cover each application and excellent performance has been observed. In addition to cost-effectiveness, ABAQUS based method for S-lay is able to capture twisting and residual stresses which are generally ignored by traditional approach but important in deep-water applications.

1. Introduction

Submarine pipe-in-pipe, hereafter PIP, has been widely used in offshore oil and gas industry to deal with thermal insulation issues. The main characteristic of a PIP is a jacket pipe (also known as outer or protective pipe) and a carrier pipe (also known as inner or production pipe) where the annulus between the two pipes is generally filled with thermal insulation materials (Bokaian, 2004; Kyriakides, 2002; Olso and Kyriakides, 2003; Zheng et al., 2014). Spacers are employed to maintain the carrier line concentric within the jacket pipe and are typically placed at intervals of several meters. In terms of structural behaviour, pipe-in-pipe system can be divided into two categories, compliant or non-compliant, depending on the method of load transfer between the jacket and carrier pipes (Bai and Bai, 2005; Bokaian, 2004). In the former case, forces continuously transfer between jacket and carrier pipes through fully welded ‘tulips’ (generally one each end of each 24.4 m lengths) produced by cold forging stock linepipe (stress relieved thereafter)(Sahota et al., 1999). In the later case, jacket and carrier pipes are structurally connected through bulkheads which may be either placed at interval of a few kilometres along the length of the pipeline length or only at both ends of the pipeline. A general illustration of a PIP is given in Fig. 1. This paper concerns non-compliant systems.

Compared with conventional pipelines (Hobbs, 1984; Hobbs and Liang, 1989), PIP systems have more sophisticated structural behaviours due to composite actions between their constituent parts including inner pipes, outer pipes, spacers, welded ‘tulips’, bulkheads etc. Extensive investigations on global responses of PIP systems have been conducted. Design approaches for PIP systems can be mainly categorized into either analytical or Finite Element Analysis (FEA) methods. Existing analytical calculation methods either assume only two bulkheads at pipeline extremities (Harrison et al., 1997) or “equivalent PIP” methods where geometries, masses, structures and stresses of equivalent lines are simply superimposed or derived (Bokaian, 2004; Malahy, 1996; Orcina, 2016). The assumptions adopted by analytical methods are useful but use artificial simplifications and generally lead to loss of prediction accuracy. In case of deep-water applications where tremendous top tensions and significantly reduced stinger radius likely result in pipeline yielding, it is subsequently crucial to provide accurate predictions of bundle behaviours (Wang et al., 2017a,b). For FEA methods, Jukes et al. (2008) and Sun and Jukes (2009) investigated extra High Pressure High Temperature (HPHT) PIP design by using both analytical and numerical method, mainly on in-place stage. Harrison and McCarron (2006), Sun and Jukes (2009) and Wang et al. (2013) studied PIP installation behaviours by detailed numerical modelling. Suwarno et al. (2014) carried out investigations on the effect of stinger stiffness on pipeline installation. Wang et al. (2014) researched effective design of spool which aims to cope with thermal expansion induced by PIP pipeline under HPHT conditions.

This paper extends the investigation to PIP S-lay, on which topic literature is somewhat limited. In S-lay method, pipeline is supported by

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E-mail address: wangfacheng@tsinghua.edu.cn.

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Nomenclature

E	is the elastic modulus of the steel
f_{true}	is the true stress of the steel
$\varepsilon_{\ln}^{pl}$	is the log plastic strain of the steel
f_{nom}	is the nominal stress of the steel
ε_{nom}	is the nominal strain of the steel

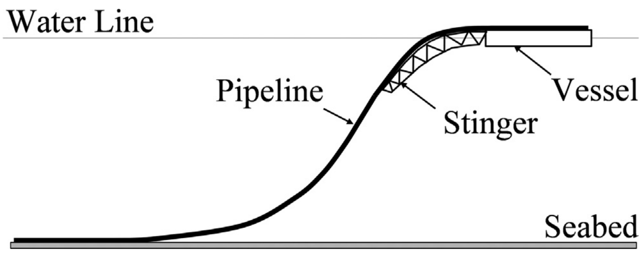


Fig. 2. S-lay illustration.

a stinger passing on a regular sequence of rollers, following an S-shape trajectory before landing on seabed. As illustrated in Fig. 2, pipelines in S-lay may confront significant axial tensions. Existing methods are deemed to be either too simplistic or very complex and detailed FEA models, requiring high skill levels and resulting in high costs. This paper aims to propose cost-effective FEA solutions which provide accurate predictions with minimum increase on numerical complexities. Methods of S-lay installation, in-place thermal expansion and spool piece arrangement have been presented in this paper.

