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Upheaval buckling of surface-laid offshore pipeline

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ABSTRACT

Offshore pipelines operating under high pressure and temperature are subjected to upheaval buckling. Pipeline behaviour in upheaval buckling depends on a number of factors including the shape of pipeline imperfection, installation stresses, loading types, seabed sediment behaviour and the flexural stiffness of the pipe. Current method of predicting upheaval buckling is based on simplified shapes of pipeline imperfection developed for idealized seabed conditions. To account for the effect of internal pressure, the pressure load is represented using an equivalent temperature. However, the applicability of these idealizations on the prediction of upheaval buckling has not been well-investigated. In this paper, the three-dimensional finite element modelling technique is used to investigate the applicability of idealized shapes and their effects on the upheaval buckling of pipeline for a seabed condition at offshore Newfoundland in Canada. The finite element model is then used to conduct a parametric study to investigate the effects of installation stress, loading types, seabed parameters and the flexural stiffness of the pipe. Finally, a design chart is developed to determine the optimum height of seabed features to manage pipeline stability against upheaval buckling under different temperature and pressure loadings.

1. Introduction

Offshore oil and gas development activities have grown rapidly over the past few decades to meet the global energy demand. Pipeline, as the most viable mean for transporting oil and gas, are being used worldwide for transporting offshore oil and gas. However, offshore pipeline design faces a number of engineering challenges, which require proper understanding of the behavior of the pipelines on and in the seabed under various operating conditions. Upheaval buckling was recognized as an important design consideration for offshore pipelines in the early 1980s when a few upheaval buckling incidents occurred in the North Sea [1].

Upheaval buckling is a mode of pipeline deformation (upward) that overstresses the pipe wall and may lead to fracture [2]. Such fracture damage in pipelines should be prevented not only to avoid the huge economic loss associated with a system shut-down, repair, and the loss of products, but also to safeguard the environment from the escaping contaminants. Therefore, the prediction of upheaval buckling and taking protective measures against this phenomenon is very important for offshore pipelines [3].

The offshore pipeline transporting oil with high internal pressure and high temperature (HP/HT) experiences high compressive force normal to the pipe cross-section when the pipe is constrained along longitudinal direction. The pipe buckles laterally, vertically or obliquely when this compressive force exceeds the critical buckling force. Theory and laboratory-scale experiments demonstrate that the high internal pressure alone can cause upheaval buckling (Palmar and King 2008). The surrounding soil offers resistance to buckling of the pipeline. The soil resistance is generally greater against lateral buckling than the upheaval buckling [1,2,4].

In addition to the operating conditions (high pressure and high temperature), the upheaval buckling of subsea pipelines is greatly affected by initial imperfection (out-of-straightness) of the pipelines [4–8]. The initial imperfection may be due to the imperfection of the existing seabed, manufacturing defect, or installation of the pipelines. The imperfection of the seabed may be influenced by trenching during installation. The behavior of the pipeline during buckling is governed by the amplitude [3,7–9] and the shape [2,5,7] of the imperfection.

For the structural stability assessment of pipelines subjected to upheaval buckling, several analytical solutions were developed for critical buckling forces using beam formulations with assumed shapes of localized imperfections [5,8,10–12]. For simplicity in analysis, different idealized shapes of initial imperfection were assumed in the development of the analytical solutions. The idealized shapes include those of Taylor and Tran [13], who developed empathetic models from mathematical reasoning for three different types of imperfections such as "basic contact undulation",

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"isolated prop" and "infilled prop". Palmer et al. [11] employed sinusoidal imperfection shape for a pipeline, and defined it using two parameters such as imperfection height and length. However, researchers have demonstrated that the imperfection geometry of pipeline in the seabed is much more complex than the idealized shapes, which has significant effect on the critical buckling load. Zeng et al. [5] investigated the pipelines with sinusoidal and other polynomial shaped imperfections using finite element analysis and showed that the imperfection shapes significantly influence the critical buckling force. The study indicates the necessity of considering realistic imperfection shapes for the assessment of upheaval buckling for subsea pipeline.

Mondal and Dhar [14] conducted a two-dimensional (2D) finite element (FE) analysis to investigate the effect of a seabed condition on the upheaval buckling behavior of surface laid offshore pipeline using a commercially available software "Abaqus". The pipeline is modeled using 2D pipe element (Abaqus element type PIPE21H) and the seabed is modeled using plane strain element (Abaqus element type CPEG8R). The node-to-surface interaction with frictional coefficient of 0.40 is applied between the pipeline and seabed. As the pipeline is modeled using 2D element, the internal pressure could not be applied directly during the FE analysis. The effect of the internal pressure is incorporated indirectly through increasing an equivalent amount of pipe temperature calculated using Eq. (1) (after [7]).

