Ocean Engineering 109 (2015) 330–343

Contents lists available at ScienceDirect

Ocean Engineering

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

Prediction of the upheaval buckling critical force for imperfect submarine pipelines

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ARTICLE INFO

Article history:
Received 16 June 2015
Accepted 14 September 2015

Keywords:
Upheaval buckling
Critical axial force
Imperfection
Curvature radius

ABSTRACT

Upheaval buckling behavior of submarine pipelines under high temperature and high pressure conditions is a primary concern for structural integrity. The critical axial force is a key factor governing the buckling behavior. There have been already some formulas to calculate critical axial force for some particular initial imperfection shapes. However, there is no universal formula to express the effects of initial imperfection shape and Out-of-Straight (OOS) on the critical axial force. In this paper, the upheaval buckling behaviors of eight groups of pipeline segments with different imperfection shapes and different OOS have been studied using the finite element method. A new parameter is defined to express the differences of imperfection shapes. An approximation and universal formula is proposed to calculate the critical axial force which covers the new parameter and the OOS of pipeline. A case study is presented which illustrates the application of the formula. Finally, comparison between this study and previous research results is conducted, and it manifests that this formula has a greater precision.

1. Introduction

The safe running of submarine pipelines has been paid more attention especially with the development of ocean petroleum industry in recent years. While for submarine pipelines, one of the key issues in engineering design is the potential for global instability-buckling. When a submarine pipeline is operated at a high temperature and high pressure conditions, it will try to expand. In general, the pipeline is not free to expand because of being axially restrained, for instance by the friction of the surrounding soil. So an axial compressive force is produced in pipeline. If the force exerted by pipeline on the soil exceeds the vertical restraint against uplift movement created by the pipeline's submerged weight, its bending stiffness and the resistance of the soil cover, the pipeline will tend to move upward and considerable vertical displacements may occur (Palmer et al., 1990). This phenomenon is called upheaval buckling. This buckling mode may lead to the final failure such as fatigue or fracture (Det Norske Veritas, 2007). Then, it will bring disastrous results to marine creature, marine environment and human.

Many researchers have investigated the upheaval buckling problem. Allan (1968) conducted analytical and experimental studies on upheaval buckling of an axially compressed frictionless strip. He found the sensitivity of the buckling problem to initial imperfections. Hobbs (1984) analyzed the upheaval and lateral buckling of submarine pipeline on the basis of related work on railroad track. He assumed the pipeline is an ideal straight and perfect elasticity pipe with a small slope when it reached critical buckling condition. So the governing equation is a second-order differential equation. By solving the governing equation he obtained a theoretical solution for the critical force. He proposed that for normal coefficients of friction, the lateral buckling occurs at a lower axial load than upheaval buckling and is dominant in pipeline unless the pipeline is trenched or buried. At last he pointed out that the initial out-of-straightness (OOS) of pipeline should be taken into account in analysis of upheaval buckling of submarine pipeline. A series of studies including some theoretical analysis and experiments on upheaval and lateral buckling problem of submarine pipelines were conducted by Taylor and Gan (1986, 1987), Taylor and Tran (1993, 1996). They focused on the effects of structural imperfections and deformation-dependent axial friction resistance on submarine pipelines buckling. For initial imperfection, they proposed three theoretical imperfection models, analyzed their characteristics of buckling and predicted the critical axial forces. They pointed out that the amplitude and wave length are very important parameters for buckling of submarine pipeline and the two parameters are covered in their equations. Ju and Kyriakides (1988) studied the effect of localized and small initial geometric imperfection on the response and

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http://dx.doi.org/10.1016/j.oceaneng.2015.09.022
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stability of pipeline. They pointed out that the critical force is sensitive to form and magnitude of the imperfections as well as the pipe material inelastic characteristics. As for critical temperature, they believed that it is dependent on the curvature of the imperfection at the horizontal position at which it occurs. Subsequently, Richards (1990) studied the effect of imperfection shape on upheaval buckling behavior. He obtained the conclusion again that the critical force is sensitive to imperfection shape of pipeline. Palmer et al. (1990) studied upheaval buckling problem of pipeline. The initial imperfection of pipeline is expressed by two parameters height and wave length. They believed the pipeline follows from elementary beam-column theory and the initial specific shape only affects the coefficients and not the general form of the equation. By defining two dimensionless quantities they obtained a semi-empirical design method. Maltby and Calladine (1995) studied the upheaval buckling of buried pipeline by experiments and theoretical analysis. They presented a formula for predicting the critical force of buried pipeline which involves three parameters-the flexural stiffness of the pipe, the initial imperfection amplitude of the pipe and the “plateau” value of the soil resistance curve. Also, they pointed out initial uplift temperature is inversely proportional to the curvature of initial imperfection at $x=0$. Croll (1997) provided a simple means for predicting the non-linear response displayed by geometrically imperfect pipelines. Also, he presented two equations for predicting the critical axial force aimed at two initial imperfection models that Taylor presented. The two equations are similar to those presented by Taylor. After that, Wang et al. (2011a, 2011b), Shi et al. (2013), Liu et al. (2013, 2014), Zhao and Feng (2015) also studied this problem. But they all did not provide an explicit and universal formula to express the effects of initial imperfection shape, wave length, and amplitude on the critical axial force of pipeline.

