Ocean Engineering 111 (2016) 398–413

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

The influence of sea state on dynamic behaviour of offshore pipelines for deepwater S-lay

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ARTICLE INFO

Article history:
Received 14 November 2014
Accepted 16 November 2015

Keywords:
Offshore pipeline
Sea state
Pipelay vessel
S-lay
Dynamic behaviour

ABSTRACT

The dynamic response of offshore pipelines induced by deepwater S-lay is highly noticeable, and directly dominates the design of such structures and the installation feasibility in practice. A comprehensive finite element model for deepwater S-lay systems using the software OrcaFlex is specially developed to explore the influences of sea state on the pipeline dynamic responses, considering surface waves, ocean currents, pipelay vessel motions, clashing contact between the pipeline and rollers. Meanwhile, a non-linear hysteretic soil model is applied to simulate the vertical pipe–seabed interaction, and the modified Coulomb friction model is used to model the lateral pipe–seabed interaction. The numerical model is then used to carry out an illustrative example analysis of a 12-in. gas export pipeline being laid onto the seabed with a water depth of 1500 m using the HYSY 201 pipelay vessel in the LW3-1 gas field in the South China Sea under various sea states. The influences of sea state on the pipeline dynamic behaviour on aspects of configuration, lateral displacement, axial tension, bending moment, stress and strain as well as pipeline embedment are estimated quantitatively. The findings show that a strong relevance exists between surface wave and resulting pipelay vessel motions, and pipeline dynamic responses.

1. Introduction

In recent years, the ever increasing demands to hydrocarbons have driven the exploration and exploitation of offshore oil–gas resources to deepwater or ultra-deepwater areas. Offshore pipelines are undoubtedly considered to be the most feasible and efficient means to transport crude oil and natural gas in large scale from remote subsea well sites to surface processing facilities. In deepwater applications, hundreds of kilometres of pipelines need be laid to the seabed, and the maximum water depth can attain several thousand metres. In general, S-lay and J-lay techniques are utilised in deepwater pipeline installations. The S-lay technique still occupies a dominant position in the current pipelay market due to its particular advantages such as better adaptability and workability to different sea states and various water depths, higher pipelay efficiency, and lower costs. Through special modifications and upgrades, Solitaire, the present largest pipelay vessel in the world, applied the S-lay technique to favourably accomplish the installation of a 24-in. gas export pipeline in water depths ranging from 35 m to 2420 m in the Independence Trail project in the Gulf of Mexico (Steenhuis et al., 2007).

In the S-lay method, a section of pipes with a certain length are first welded and inspected, and the field-joints are coated in the horizontal firing line of the lay barge. Then, the assembled pipeline passes through a tensioner which carries the axial tension needed to support the suspended span, and slides over the stinger at the stern of the vessel via a sloping ramp before reaching the sea floor. The entire pipeline characterises as an S-shaped curve on the way to the sea floor, and is generally divided into two main regions. The upper curved part of the pipeline is known as the overbend, which extends from the tensioner to the inflection point. The suspended part from the inflection point to the sea floor is denoted as the sagbend, as shown in Fig. 1. The tensioners mounted on the lay vessel are mainly used to apply a horizontal tension to the pipe at the top end and control the pipeline configuration in the sagbend. The stinger is usually designed to control the deflection of the pipeline in the overbend as a long boom-like curved structure, which is made up of several sections of truss structures mutually connected via hinges. The pipeline in the overbend is intermittently supported by the V-shaped rollers more or less uniformly distributed along the vessel deck and the sternward stinger. The S-lay method for the pipeline installations is applicable to various water depths. As to deepwater applications, its feasibility heavily depends on applied tensions of the tensioner and geometric characteristics of the stinger.

It is increasingly recognised that the dynamic response of offshore pipelines induced by S-lay in deep waters becomes more remarkable and significant, and directly dominates the design of such structures and the installation feasibility in practice. Design

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http://dx.doi.org/10.1016/j.oceaneng.2015.11.013
0029-8018/

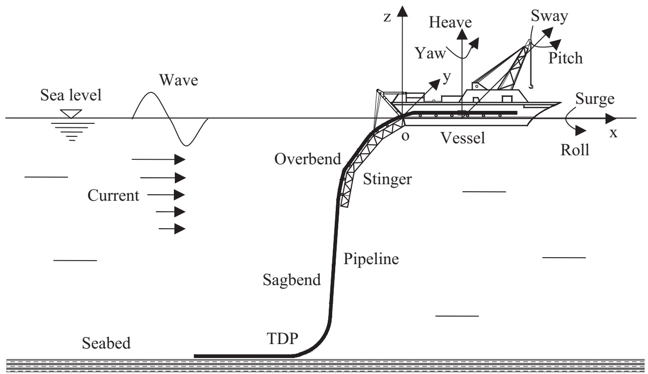

Fig. 1. Schematic diagram of S-lay pipeline installation.

uncertainties arise due to the limited understandings of the influence of various pipelay parameters on the pipeline dynamic behaviour during deepwater installation, pertaining to geometry and material properties of the pipeline, environmental loadings, pipelay vessel motions, and seabed characteristics. Thus, having a good understanding of the dynamic behaviour of offshore pipelines during deepwater S-lay operation is vitally important for its applications, which may not only promote the reasonable design of the pipe structures, but also improve the control of the pipelay parameters. This understanding can be acquired from the numerical simulations based on the finite element model, which should sufficiently include the structural model of the pipelines, environmental loads such as surface waves and ocean currents, pipelay vessel motions induced by surface wave, clashing contact between the pipeline and rollers, and pipe–seabed interactions, etc.