2. PIP installation phase

Dedicated FEA-based pipeline installation program "OFFPIPE" has been frequently employed to obtain optimum parameters for achieving a viable installation and has been widely recognized by industry. However, the "Equivalent PIP" employed by OFFPIPE (Malahy, 1996) is a useful but artificial assumption, especially in deep-water applications. Detailed structural interactions between outer and inner pipeline during installation phase cannot be included by OFFPIPE. In addition, it is not possible for OFFPIPE to consider unstable rotations of the pipe, known as twisting which is a known problem with S-lay installation since OFFPIPE assumes 2D geometry. In addition, although non-linear material properties can be included in OFFPIPE, the reduced flexibility of defining nonlinear material directly limits the depth of investigation on the effect of stinger, especially the overbend induced residual strain. Furthermore, OFFPIPE, which performs analysis at single point of time, limits designer's understanding of the entire structural performance throughout the installation process. For example, an in-line structure installation analyst will prefer a complete time domain three-dimensional (3D) simulation of the S-lay to capture peak strain during a whole process.

To overcome the challenges presented above, a novel methodology, based on general FEA software has been suggested. The method reflects the structural behaviour of PIP in each procedure, from installation to in-place, but with an acceptable level of increase in design complexity. S-lay installation has been investigated here. This method has been developed by adopting a detailed FEA model via ABAQUS package (ABAQUS, 2014). Details about the modelling and analysis procedure are presented in the following sections.

2.1. *FE modelling*

2.1.1. *Pipe*

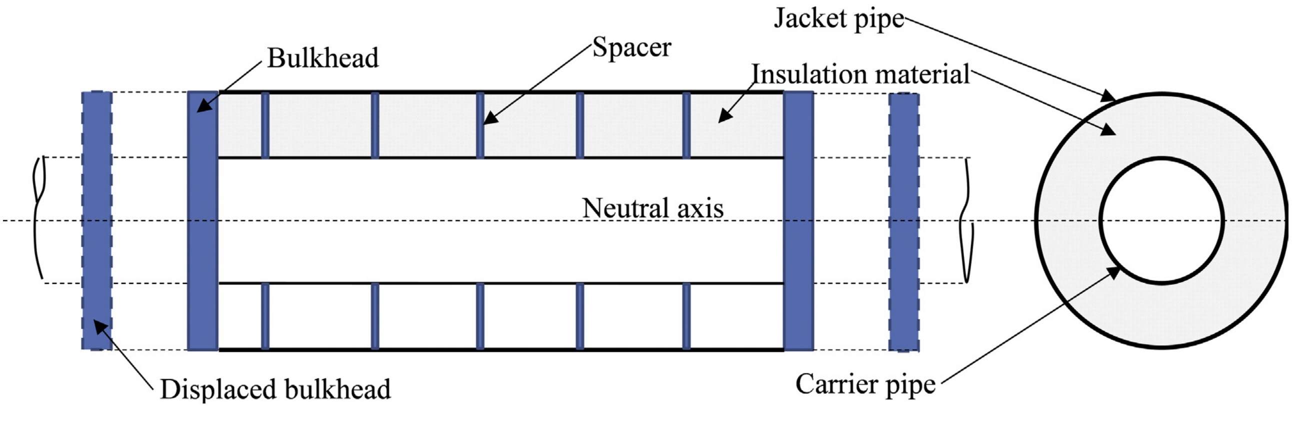
Outer and inner pipes are modeled using PIPE31H, 2-noded hybrid formulation pipe element with 8 integration points (ABAQUS, 2014). These elements are selected as they are particularly well suited to model long, slender flowlines with better convergence behavior than standard pipe elements.

2.1.2. *Spacer*

Spacers, as illustrated in Fig. 1, usually employed as centralizers to constraint the clearance between inner and outer pipes, are modeled through 3D tube-to-tube contact elements (ITT31). Both lateral and axial movements can be constrained by defining clearance and friction. A sliding line is defined to specify the interaction between jacket and carrier pipes. Contact parameters such as smoothness and offset allowance can be considered. Details can be found in "Abaqus Keywords Reference Guidance - *SLIDE LINE" (ABAQUS, 2014).

2.1.3. *Bulkhead*

Bulkheads are commonly employed by PIP systems to meet manufacturing requirements. However, from perspective of structural performance, the influence of bulkhead arrangements on the axial section force distributions between jacket and carrier pipes is significant. For instance, axial force distribution on pipeline with one bulkhead per 10 km (km) has different structural performance on pipeline with one bulkhead per 1 km. A design study has been carried out and the details



(a) Side view (b) Sectional view

Fig. 1. Pipe-in-pipe illustration.