Taking into account the imperfection out-of-straightness as a whole, Zeng et al. (2014) presented a new formula of critical force based on dimensional analysis. The formula is

$$P_L = g(w_0/L_0)(q^2EI)^{1/3} \tag{1}$$

He defined a coefficient function $g(w_0/L_0)$ to express the effect of initial imperfection on the critical force. Here w_0/L_0 represents the OOS of pipeline. He pointed out that different initial imperfection shapes correspond to different coefficient values. Specific to three different initial imperfections, he obtained three formulas by finitely element analysis. Karampour et al. (2013) provided some analytical solutions based on a long heavy elastic beam resting on a rigid frictional foundation. The shape influence on the critical force was verified again in his work. Their works made the effect of initial imperfection on critical force more explicit. But they did not explain why different initial imperfection shapes correspond to different critical forces. And they did not give a united formula to express the effect of the initial perfection shape of pipeline on the critical axial force.

Many researchers found that the pipe/soil interaction characteristics also affect the upheaval buckling behavior of submarine pipeline (Ellinas et al., 1990; Schaminee and Zorn, 1990; Palmer, 2003; Newson and Deljoui, 2006; Cheuk et al., 2007; Merified et al., 2008). The uplift resistance and the mobilization distance are two important parameters which affect the critical axial. Nonetheless, the current study mainly discusses the effect of initial imperfection on critical force.

Previous researches have shown that both initial imperfection and pipe/soil interaction characteristics affect the upheaval buckling behavior. For initial imperfection, the critical axial force of upheaval buckling is sensitive to the imperfection shape and OOS of pipeline. Although many researchers have presented some formulas to calculate critical axial force for some particular initial imperfect shapes, there is no united formula to express the effects of the initial perfection shape and OOS of pipelines on the upheaval buckling critical axial force. This paper focuses on the effect of initial imperfection on the critical axial force. In this paper, eight different initial imperfections are analyzed using the finite element software ABAQUS. The reason why different initial imperfection shapes have different critical values is presented. A new parameter is defined to express the differences of initial imperfection shapes. Finally, based on the works of previous researchers especially Zeng et al. (2014) and Karampour et al. (2013), a simple and united formula to calculate critical axial force is presented which covers both the effects of initial imperfection shape and the OOS. It can be used to predict the critical axial force for any known initial imperfection.

2. Analytical model

According to the research of Taylor and Tran (1993), an initial configuration of a submarine pipeline can be illustrated in Fig. 1. The pipeline is laid on an uneven sea bed. The soil of the seabed is very hard, so the sea bed can be treated as a rigid foundation. It is assumed that the system is symmetric on the w axis, as shown in Fig. 1. A pipeline segment with a length of L is selected for research. The pipeline segment has an imperfection due to the uneven sea bed. L_0 denotes the wave length of imperfection. And w_0 denotes the maximum height of imperfection. Because of downward loads, for instances of the pipeline submerged self-weight and covering soil, the pipeline is closely in contact with the rigid foundation.

The axial force P caused by temperature is (Hobbs, 1984)

$$P = EA\alpha T \tag{2}$$

The axial force P caused by internal pressure is (Hobbs, 1984)

$$P = \frac{ApD}{2t}(0.5-\upsilon) \tag{3}$$

where parameters A, D and t denote pipeline cross-section area, external diameter and thickness, respectively. E and υ denote Young's Modulus and Poisson ratio of pipeline material, respectively. T, α and p denote temperature change, thermal expansion coefficient of pipeline and internal pressure, respectively. It is assumed that the initial imperfections have some forms as follows.

2.1. Initial imperfection forms

Based on elementary beam-column theory of idealized pipeline (Palmer et al., 1990), the equilibrium equation is

$$EI\frac{d^4w}{dx^4} + P\frac{d^2w}{dx^2} + q = 0 \tag{4}$$

Tore Soreide et al. (2005) pointed out that the equation has a general solution

$$w(x) = A_0 + A_1 \cos(kx) - \frac{q}{2P}\cdot x^2 \tag{5}$$

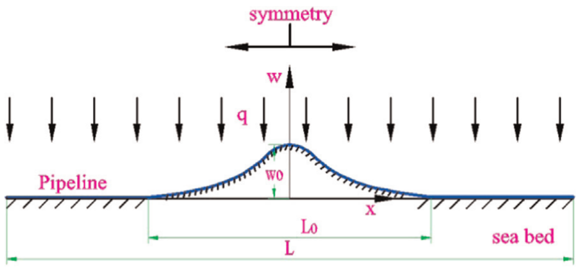

Fig. 1. Analytical model.