Over the past forty years, this problem has attracted extensive attentions. Initially, the dynamic behaviours of offshore pipelines under laying operations were investigated on the basis of the asymptotic expansion method of stiffened catenary theory (Brewer and Dixon, 1970). Subsequently, the finite element methods were developed to carry out the dynamic response analysis of offshore pipelines for S-lay in shallow waters (Hall and Healey, 1980; Suzuki and Jingu, 1982; Vlahopoulos and Bernitsas, 1990; Clauss et al., 1992; Tikhonov et al., 1996). The early research works simplify the interactions between pipeline and stinger to some extent, and assume the seabed to be rigid, horizontal and flat, which leads to very rough results at some critical positions such as touch down point (TDP) and lift-off point. Yun et al. (2004) and Xie et al. (2013) studied the effect of loading history on the level of the pipe strain concentration on the stinger and the plastic deformation of the overbend pipe during deepwater S-lay operation, respectively. On the other hand, the dynamic responses of the catenary pipelines under wave and ocean current in a J-lay operation were modelled taking into account the effects of hydrodynamic drag, pipelay vessel dynamics, and pipe–seabed interaction (Jensen et al., 2010; Szczotka, 2011; Chatjigeorgiou, 2013; Quéau et al., 2013). A more comprehensive finite element model for deepwater S-lay systems still need be developed including the influence of the pipelay vessel motions, the interaction between pipeline and stinger, as well as pipe–seabed interactions.

With the development of numerical tools such as ABAQUS, OFFPIPE, RIFLEX and OrcaFlex, etc, the modelling of offshore pipelines in the process of deepwater S-lay has become an important means to obtain the structural behaviour of the pipelines (Torselletti et al., 2006; Marchionni et al., 2011). Moreover, O'Grady and Harte (2013) presented a more advanced S-lay analysis approach which took a detailed and localised view of the pipe cross-section during ultra-deepwater installation to investigate the level, and indeed the effect, of residual curvature and pipe roll on the pipe section behaviour. Lately, Gong et al. (2014) established a comprehensive finite element model for deepwater S-lay systems to investigate the dynamic lay effects of the pipeline, and observed the significant differences between static and dynamic analysis results. However, these results are still difficult to meet the precise design requirements, and the influence of various pipelay parameters on the pipeline dynamic behaviour during deepwater installation should be fully identified. Therefore, an extensively quantitative estimation of the influence of sea state on the dynamic response of offshore pipelines need be further investigated in detail.

The pipe–soil interaction is of prime importance in estimating dynamic responses and structural behaviours of a pipeline or catenary riser in contact with the seabed. Their stresses and deformations in the touchdown zone (TDZ) are very sensitive to the seabed model. Some researchers have focused on elaborating the pipe–seabed interaction. In the early stage, the seabed was generally deemed to be a continuous, elastic-frictional foundation in the pipelay analysis, and it was assumed to be linearly elastic with respect to the deformation (Schmidt, 1977). Based on the model experiments, numerical simulations and analytical solutions using the classical plasticity theory, several non-linear seabed models in clay soils were developed to predict the vertical pipe–soil interactions, respectively (Murff et al., 1989; Bridge et al., 2004; Aubeny et al., 2005; Hodder and Cassidy, 2010; Yuan et al., 2012; Wang et al., 2012). However, for the dynamic piplay analysis, aforementioned seabed models are still incapable of sufficiently describing the vertical pipe–soil interaction of varying soil stiffness with the magnitude of pipeline penetration under cyclic motions. Aubeny and Biscontin (2009), and Randolph and Quiggin (2009) proposed a non-linear hysteretic model of the reaction force normal to the seabed with the pipeline penetration, respectively, which is very suitable to predict the dynamic behaviour of a pipeline or catenary riser in contact with the seabed during their cyclic movements. The non-linear seabed model includes the features such as pipe embedment, pipe breakaway, varying soil stiffness, soil suction, cyclic loading motions, and so on. Meanwhile, the non-linear hysteretic seabed model proposed by Randolph and Quiggin (2009) was validated against the laboratory and field-scale experiments with reasonable accuracy. This model has been implemented in the software OrcaFlex (Orcina, 2014) which is widely used for the pipelay analysis. Then, Westgate et al. (2010) applied the non-linear seabed soil model in OrcaFlex to investigate the influence of sea state on as-laid pipeline embedment. Similarly, Elosta et al. (2013) developed the non-linear SCR-seabed vertical and lateral interaction models to analyse the seabed resistance and determine the interaction influence on global riser structural dynamic behaviour under cyclic SCR movements.

The goal of this paper is to offer a quantitative assessment of the influence of sea state on the dynamic behaviour of offshore pipelines during deepwater S-lay operation. Thus, a comprehensive finite element model for deepwater S-lay systems using the software OrcaFlex (Orcina, 2014) is developed to simulate the three-dimensional dynamic responses of offshore pipeline under various sea states. The numerical model includes the pipelay vessel motions, the clashing contact between the pipeline and rollers mounted on the barge stern and stinger, and the pipe–seabed interactions. The hydrodynamic forces of the pipeline are considered, likewise. A non-linear hysteretic soil model proposed by Randolph and Quiggin (2009) is applied to simulate the vertical pipe–seabed interaction, and the modified Coulomb friction model is used to model the lateral pipe–seabed interaction. Then, the influence of sea state on the dynamic behaviour of offshore pipelines is sufficiently discussed using an illustrative example of a 12-in. gas export pipeline being laid onto the seabed with a maximum water depth of 1500 m using the HYSY 201 pipelay vessel in the LW3-1 gas field in the South China Sea.