$$\Delta T_p = \frac{pD(1-2\nu)}{4tE\alpha} \tag{1}$$

Where ΔT_p is the temperature change required to result in the same effect as that of an internal pressure of p. The other parameters in the equation such as D, t, E, α and ν correspond to pipe outer diameter, pipe wall thickness, modulus of elasticity, coefficient of thermal expansion and Poisson's ratio, respectively. Eq. (1) is based on the assumption of fully restrained longitudinal expansion of the pipeline, which is expected for pipelines undergoing upheaval buckling. Longitudinal expansion of offshore pipelines is inhibited by the friction between the pipelines and the seabed soil [15,16]. The pipelines are also anchored using rock dump over a length that restrains the axial movement [17]. Mondal and Dhar [14] revealed that the local seabed condition affects the upheaval buckling behavior. The initial shape of the pipe with the local seabed profile was different from the idealized shapes recommended in the design codes. The temperature required to initiate upheaval buckling was also found to be less for the pipe affected by the local seabed profile, implying that the critical buckling temperature based on the idealized initial shapes might be unconservative with respect to the 2D FE calculation. It is however to be noted that the two-dimensional idealization in FE analysis is unable to account for the embedment or partial embedment of the pipe into the foundation soil that is expected during upheaval buckling. Applicability of idealization of the internal pressure with an equivalent temperature also requires evaluation. As a result, the predications using 2D idealization remain questionable. Liu et al. [18] earlier reported discrepancies in the results of 2D and 3D analyses for global buckling in offshore pipelines. Three-dimensional analysis is therefore employed in this study for the analysis of upheaval buckling.

The objective of this study is to investigate the influence of local seabed conditions on the upheaval buckling of offshore pipelines using three-dimensional (3-D) FE modelling. The initial shape of unburied pipeline laid on imperfect seabed is developed by FE modelling. The developed shape is compared with the existing models for initial imperfection [7,13]. The upheaval buckling behavior of the pipeline subjected to pressure and temperature is then investigated. A parametric study is conducted to investigate the effects of imperfection geometry, pipe cross-sectional property and seabed soil conditions on the upheaval buckling. A remedial measure against upheaval buckling is proposed through management of seabed imperfection.

2. Seabed profile

A real seabed profile of offshore Newfoundland in Canada is first considered for this study. Seabed profile and the geotechnical information of the subsea soil along a potential pipeline project were obtained through collaboration with Husky Energy. Fig. 1 shows the seabed profile over the length of 350 m from a reference point. A length of 350 m is employed in the analysis based on a preliminary study revealing that the length is sufficient for the analysis of the upheaval buckling. Fig. 1 represents profile with respect to the depth of water. Fig. 1 also shows elevation of the seabed profile with respect to an arbitrary datum located at 76 m below the water surface. The figure reveals that seabed is irregular and has an upward prop of about 2.2 m height between the distance of 150 m and 250 m. Pipe laid on this seabed will develop an initial shape of imperfection that will be governed by the shape of the seabed, stiffness of the seabed and the flexural rigidity of the pipeline.

3. Shape of initial imperfection

Several different idealized profiles for subsea pipeline exist in the literature to represent the initial shape of pipeline imperfection. Taylor and Tran [13] proposed the shape of initial imperfection for an isolated prop of seabed imperfection (Eq. (2)).

$$y = \frac{q}{72EI}\left[2L_o\left(\frac{L_o}{2}-x\right)^3 - 3\left(\frac{L_o}{2}-x\right)^4\right] \tag{2}$$

Where,

y = height above the lowest point
H = maximum height of imperfection
L_o = wave length of imperfection = $5.8259\left(H\frac{EI}{q}\right)^{\frac{1}{4}}$
x = distance measured from the symmetric point of imperfection
q = submerged otherwise self-weight of pipeline per unit length
I = moment of inertia of pipe section
E = modulus of elasticity of pipe material

For infilled prop imperfection where the pipeline is perfectly fitting with the seabed, the proposed shape of imperfection is [13]:

$$y = H\left[0.707 - 0.26176\frac{\pi^2 x^2}{{L_o}^2} + 0.293cos\left(\frac{2.86\pi x}{L_o}\right)\right] \tag{3}$$

Palmer and King [11] employed sinusoidal profile of imperfection (Eq. (4)) to develop universal design curve for upheaval buckling.

$$y = \frac{H}{2}\left[1 + cos\left(\frac{2\pi x}{L_o}\right)\right] \tag{4}$$

Karampour et al. [7] used two other imperfection shapes (Eqs. (5) and (6)) to account for possible undulations of the seabed.

$$y = H\left(8\frac{x}{L_o}+1\right)\left(\frac{2x}{L_o}-1\right)^4 \tag{5}$$

$$y = H\left[\frac{32}{3}\left(\frac{x}{L_o}\right)^2 + 6\left(\frac{x}{L_o}\right)+1\right]\left(1-\frac{2x}{L_o}\right) \tag{6}$$

The seabed profile shown in Fig. 1 is assumed to result in the infilled prop type imperfection (or basic contact undulation) of the pipeline. The shapes given in Eqs. (3)–(6) would thus represent the idealized initial shape, which are investigated here for comparison. However, the initial shape given by Eq. (4) is used to model the pipeline imperfection for the parametric study.

In the above idealized imperfection shapes, only Eq. (2) includes a term for flexural rigidity (EI) of the pipeline. The effects of soil